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JOINT INSTITUTE FOR AERONAUTICS AND ACOUSTICS
STANFORD UNIVERSITY

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Progress Report

NASA GRANT NCC 2-55

THE RESEARCH AND TRAINING ACTIVITIES FOR THE JOINT INSTITUTE FOR AERONAUTICS AND ACOUSTICS

Submitted To The

NASA Ames Research Center
Moffett Field, CA 94035

Report Covering the Period

October 1991 - September 1992

BY THE

DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
STANFORD UNIVERSITY
STANFORD, CALIFORNIA 94305

Principal Investigator

Prof. Leonard Roberts

December 1992

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Research and Training Activities of the Joint Institute for Aeronautics and Acoustics

During the period October 1991 to September 1992 progress was made on each of the following tasks:

1. Fundamental Studies of Free Shear Flows
2. Experimental and Theoretical Studies of Vortex Flows
3. Analysis of Conical Flow with Blowing or Suction
4. Computation of High Speed Transport Aerodynamics
5. Aircraft Attitude Control Using Active Flow Control

The details of this work have been discussed with the technical and management staff at Ames Research Center.

1. Experimental Studies of Free Shear Flows

An experimental investigation has been completed on the three-dimensional structure of curved plane wakes developing from tripped and untripped initial boundary layers. The curved wake represents an important area of study because of its applications to various facets of aerodynamics and hydrodynamics. The curved wake is particularly interesting since it contains both destabilizing (inner half) and stabilizing (outer half) regions. The effects of mild streamwise curvature ($b/\bar{R} < 5\%$) on a wake generated at the trailing edge of slowly tapering splitter plate were investigated at a Reynolds number of about 30,000. Measurements at eleven streamwise locations were obtained on large cross-plane grids with a rotatable cross-wire probe. With the initial boundary layers laminar, well-organized streramwise vorticity was generated in the form of quadrupoles which caused

relatively large spanwise variations in the mean velocity and Reynolds stress distributions (Refs. 1,2). With the initial boundary layers turbulent, spatially-stationary streamwise vorticity was not observed (Ref. 3.). The curvature affected the wake growth and defect-decay rates, but in different ways for each of the two initial conditions. The effects of curvature were also apparent in the Reynolds stress results, especially in the primary shear stress distributions, which showed that the levels on the unstable side were increased significantly compared to those for a straight wake, while those on the stable side were decreased, with the effect stronger in the initially laminar wake.

A study which addressed the question of streamwise vortex meander in plane mixing layers was also completed (Ref. 4). Some of our previous measurements of the streamwise vortical structures in a two-stream plane mixing layer showed that the mean streamwise vorticity decayed with downstream distance (Ref. 5). It was not clear at that time if this measured decay was a result of actual vortex diffusion or increasing vortex meander within the mixing layer. The present experimental study was conducted in order to determine the existence of streamwise vortex meander in a mixing layer, and if present, its significance on the measured properties. The dependence of the velocity cross-correlation on the fixed probe location is considered a good indicator of the stationarity of the streamwise vortex location. The cross-correlation measurements of this study indicate that the spanwise meander is negligible while the transverse apparent meander (normal to the plane of the mixing layer) is relatively large. The transverse meander, exemplified by the elliptical shape of the mean streamwise vorticity contours, was expected, since the streamwise vorticity resides in the inclined braid region convecting downstream. So the balance of evidence suggests that the decay of mean streamwise vorticity recently observed in mixing layers is most probably due to actual diffusion, rather than an artifact of vortex meander.

A modified version of the stochastic estimation was also explored as a means of studying the dynamic (time-dependent) aspects of the mixing layer structure (Ref. 6). The estimation-reference and reference-reference cross-correlations are traditionally used to ob-

tain linear mean-square (MS or stochastic) estimation coefficients. Since the estimation-reference cross-correlation typically decreases rapidly with increasing separation distance, the resulting estimated fluctuations diminish away from the reference locations. A new technique has been developed to determine the linear estimation coefficients by minimizing the squared error in *both* the estimation covariance and the estimation-reference cross-correlation. By also minimizing the error in the estimation covariance, realistic velocity fluctuations can be estimated without significantly altering the correlation between true and estimated velocity signals as given by the traditional method. Comparisons of the proposed method to MS estimation of a plane mixing layer have been used to demonstrate the effectiveness of the proposed technique. The new technique is particularly useful for free-shear flows when the interest is in the large scales.

Publication of some previously completed research has also been achieved during this time period (Refs. 4,7-10).

References

1. "Three-Dimensional Structure in a Curved Wake", J. H. Weygandt and R. D. Mehta, Presented at the 44th APS Meeting and abstract published in the Bulletin of the Americal Physical Society, Vol. 36, No. 10, P. 2682, 1991.
2. "Three-Dimensional Structure of a Curved Wake", J. H. Weygandt and R. D. Mehta, AIAA Paper 92-0541 presented at the AIAA 30th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1992.
3. "Effects of Initial Conditions on the Development of Curved Wakes", J. H. Weygandt and R. D. Mehta. AIAA Paper 93-0655 to be presented at the 31st Aerospace Sciences Meeting, Reno, Nevada, January 11-14, 1993.
4. "Streamwise Vortex Meander in a Plane Mixing Layer", R. L. LeBoeuf and R. D. Mehta, AIAA Paper 93-0553 to be presented at the 31st Aerospace Sciences Meeting, Reno, Nevada, January 11-14, 1993.

