A HYBRID PANEL/IMAGE METHOD FOR CALCULATING WALL CONSTRAINT EFFECTS IN SUBSONIC WIND TUNNELS

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Abstract

This paper describes an efficient and robust method for predicting the constraint and support interference effects found in wind tunnels tests. The method is based on the use of a panel method to represent the wind tunnel walls. However, by itself, a panel method representation of the walls may not be sufficiently accurate or robust and great care is needed in modelling wind tunnel flows. Particular problems arise if the panelling is relatively coarse or the model under test or its wake approaches a tunnel wall closely. The discrete nature of the panels becomes apparent and 'leakage' effects can corrupt the solution. A hybrid method is described here that circumvents these problems by constructing 'first images' of the wind tunnel model by reflecting the model in each of the tunnel walls. These images are used in conjunction with the panel method to model the flow in the wind tunnel. The hybrid method produces very accurate results even for a coarse panelling of the tunnel walls. The hybrid approach has been applied to both two- and three-dimensional flows giving excellent agreement with analytical results for lift and blockage corrections. Results are given showing the accuracy of the method and its use with complex models, including wake roll up.

Introduction

Modern wind-tunnel testing is striving for new levels of accuracy in results from aerodynamic tests. Advanced tunnels, such as the 5 metre pressurised tunnel in the UK, the F1 pressurised tunnel in France and the European ETW cryogenic wind tunnel, can achieve full-scale Reynolds numbers so removing the doubts concerning scale effects on lift and drag and the need to extrapolate to full-scale conditions. Reference[14] presents results that highlight the importance of scale and compressibility effects in tunnel testing at low Mach numbers. However, even though tests may be conducted at the equivalent of full scale conditions corrections must still be made for the interference of model support systems and the constraining effects of the tunnel walls on the flow if results equivalent to free-air conditions are to be obtained. These constraint and interference effects assume a dominant role in determining the accuracy of the results. Furthermore, the vital role of wind tunnel tests in providing data for the verification of CFD codes has also required that the actual (constrained) flow about the model in the tunnel is known accurately if reliable data is to be obtained.

There is therefore considerable importance attached to developing accurate methods for correcting for these constraint and interference effects. With high wind-tunnel utilisation rates and the need to process data quickly, a subsidiary, but still important, goal is to develop methods that are robust, simple and rapid to use on a day-to-day basis. A wind tunnel correction method meeting these requirements of robustness, ease of use and accuracy is described in this paper.

Constraint and Blockage Effects

A particularly important correction that must be applied to results from wind tunnels is the lift constraint correction. This correction is necessary because of the confining effect of the tunnel walls on the lifting flow about a model. The lift produced by the model is associated with a downwards deflection of the flow past the model. However, because of the presence of the tunnel floor and walls, the downwards deflection of the air is prevented at the tunnel floor. The wind tunnel walls, by constraining the flow in this way, effectively attempt to 'push' the flow back up, i.e. it produces an upwash. This upwash is felt back at the model as an increase in incidence, so the angle of attack of

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the model is not simply the geometric incidence of the model. The increase in incidence due to tunnel-induced upwash must be added to the geometric incidence as the lift constraint correction. The correction is especially important in high-lift testing because of the high lift coefficients and large downwash produced in these tests.

There are two other constraint effects that must be accounted for. The first is that the cross-sectional area of the flow about even a non-lifting body is reduced by the presence of the tunnel walls. The flow is 'blocked' by the presence of the body and thus accelerates around it to higher speeds than if the model was tested in free air. A similar effect occurs if there is a large separated wake behind the body - the flow is constrained or blocked and increases the flow speed in the vicinity of the model. The net result of these two blockage effects (respectively solid blockage and wake blockage) is that the reference speed for the test is increased, and the aerodynamic coefficients have to corrected accordingly.

Finally, the model support system (struts, stings, etc) can have a marked effect on the loads experienced by the model. These support interference effects must also be accounted for in the correction of wind tunnel results.

Review of Existing Methods

The classical method for calculating the tunnel-induced upwash and associated incidence corrections is the method of images. In this method, first described by Glauert[4], the tunnel working section is considered to be of infinite length and rectangular cross section. The lifting model under test is represented by a simple horseshoe vortex system. An image system is set up by reflecting the vortices representing the lifting surfaces in the walls, floor and roof of the tunnel, then reflecting the images again, *etc.* to give an infinite set of images that, in conjunction with the flow induced by the vortex system representing the actual model, give a flow parallel to the tunnel sides. The velocity induced by the images alone at the model is then calculated and used to determine the effective change in incidence of the flow at the model due to the constraint effect.

Image systems of this type can only be set up for simple tunnel cross-sectional shapes – circular, elliptic and rectangular, though Batchelor (see[7]) has presented an approximate image method for tunnels with corner fillets. Results for models not on the tunnel centreline may also been obtained by the image method, but the analysis becomes very involved. To aid the application of tunnel corrections, a compendium of results from the image method is presented in reference[7]. However this only shows results for specific tunnel shapes, and does not include the cross-sectional shape of the 5 metre tunnel, for example.