5. "Measurements of the Streamwise Vortical Structures in a Plane Mixing Layer", J. H. Bell and R. D. Mehta, *Journal of Fluid Mechanics*, Vol. 239, pp. 213-248, June 1992.
6. "An Improved Method for Linear Estimation of Velocity Records", R. L. LeBoeuf and R. D. Mehta, submitted to *Physics of Fluids*, August 4, 1992.
7. "Some Effects of Swirl on Turbulent Mixing Layer Development", R. D. Mehta, D. H. Wood and P. D. Clausen, *Physics of Fluids*, Vol. 3, No. 11, pp. 2716-2724, November 1991.
8. "Spanwise Averaging of Plane Mixing Layer Properties", J. H. Bell, M. W. Plesniak and R. D. Mehta, *AIAA Journal*, Vol. 30, No. 3, pp. 835-837, March 1992.
9. "Structure of a Swirling Turbulent Mixing Layer", D. H. Wood, R. D. Mehta and S. G. Koh, *Journal of Experimental Thermal and Fluid Science*, Vol. 5, No. 2, pp. 196-202, March 1992.
10. "Sensitivity of the Structure of Untripped Mixing Layers to Small Changes in Initial Conditions", M. W. Plesniak, J. H. Bell, and R. D. Mehta, Department of Aeronautics and Astronautics, Stanford University, JIAA Report TR-107, August 1992.

2. Experimental and Theoretical Studies of Vortex Flows

The use of a lateral blowing jet to augment lift on delta wings has been reported in several references[1-6]. An experimental study has been undertaken to investigate the effects of spanwise blowing on a delta wing at low to moderate angles of attack. The wind tunnel model (figure 1), comprising an instrumented delta wing with independent internal plena has been designed, fabricated and initially wind tunnel tested to give the effects of blowing on the lift (figure 2) and rolling moment (figure 3) on the wing. The motivation for the study was (1) to augment the normal force by symmetric blowing and (2) to produce a rolling moment by asymmetric blowing at the sharp leading edge of the model.

Balance measurements showed that the normal force can be increased by symmetric blowing and a rolling moment can be increased by asymmetric blowing. There is only a very

weak coupling between the two sides of the wing so that blowing on one side does not effect the vortex on the other side. Initially, a few smoke visualization tests were conducted at $\alpha = 10$ degrees. The observations indicated that the strength of the vortex sheet increases with blowing momentum which causes the flow to roll up and merge with the leading edge vortex sheet. This smoke visualization was carried out at a low velocity, 8m/sec, because of the rapid dispersion of the smoke at higher velocities. Surface-flow oil experiments will be conducted at higher velocities to examine the changes in surface flow under the influence of lateral blowing. To determine the effectiveness of blowing, measurements were made up to $\alpha = 30°$. At small angles of attack ($\alpha = 5°$) the blowing jet rolled down and formed a strong vortex on the lower surface of the model and produced a negative increment in lift. At higher angles of attack (say up to 15°) the normal force increases with increasing jet momentum at moderate to high blowing rates, but may decrease for low blowing rates ($C_m < .03$) for $\alpha = 20°$; its cause has not been determined yet.

The other aspect of the study has been to explore the use of differential blowing to produce rolling moment. Experiments indicated that the variation of rolling moment can be combined as a single curve at $\alpha = 12\frac{1}{2}°$ for all roll angles of between 2° and 10°. Partial blowing was also implemented by blocking the forward portion of the blowing slot, creating the effect of an aileron under asymmetrical blowing conditions. Use of partial blowing was found more effective than full blowing in creating rolling moment at small blowing rates.

Further experiments are in progress to measure the pressure distribution on the wing under blowing and partial blowing conditions and will provide more information to understand the mechanics of lateral blowing and will enable a comparison with theory and previous experiments with different models. The ultimate goal is to explore the feasibility of control by lateral blowing for example for a supersonic configuration, in the absence of conventional control surfaces, during landing and takeoff.

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1. Trebble, W.J.G., "Exploratory Investigation of the Effects of Blowing from the Leading Edge of a Delta Wing", R & M No. 3518, April 1966.
2. Barsby, J.E., "Calculations of the Effect of Blowing from the Leading Edges of a Slender Delta Wing", R & M No. 3692, April 1971.
3. Brown, C.E. and Michael, W.H., "On Slender Delta Wings with Leading-Edge Separation", NACA TN-3430, January 1955.
4. Tavella, D. A., "Lift on Delta Wings with Leading-Edge Blowing", Journal of Aircraft, Vol. 25, No. 6, June 1988.
5. Tavella, D. A. and Roberts, L., "The Concept of Lateral Blowing", AIAA Paper 85-5000, 1985.
6. Lee, C. S., Tavella, D. A., Wood, N. J. and Roberts, L. "Flow Structure and Scaling Laws in Lateral Wing-Tip Blowing", AIAA Journal, Vol. 27, No. 8, p. 1002, August 1989.