To cater for arbitrary tunnel cross-sectional shapes a more flexible approach was introduced in the early 1970s by Joppa[12], who used a vortex-lattice to represent the tunnel walls. The tunnel walls are panelled as shown in figure 1. The panels at the downstream edge of the tunnel are extended downstream (as semi-infinite trailing legs) to enforce a Kutta-condition at the 'trailing edge' of the tunnel and thus to fix the overall circulation about the tunnel walls. Without this condition, the method is ill-posed. Again simple vortex representations of the lifting model were used to estimate the downwash produced at the tunnel walls by the model and then the strength of the vortices in the lattice were found so that the tunnel wall was a stream surface. The velocity induced by the vortex lattice system at the model location was then used to calculate the incidence correction. Holt and Hunt[9] also present results from a panel method for calculating wall constraint effects, though in this case source panels are used to represent the tunnel walls instead of a vortex lattice. Wässerstrom *et al*[21] use a vortex-lattice method used to predict lift constraint effects in closed, partially and completely open (free-jet) tunnels.

Although the panel method approach has permitted the lift constraint of tunnels of arbitrary cross-section to be calculated, care was needed in the details of how many panels to use, the size and distribution of the panels, where the model is positioned with respect to the working section, etc. Particular care was required when the model approaches the tunnel walls, as leakage can occur if the panel density is too low leading to large errors in the calculated constraint effect. This leakage occurs because the panels do not prevent flow across all their face, but only at the control points used in the calculation. When a model approaches closely to the wall or floor of the panel representation of the tunnel, it effectively 'sees' holes in the panels. To quote from reference[9]

> *"If some type of estimate is not made to 'guarantee' the adequacy of the wall panel density, then the results of the numerical (panel program) calculation....must be held in doubt. The alternative 'guarantee', by using a very large number of panels on the tunnel walls, is computationally expensive ..."*

More recently, a method for estimating lift constraint and blockage effects has been developed that relies on static pressure tappings in the tunnel wall to measure tunnel wall pressure distribution during the test. An example of this type of method is described in reference[2]. This method is very effective and can, in principle, account for all forms of constraint correction. Two disadvantages of this method are that a large number of pressure tappings must be placed in the tunnel wall, and the constraint and blockage effects can not be estimated until the test is complete. Some *a priori* estimate of lift constraint is essential when sizing tunnel models but the wall pressure method cannot provide this. Furthermore, separate support interference effects cannot be determined by this method.

With the growth in speed and memory capacity of modern computers, computational fluid dynamics is being used to compute the flows about complex shapes in wind tunnels – for example, Takakura *et al*[19] show results for the computed flow past a sting–mounted wing-body-tail combination in a transonic wind tunnel obtained by solving the thin-layer Navier-Stokes equations. However, this approach cannot yet be recommended for regular use in correcting wind–tunnel results.

Perhaps the ultimate treatment of tunnel wall effects is to remove them altogether, and this is achieved by adapting the wall shape to follow the stream surface that would exist in an unbounded flow, as described in reference[6]. This requires an estimate of the unbounded flow and then aligning flexible tunnel walls with the calculated stream surface. The reward for this effort is that no constraint corrections need to be applied to the results. However the technique requires the use of flexible walls and has been used only rarely, predominantly for two-dimensional flows. Its main attraction is for transonic wind tunnel testing, where the need to avoid shock reflections from the tunnel wall and excessive blockage is paramount and is effectively 'uncorrectable' if it occurs.

The use of panel methods for the calculation and understanding of support interference is well-established. For example reference[8], gives an account of the complex and subtle lifting interactions that can exist between a model and its support strut fairings, Joosen[11] gives theoretical results for the effect of a sting support system on a complete Airbus A300 model in the DNW tunnel, while Steinbach[17] examines the effects of vertical and rear sting supports on an AGARD tunnel calibration model. More sophisticated analyses, examining support interference in the presence of tunnel walls are described by Vaucheret[20], Rueger and Crites[13] and Steinbach[18]. However, in each of these cases, great care is taken to refine the panel density for the tunnel walls near the model and its support system, for example, in reference[18] by clustering the panels near the aerodynamic centre of the model. This leads to large number of panels being required - typically over 3000 panels for the tunnel walls alone.

The Hybrid Panel/Image Method

The method described in this paper combines the best features of the classical image method and modern panel methods to overcome the drawbacks of each. The starting point for the present method is the recognition that the majority of tunnels in use today have nearly rectangular cross-sections with corner fillets. Thus the image method should give a good initial approximation to the constraint effect. It cannot readily calculate the effect of fillets or of placing the model off the tunnel centreline. However, these last effects are easily represented by a panel method. A combination or hybrid scheme is thus needed.

The hybrid method initially follows similar lines to those proposed by Joppa[12], i.e. the tunnel walls are represented by a vortex lattice (or a distribution of source panels, if preferred), but the images generated by reflecting the test model once in the floor, walls and roof (the "first images") are also constructed, as illustrated in figure 2. The effect of the first images is to reduce the flow velocity normal to most of the bounding walls of the tunnel cross section - the tunnel-wall panels then eliminate the small residual normal velocities. The first images contribute most to stopping the flow through the wall and contribute most of the upwash. The vortex lattice panels have merely to account for the the effects of residual normal velocities, fillets, etc.

The velocities normal to the tunnel walls induced by the lifting model and its images at the panel collocation points are then calculated. This velocity field will not, in general, produce a flow that is parallel to the tunnel walls, so the strength of the vortex lattice is chosen to eliminate the remaining velocity component normal to the tunnel walls. However, the panels representing the tunnel walls have to provide a smaller contribution to the total velocity at the tunnel walls in the hybrid method when compared to Joppa's original method without the use of images, and the variation in normal velocity at the collocation points is much smoother than if the first images were not used. The strength of the vortex lattice representing the tunnel walls is found by first calculating the influence matrix for the normal velocity at the collocation points induced by the vortex lattice and using this matrix to find the strength of the vortex rings that give parallel flow at the collocation points (vortex ring centres). At the same time, the influence matrix for the effect of the vortex lattice on the model may be computed.

Once the strength of the tunnel wall vortex lattice has been found, the velocities induced by the vortex lattice *and* the images of the wind tunnel model on the model itself are computed. This gives the velocity field induced by the tunnel walls on the model and this is processed to give the constraint and blockage factors. These are obtained from the vertical (upwash) component w of the velocities thus calculated (leading to the lift constraint correction), and the streamwise component u (leading to the blockage correction).

Comparison with Exact Results

To validate the hybrid approach, the classical problem of estimating the lift constraint correction of a simple horseshoe vortex model on the centreline of a rectangular tunnel is used. Results are given for the upwash induced at the bound (transverse) segment of the horseshoe vortex. This is the simplest result to derive in the classical image method, as the upwash in this case is due entirely to the trailing segments of the image vortices.

The mean incidence correction factor δ_o, is defined by

$$\delta_o = \frac{\Delta\alpha C}{C_L S}$$

and $\Delta\alpha$ is the mean change in incidence induced by the constraint effect, C is the tunnel cross-sectional area, C_L is the lift coefficient of the model and S is the model reference area, is found from the upwash velocity field.

As the aim of the present method is to reduce the extent and number of panels needed for an accurate representation of the tunnel walls an important consideration is the length of tunnel working section that must be represented. A numerical study was conducted to investigate this and has shown that it is necessary for the front of the lattice to extend upstream some one and a half times to two the tunnel height of the test model location. Results from this study are shown in figure 3. A similar study has shown that about two tunnel heights are also required downstream of the model.

The next issue is the number of panels required around the periphery of the tunnel. As an illustration of the number of panels needed to represent the tunnel walls, figure 4 shows the convergence of δ_o (the upwash factor at a given spanwise position) with increasing number of panels for a square tunnel. The 'model under test' in this case is again a horseshoe vortex, so that a comparison with analytical results from the classical image method can be made. The spanwise variation of upwash factor is shown. Even with just three panels representing each side of the tunnel the hybrid scheme gives results close to the exact values, while the vortex lattice alone is grossly in error with so few panels. About eight panels per side of the tunnel is seen to be sufficient for almost exact agreement with the analytical results as long as the first images are used. If the vortex lattice alone is used considerably more panels are required to achieve comparable accuracy.

The unswept horseshoe vortex is a special, but convenient, test case. To investigate the accuracy of the hybrid method when applied to more representative examples, a swept-wing model was used. A further check on the accuracy of the present method is given in figures 5 and 6, which show the predicted variation of upwash factor across the span and downstream along the model centreline respectively. The results are compared with those given in the AGARD compendium[7], with excellent agreement.

A particular advantage of the present method is that the inclusion of the first images mitigates the problems associated with a model approaching a tunnel wall of floor closely. As the model approaches the wall the first image reflected in that wall also moves nearer and large flow velocities through the wall are prevented by the image system. To estimate the lift constraint the velocities induced at the lifting model by the vortex lattice representing the tunnel walls and the first set of images is calculated. This is illustrated in figure 7, which shows the predicted effect of model position on the mean upwash factor as the model approaches the tunnel floor. Using just four panels per side the vortex lattice method predicts completely the wrong trend for low model positions (due to increase leakage), while the first images alone produce improved, but inaccurate, results. However, when used in combination in the hybrid scheme the exact curve is followed very closely.

Testing in Ground Effect

Tests are occasionally carried out for models near the ground by introducing a groundboard or rolling road under the model. The hybrid method can readily accommodate this case. When correcting for the effects of lift constraint, the image of the model in the ground plane (the tunnel floor) is not included when evaluating the tunnel-induced upwash at the model, though the other images and all the vortex lattice elements are. This may be easily carried out in the present method by simply omitting the contribution of the appropriate image. The hybrid method therefore provides a simple way of correcting tests in ground effect that explicitly recognises the 'real' image system reflected in the ground plane.

Example Applications

With the accuracy of the basic method proven for idealised test cases, some 'real' applications of the method are now described, to illustrate the flexibility of the method.