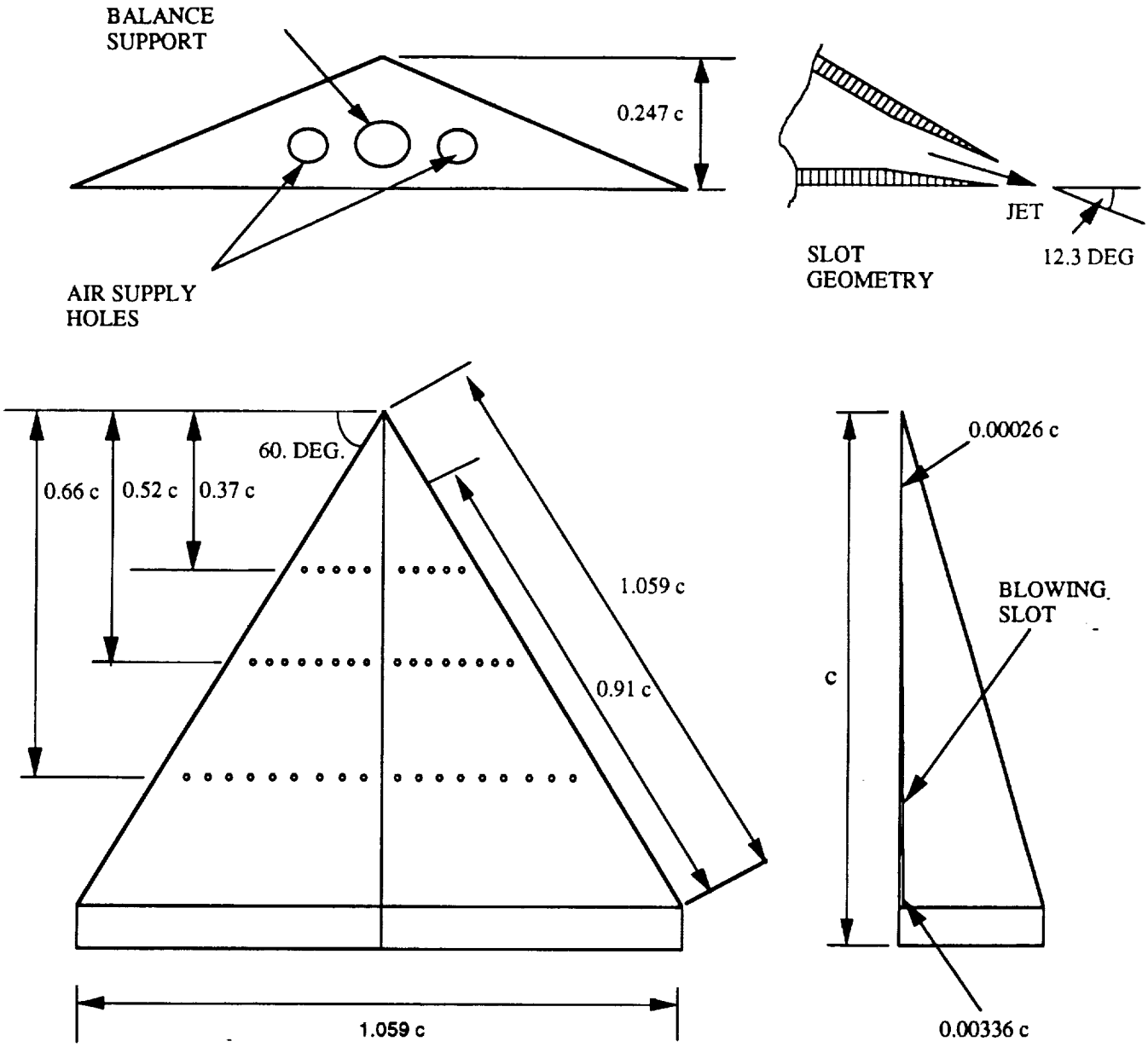
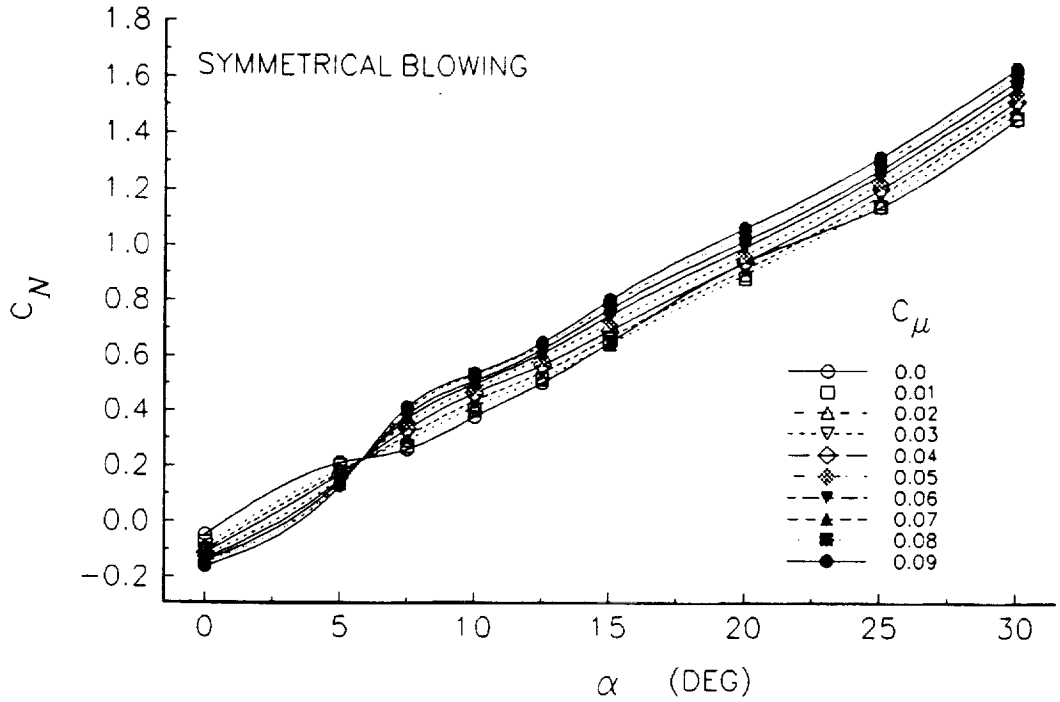
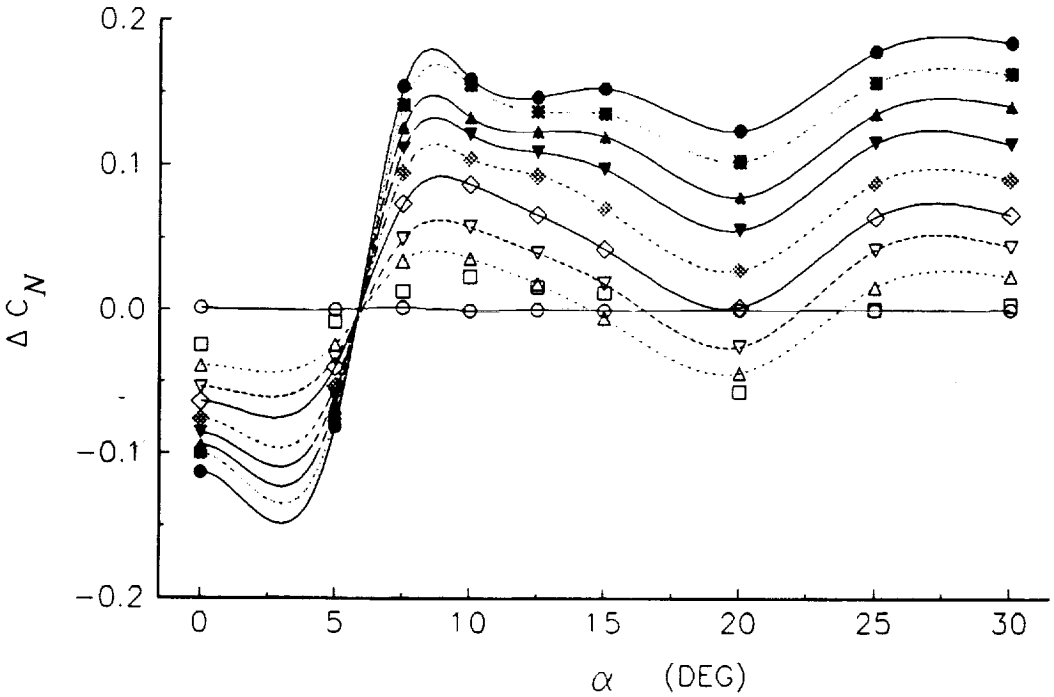