Lift Constraint in Compressible Flows

The hybrid method has also been applied to compressible flows, to predict the lift constraint correction on a model tested at transonic conditions. The compressibility effects were incorporated in the hybrid panel/image method by an affine transformation of the model, increasing the streamwise ordinates by an amount given by usual Prandtl-Glauert rule of $(\sqrt{1-M_\infty^2})^{-1}$.

To assess the accuracy of the method for these flows, results from a half-model of a 34° swept wing of aspect ratio 3 tested in transonic tunnel at Mach numbers of 0.6 and 0.8 were used. Accurate wind tunnel corrections were vital in this case as the tests were performed to obtain test case data for new methods in computational fluid dynamics and so wall-pressure measurements were taken to estimate the corrections via the method of Ashill and Weeks[3].

A comparison of the predictions of the hybrid scheme and the results from the wall-pressure method are compared in figure 8 for each of the two Mach numbers. The level of agreement between the two methods is very satisfactory. Of note is that the upwash can be represented in a free-air calculation of the wing by including a simple chordwise camber distribution that is almost independent of spanwise position.

Detailed Models

The hybrid method can be used with quite sophisticated panel method models describing the test model, its wake and support system.

It should be noted that it is not necessary to create a set of 'panelled' model images of the test model explicitly – it is the relative position of the singularity and its collocation point that are important in a panel method and so it is possible to obtain the image influence coefficient by calculating the effect of panels on the model on 'reflected' collocation points. This greatly simplifies the procedure.

The panel representation of the test model can also include the effect of wake-roll up in the presence of tunnel walls. The trajectory of the wake in the wind tunnel is different from its free-air path, so the pitching moment will be affected. Joppa[12] describes the importance of the wake position on downstream lifting elements, e.g. tail surfaces, although a wake relaxation calculation may be prohibitive in panel methods without the hybrid approach[18].

Figure 9 shows a high–lift model as tested in a low-speed wind tunnel. The model was fitted with a part span flap. Note that a relatively coarse panelling of the tunnel is used in combination with a much finer panelling of the model. The wake from the flap and wing were allowed to roll-up in the calculation, and the results shown in figure 9. The hybrid scheme gave no problems in this calculation, despite the mismatch in model and tunnel panel densities.

Support Interference

A key feature of the present method is its potential for application to support interference estimation. An example of a rather subtle support interference effect is shown in figure 10, where an unswept rectangular wing fitted with high-lift devices is supported in the tunnel on a pair of struts fitted with aerodynamic fairings. The wakes shed by the wing and strut fairings is shown. The sidewash induced by the trailing vortex system of the wing puts the strut fairings at an aerodynamic incidence, so that they too shed a wake that rolls up and in turn induces an upwash on the wing under test. The hybrid method used 2000 panels for the wing, supports and wind tunnel walls in this example – a considerable reduction from earlier studies for results of similar accuracy.

Finally, figure 11 shows the panelling used to represent a combat aircraft model mounted on a very simple support system in a low-speed tunnel. It was hoped that because of the distance of the main struts from the model there would only be a small amount of interference that could be treated as a simple blockage giving a uniform streamwise velocity increment at the model. The hybrid method permitted a relatively crude representation of the tunnel walls to be used in conjunction with a detailed representation of the model and its support system. The hybrid method predicted a substantial effect of the mounting system on the pressure distribution over the wing, particularly on the lower surface where the support system leads to a marked lowering of pressure under the wing (see figure 12) with a substantial effect on the wing lift-curve slope. The level of interference predicted by the hybrid method was confirmed by the tunnel tests, which were then corrected using the results from the hybrid method. This study shows the importance of representing a detailed model of the support system - the major blockage effect is an asymmetric one, leading to a change in the lift-curve, and not a simple change in tunnel reference speed (Δq) for the whole model.

Conclusions

A new hybrid panel/image method for calculating tunnel-wall constraint in three-dimensional flows has been described. The hybrid panel/image method has been shown to be an accurate method for predicting tunnel lift constraint and blockage corrections. The use of the hybrid panel/image method has two major strengths – it allows a simple to use as a 'black box', as the method is not sensitive to details of the tunnel panelling, and permits detailed studies of model and support interference effects (including wake roll up) for a small overhead on the free–air panel method calculation.

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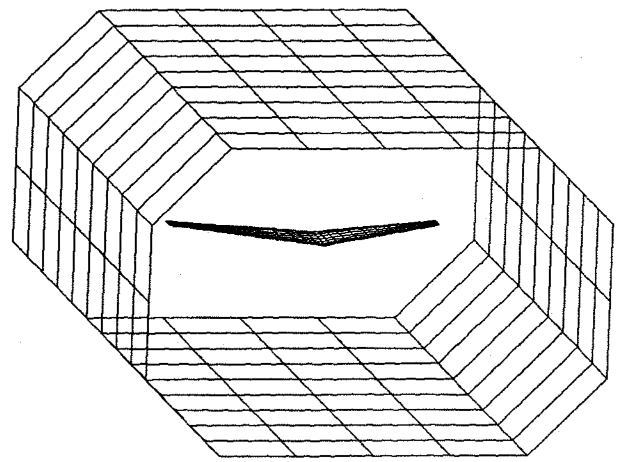