Figure 1: Schematic of the delta wing with leading edge blowing slots



(a)



(b)

Figure 2: Normal force coefficient as a function of angle of attack

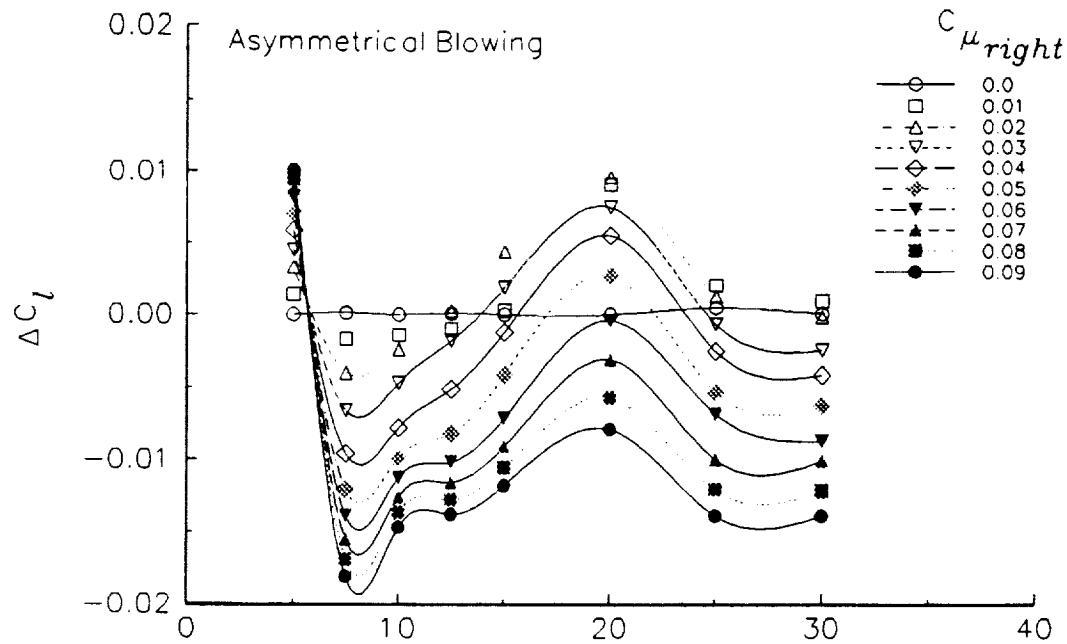


Figure 3(a) Rolling moment coefficient as function of angle of attack. Right side blowing.

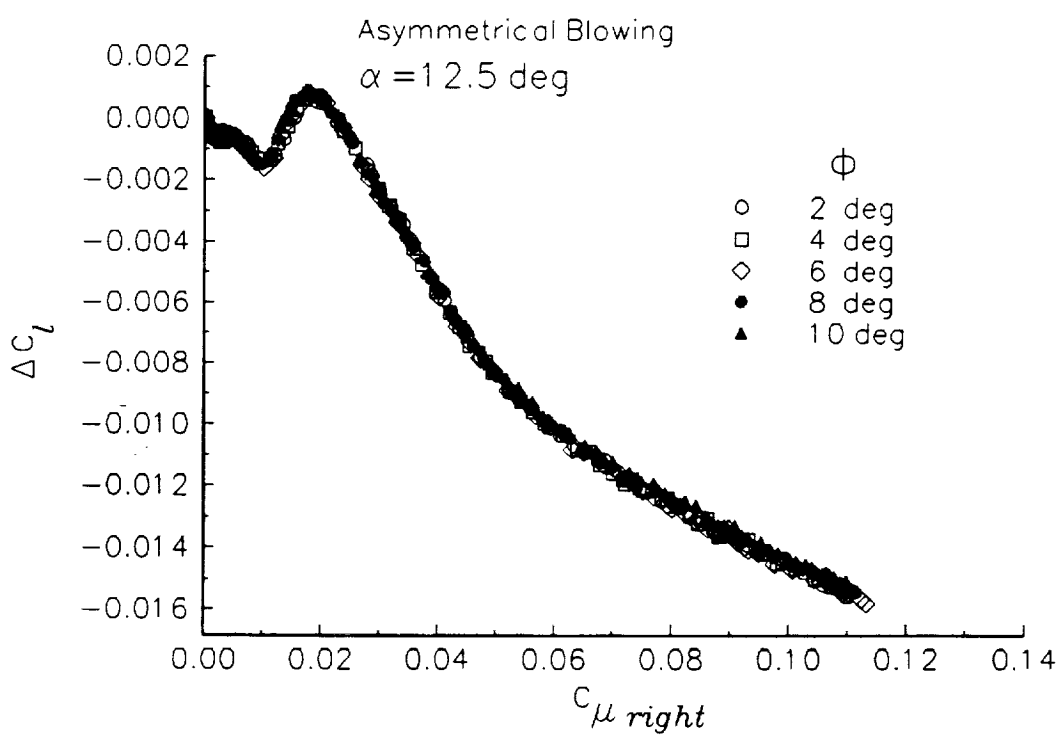


Figure 3(b) Rolling moment coefficient at different roll angles at $\alpha = 12.5°$. Right side blowing.

3. Analysis of Conical Flow with Blowing or Suction

Computations were performed using the Brown Michael (surface line vortex) theory for both the cone and flat plate and improved computations were carried out, using the vortex cloud theory development by Oh (for a cylinder), also on the cone and the flat plate. This latter approach uses the unsteady introduction of vortices at the separation line in the conical flow and allows these vortices to form a cloud giving the vortex configuration after a long enough computation time. Although all computations were carried out for a circular cone the results can be expressed as the flow over the flat plate (delta wing).

The computation was also completed for the flow with a leading edge jet placed on the delta wing to give effects on lift and rolling moments as functions of the blowing coefficient of the jet. Figure 1 shows the vortex configuration and the pressure distribution on the flat plate delta wing for the case of no blowing, where the flow separates at the leading edge of the wing. Figure 2 shows the result when a small amount of blowing is introduced at the right leading edge causing the flow to separate at the inboard location on the right while remaining separated at the leading edge on the left. Figure 3 shows the fully attached flow over both leading edges associated with massive blowing at those locations. Suprisingly it is found that the jet can overcome the singularity at the leading edge of the delta wing and can provide a rolling moment to be used in control even for a zero thickness wing. The results of the research will be given in an AGARD paper (ref. 2).

Results were also obtained experimentally for blowing on hemispherically and pointed tip cone-cylinders in the 45 cm square wind tunnel at Stanford in which the vortex pair was illuminated by a laser light sheet and the side force was measured using a balance.

References

1. Roberts, L., Hong, John; Stanford University; Greenwell, D. I., Wood, N. J., University of Bath, UK, "Theoretical and Experimental Investigation of a Delta Wing with Turbulent Leading Edge Jets", paper #28 to be presented at 72nd FDP meeting,

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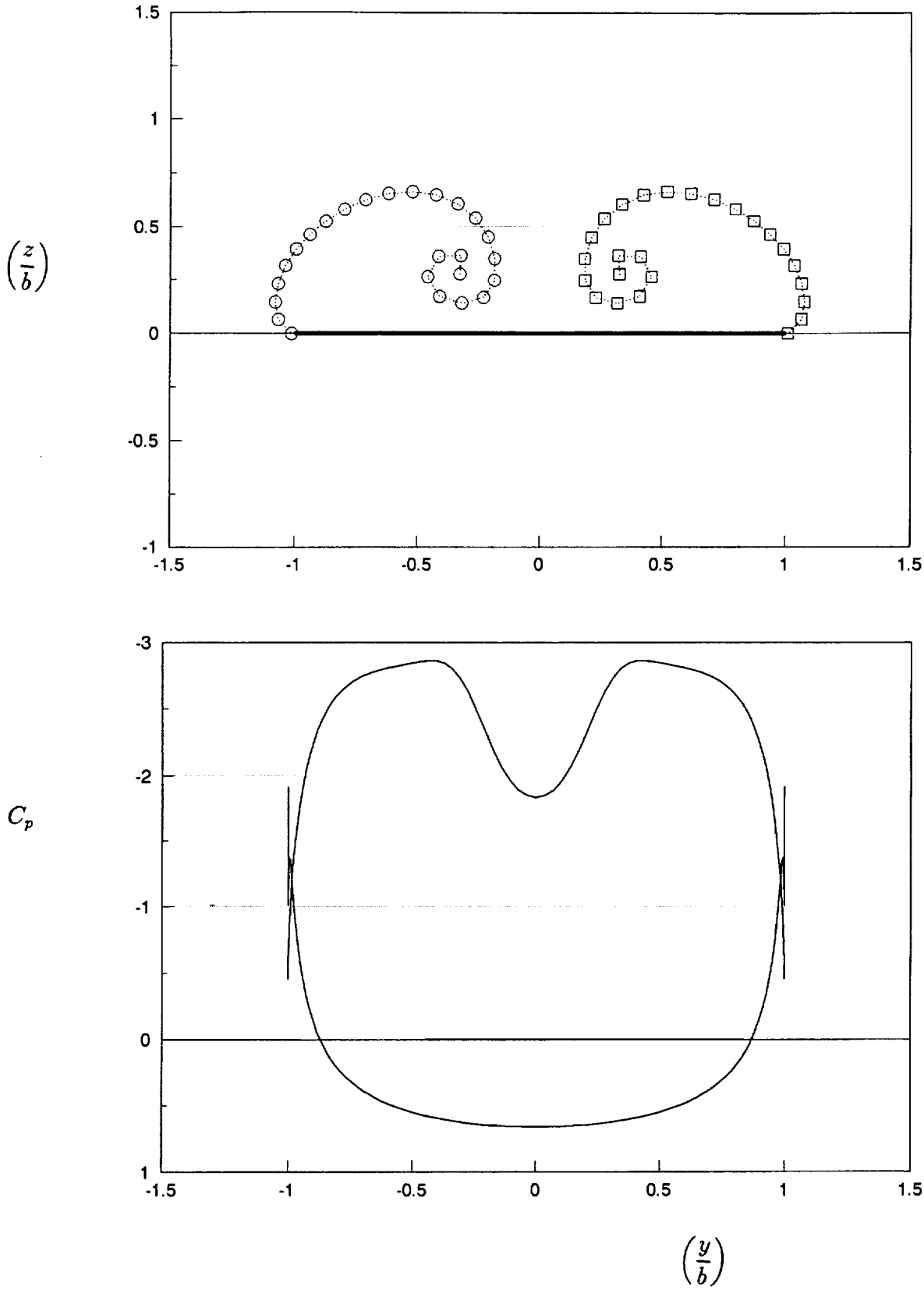

Figure 1 Vortex configuration and pressure distribution - flat plate (no blowing).