Figure 1

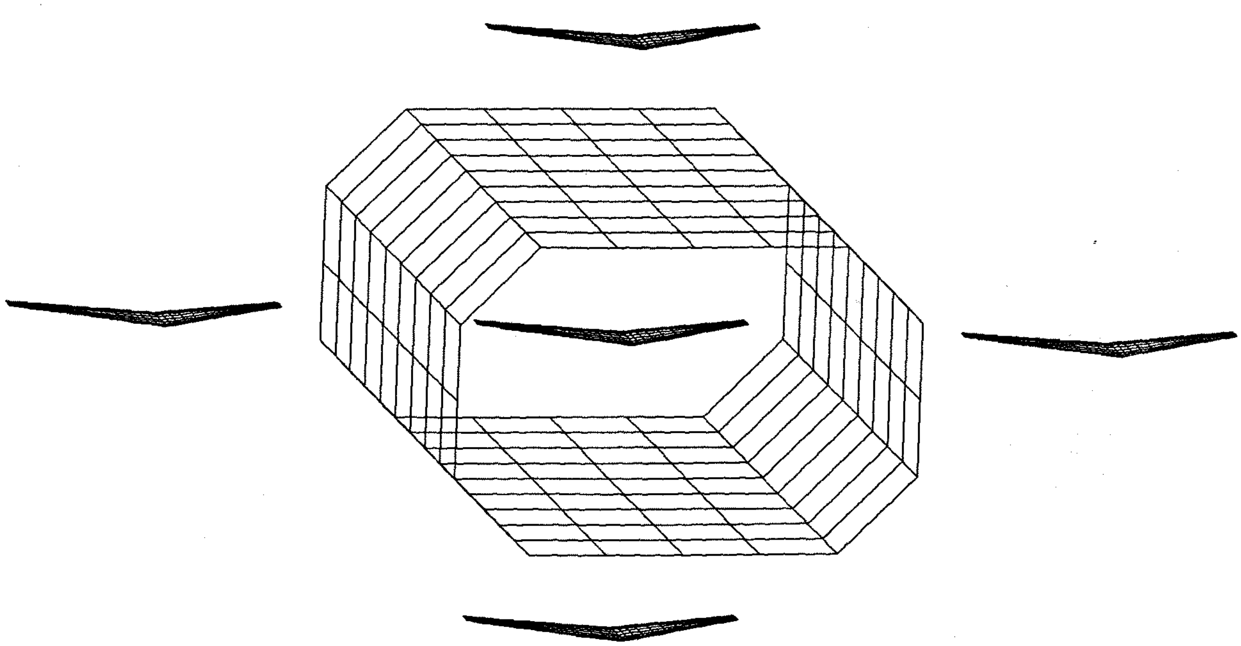
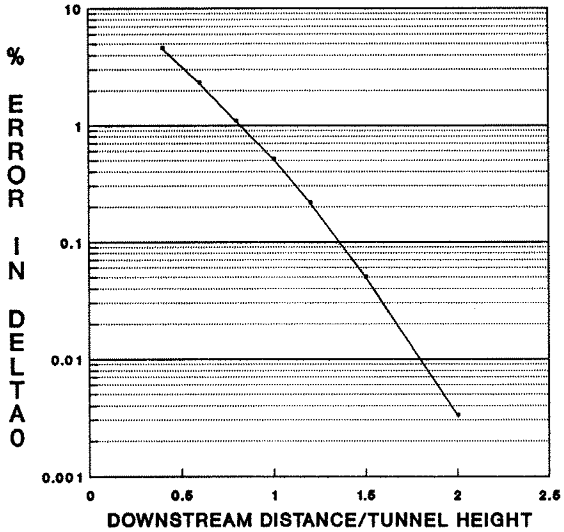