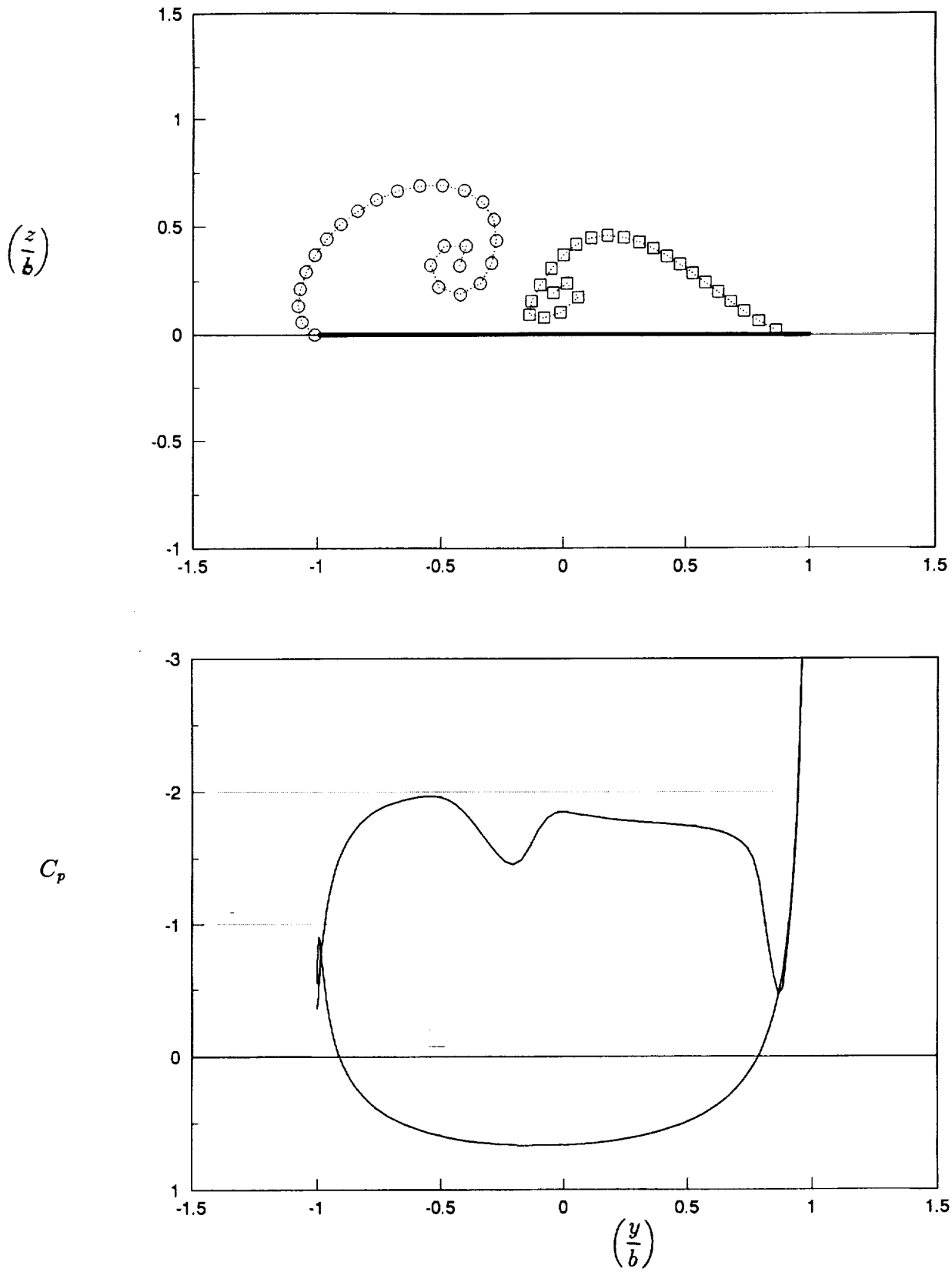

Figure 2 Vortex configuration and pressure distribution - flat plate (right side blowing).

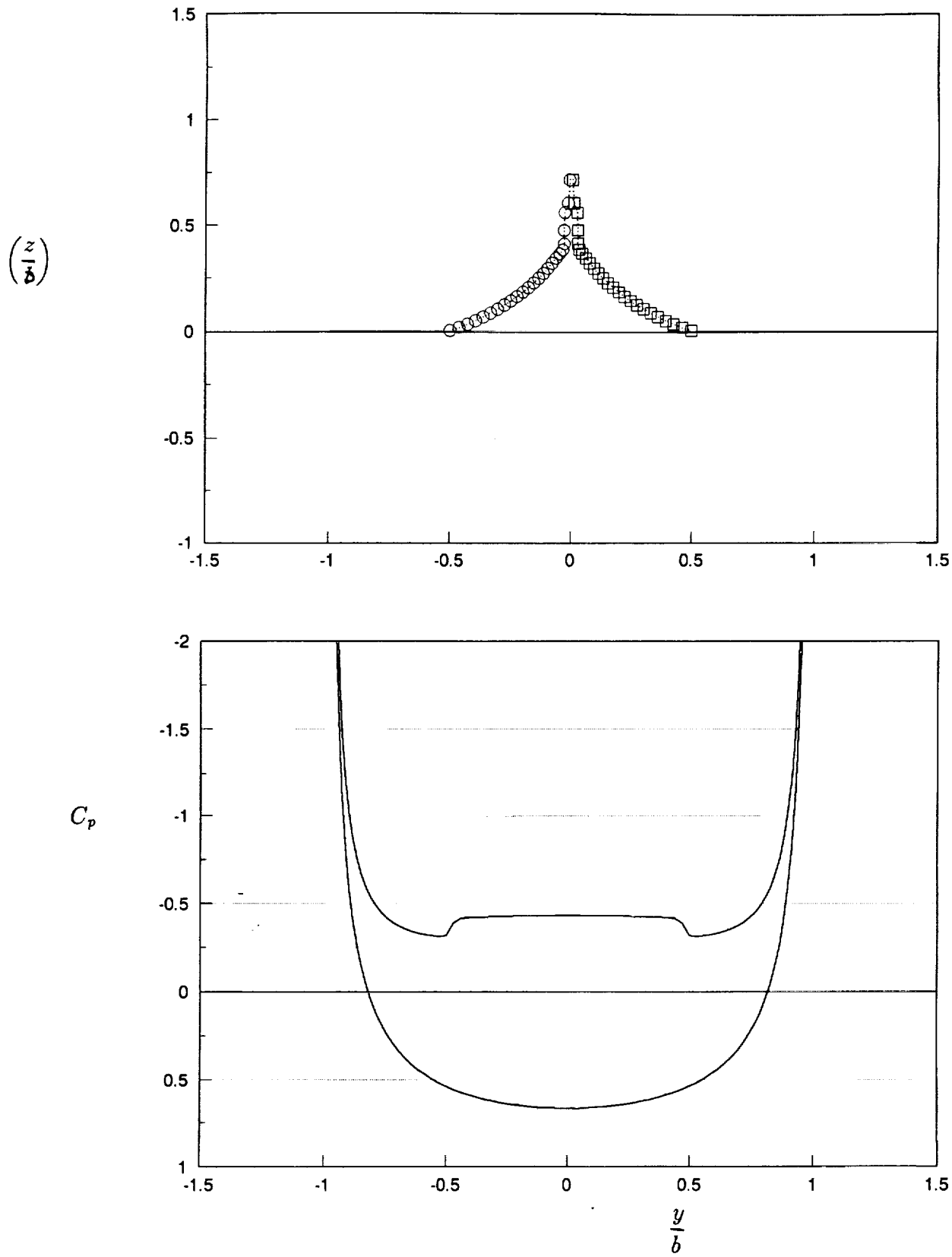

Figure 3 Vortex configuration and pressure distribution - flat plate (both sides blown).

4. Computation of High Speed Transport Aerodynamics

Alternative configurations suitable for high speed cruise have, in the past, been defined by linear analysis and extensive experimental testing, particularly for supersonic cruise conditions. In order to utilize modern CFD techniques efficiently these techniques must be applied as a configuration screening process before undertaking an experimental program on a fewer number of design configurations.

The results of Euler and Navier-Stokes computations (ref. 1) are used to give an overall expression for the drag components of a nominal supersonic cruise configuration when systematic variations in shape are made about a baseline. Computations have been carried out for a family of wings and are sufficiently complete to demonstrate the methodology and define appropriate scaling laws to give the effects on drag and on achievable $\frac{L}{D}$ (ref.2) permitting the number of computations to be minimized.

Results of the Euler and Navier-Stokes solutions show that

$$C_D = k_F + k_o p^2 \left(\frac{s}{l}\right)^2 + \frac{C_L^2}{\left(\frac{s}{l}\right)} \left[k_v + k_w \left(\frac{s}{l}\right)^2\right]$$

where $p = \frac{s}{2sl}$, and $\frac{s}{l}$ are geometric parameters of the family of wings.

The variation of $\frac{L}{D}$ with $\frac{s}{l}$ shows that a maximum exists when $\frac{s}{l}$ is varied. Typically for the configurations computed a maximum value of $L/D \approx 8.6$ was found for a value of $\frac{s}{l} \approx 0.4$. The computations thus far have concentrated on planform effects (i.e. effects of p and s/l). Extension of the approach will include the effects of thickness distribution variations and possibly the effect of adding a body to the wing configuration.

1. Goodsell, A., Private communication.
2. Roberts, L., "High Speed Transport Cruise Drag", JIAA Report TR-106, Stanford University, Stanford, CA 94305.

5. Aircraft Attitude Control Using Active Flow Control

The two tasks addressed, one theoretical and one experimental, were:

(a) to develop and apply models to the simulation and to the control on nonlinear systems, and

(b) to demonstrate experimentally the use of blowing to control the lateral - directional motion of an aircraft at high angle of attack including the roll and yaw motions.

(a) Nonlinear aerodynamic models for aircraft simulation and control

Aircraft simulation, and especially control law design, is often based on a simplified aerodynamic model that may not capture important nonlinear aerodynamic effects. The classical approach uses a linear aerodynamic model, based on stability derivatives. When substantial nonlinearities are present, a new linearization about another flight condition is created, and control systems may employ gain scheduling based on the revised model.

This approach works well when the aerodynamic characteristics of an aircraft are only mildly nonlinear in one or two state variables. However, flight at high angles of attack with unconventional control schemes introduces a problem for this approach: characteristics may be strongly coupled and very nonlinear over a large region of the parameter space.

This is the case, for example, for aircraft that maneuver with forebody blowing schemes. Here the control effectiveness is strongly nonlinear in blowing rate, but also depends (in a coupled and nonlinear way) on angle of attack. Additional influences of yaw and rate and effects on other control surfaces are not easily modeled with the traditional approach. With just 5 important states (α, β, p, q, r) along with Mach number, and just 4 controls, the nonlinear aerodynamics could be represented in a tabular format, but this requires a 10 dimensional table - far larger than is practical even with just a few entries for each variable. Even in cases where the nonlinearities are not too strong so that 3 points are sufficient to represent the effect of any one parameter, and only first order coupling exists only among pairs of variables, 75 runs of the aerodynamic analysis are required to characterize the

design. In practice, this sort of quadratic approximation is too restrictive.