Figure 2

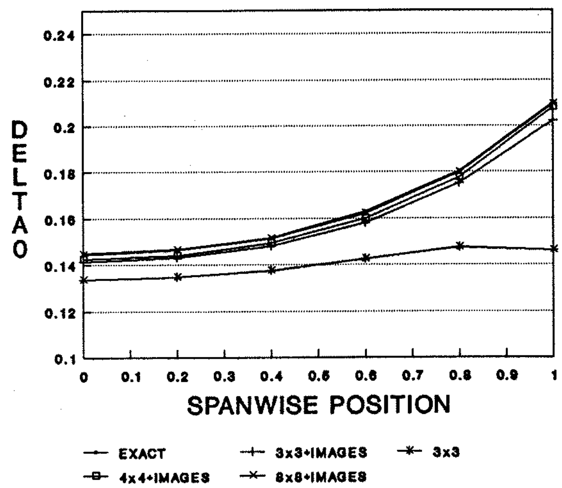
EFFECT OF DOWNSTREAM MODEL POSITION



SQUARE TUNNEL
SPAN/WIDTH • 0.6

FIGURE 3

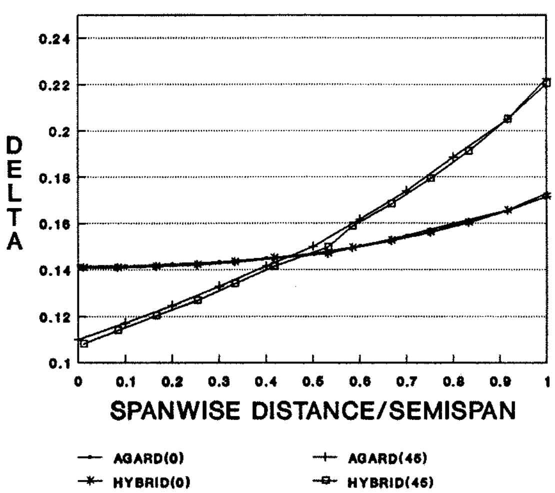
CONVERGENCE WITH INCREASING NUMBER OF PANELS



SQUARE TUNNEL
SPAN/WIDTH • 0.7

FIGURE 4

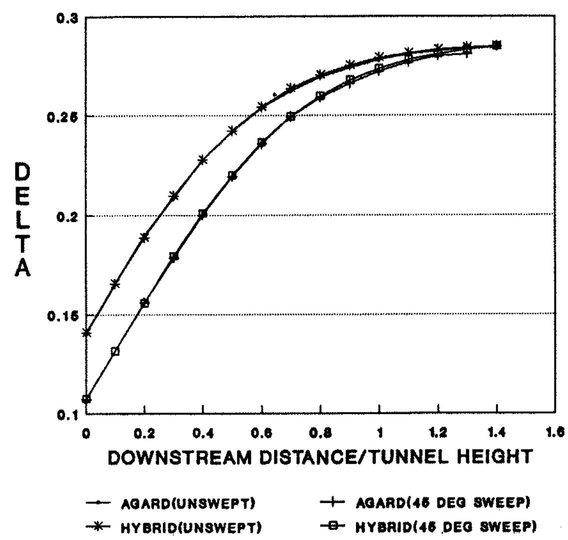
EFFECT OF SWEEP ON VARIATION ACROSS SPAN