One approach to resolving this dilemma involves the use of an adaptive fitting procedure, in which the important couplings and regions of nonlinearity are identified and refined. Neural networks are one approach to this sort of adaptive fit and work over the last year has focused on identification of the appropriate types of artificial neural networks for this purpose. A literature search was performed to identify other approaches to this problem and to become more familiar with the application of neural networks in controls. A neural net simulator was written and tested on several functions to determine the types of nonlinearities that could be modeled, the number of input, output, and hidden layer nodes required, and the number of training sets that lead to acceptable behavior. Current and future work focus on the application of this network to problems of interest in dynamics and control of aircraft.

(b) Experimental demonstration of coupled roll/yaw motions

In order to achieve this objective in the wind tunnel most of the effort was placed in the design and fabrication of a yaw support system, complementing the current roll device, to allow coupled yaw/roll motion. The device is shown in figure 1 and consists of an offset yaw support mechanism attached to the roll balance to allow the combined motion at high angle of attack. The program using this device consists of static measurements of the aerodynamic loads, which are currently being performed, together with dynamic tests where the motion is controlled by forebody blowing to be carried out in 1993. Figure 2 shows the model (a generic wing body combination) installed in the 45cm/45cm wind tunnel at Stanford. For small roll angles the motion is approximately a pure roll/yaw motion and the design has made possible the investigation of lateral-directional characteristics for the range of angles of interest. To minimize the inertia of the moving parts the support is partly upstream but below the model and is expected to keep the ratio of roll to yaw inertias to a reasonable value and thus avoid degeneration of the dynamics characteristic

of the system. The apparatus was built so as to minimize setup time before test and has common parts with other experiments going on in the wind tunnel (model, strain gage balance, valves for controlling blowing intensity, electric motor for the free to roll system, amplifier, power supplies computer and delta aquisition boards).

Presently, work involves measurement of the plenum pressure, requiring adjustment of the hose system for blowing, and wiring for reading the strain gage balance and position potentiometer. Also software for data acquisition is being written.

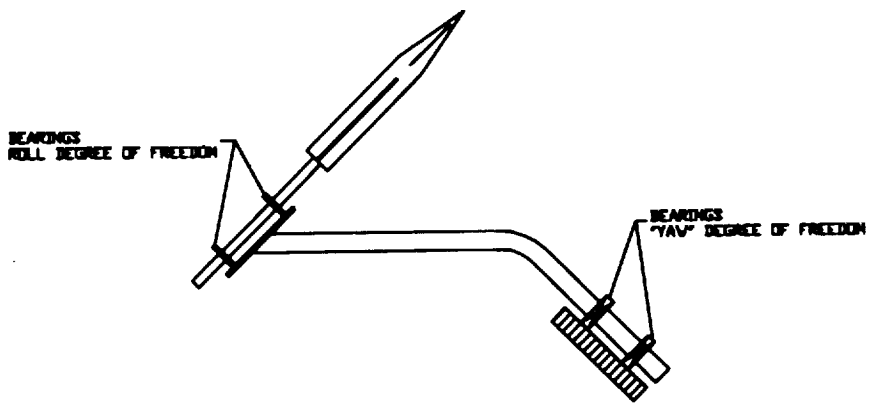

Fig. 1 - Schematic View of the Apparatus

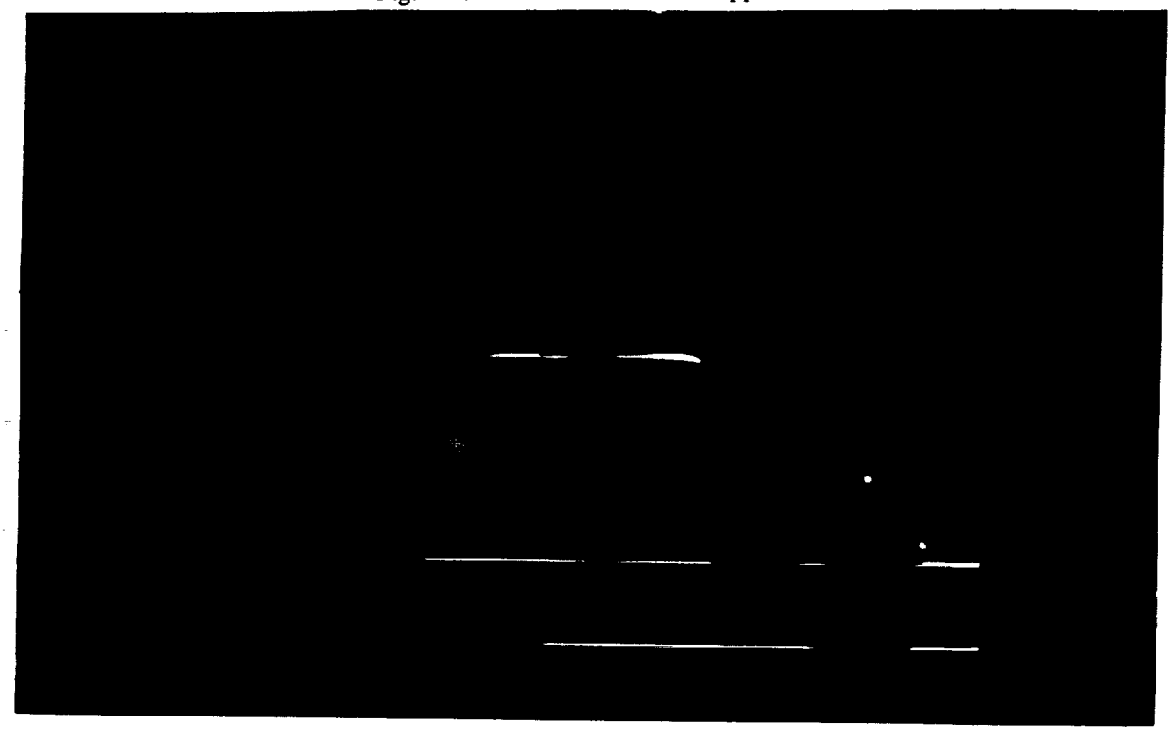

Fig. 2 - Test Section - Side View