SQUARE TUNNEL
SPAN/WIDTH • 0.6

FIGURE 5

UPWASH FACTOR ON CENTERLINE



SQUARE TUNNEL
SPAN/WIDTH • 0.6

FIGURE 6

MEAN UPWASH FACTOR
FOR MODEL NEAR FLOOR
4x4 PANELS

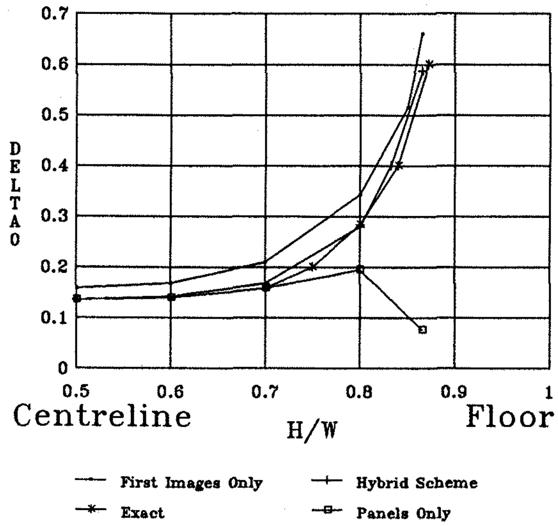


FIGURE 7

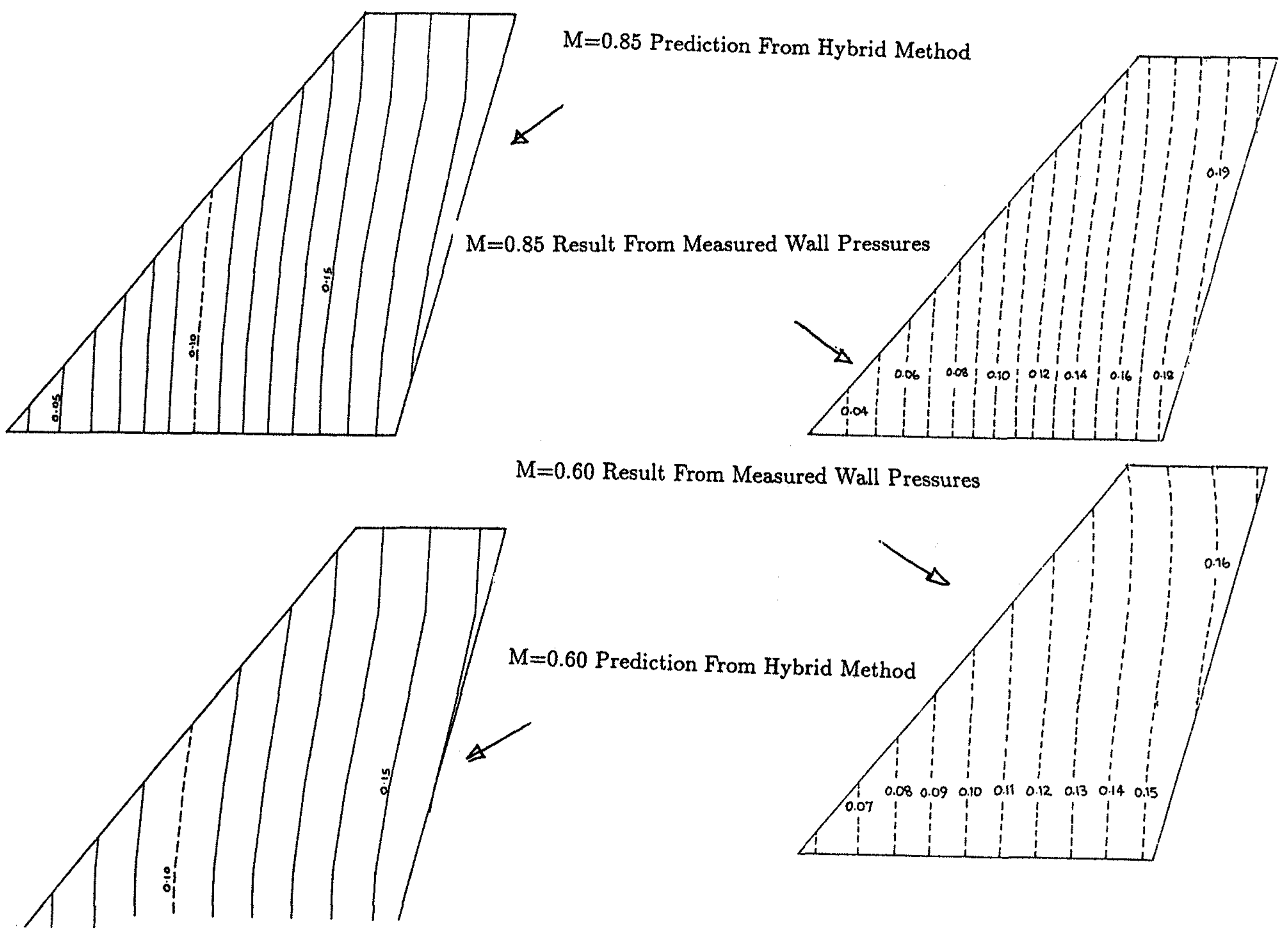


FIGURE 8
Lift Constraint for High Speed Flows

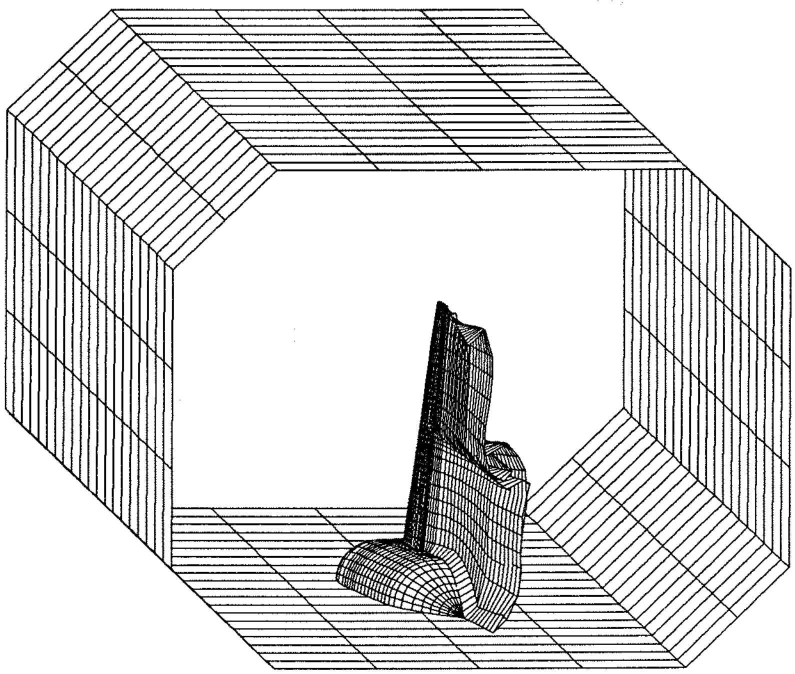


FIGURE 9
HIGH-LIFT HALF MODEL
WITH WAKE ROLL UP

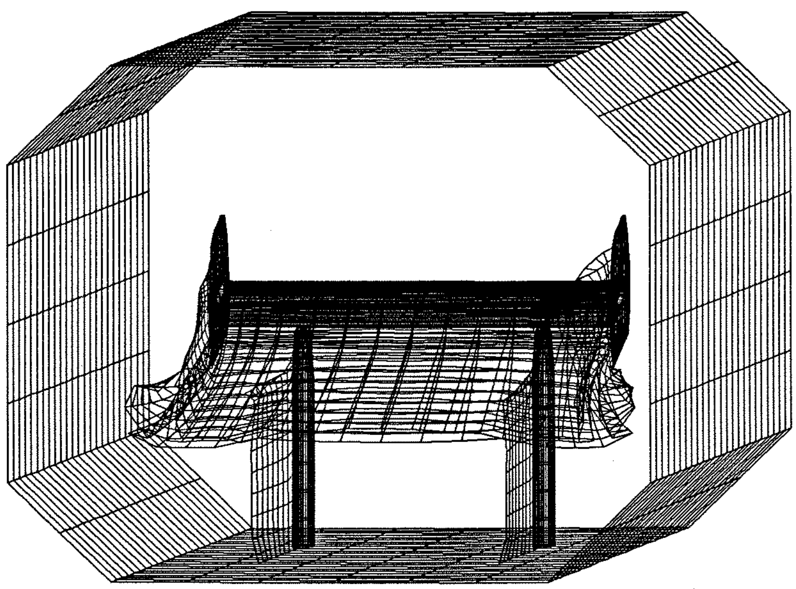


FIGURE 10
HIGH-LIFT ENDPLATE MODEL
WITH WAKE ROLL UP

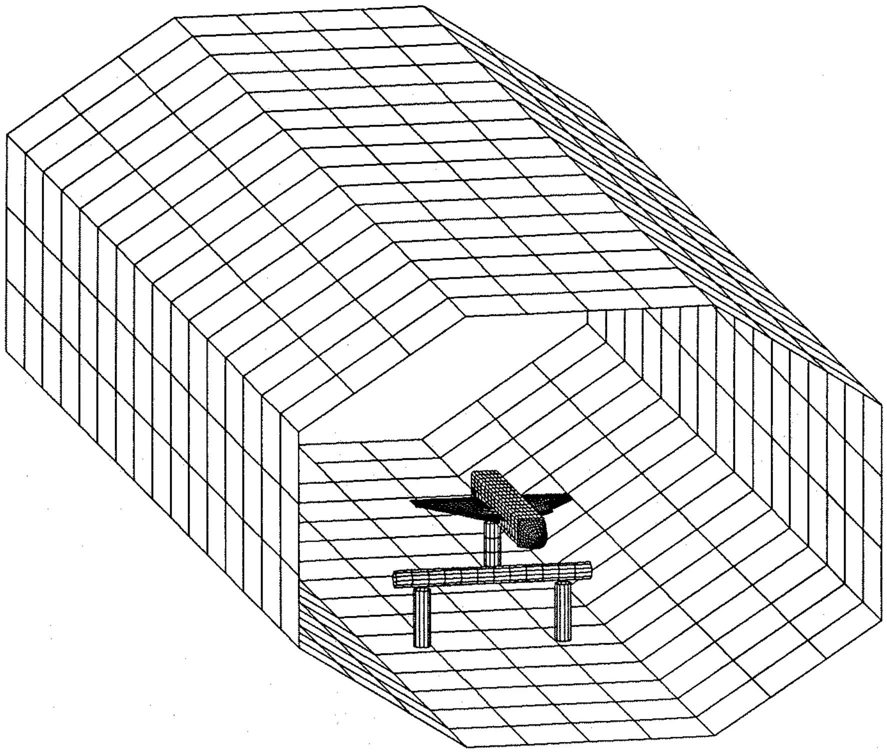


FIGURE 11
CANARD MODEL ON A
SIMPLE SUPPORT SYSTEM

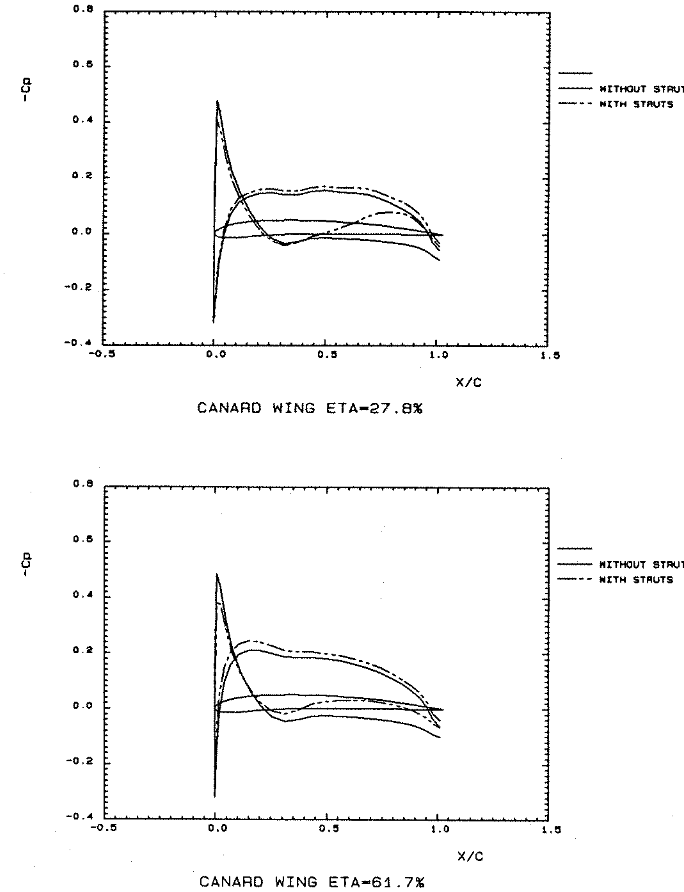


FIGURE 12
SUPPORT INTERFERENCE
WING PRESSURES