Control of Asymmetric Vortical Flows over Delta Wings at High Angles of Attack

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Results from a wind tunnel experiment will be used to confirm that tangential leading-edge blowing is capable of controlling the vortical flow over a delta wing to very high angles of attack. The production of significant rolling moments and the ability to unburst a vortex has been demonstrated to 55-deg angle of attack. Strain gauge balance measurements and upper surface pressure distributions will be presented that illustrate the various modes of operation and that, in particular, identify the uncoupled/coupled nature of the vortex control at pre- and poststall angles of attack. At angles of attack beyond 40 deg, rolling moments are produced that exceed those produced by 20 deg of aileron deflection at 0-deg angle of attack.

Nomenclature

A_j = slot exit area
b = local semispan
C_L = wing rolling moment coefficient
C_N = wing normal force coefficient
C_M = wing pitching moment coefficient about the midchord
C_p = pressure coefficient
C_μ = blowing momentum coefficient, = jet momentum/$(q \cdot s)$
c = wing chord
q = freestream dynamic pressure
S = wing reference area
V_j = jet velocity
V_∞ = freestream speed
x,y = Cartesian coordinates
α = angle of attack
Δp = difference between internal plenum pressure and freestream static
ρ = freestream density

Subscripts

L = left side blowing only
R = right side blowing only
T = total wing blowing, = $L+R$

Introduction

THERE is currently considerable interest in developing and understanding techniques to enable delta wing aircraft to operate for extended periods at angles of attack beyond stall.[1,2] The flow characteristics over this type of wing have been well documented and have been shown to be dominated by the dynamics and stability of the leading-edge vortices. If a controlled maneuver is to be executed through this poststall regime, then a mechanism is required that can stabilize and modify the properties of these vortices and do so with a minimum impact upon other vehicle parameters, e.g., installed thrust, thrust to weight ratio, lift to drag ratio, and maximum lift coefficient. An additional consideration is the point and shoot maneuver in which the vehicle is angled relative to the flight path without modification to the trajectory. Such a vehicle would need to be able to control and modify the strongly asymmetric separated flowfields that would occur at high pitch and yaw angles. Chody et al.[3] describe the control requirements anticipated for next-generation agile aircraft and suggest the need for rapid lateral control as being as important as pitch control. This paper will address problems associated with the aforementioned flowfields and in particular the production and control of rolling moment at very high angles of attack.

Phenomena associated with high pitch and yaw angles may be grouped into two categories: those associated with vortex asymmetry and those associated with vortex burst. In the first, aerodynamic moments induced by the vortex motions lead to a limit cycle wing rock motion,[4-6] whereas in the latter, the motion is divergent.[7] It should also be noted that as the angle of attack increases so the effectiveness of conventional moving surface controls decreases.[8]

There have been few previous attempts to provide lateral control for vehicles operating at such high poststall angles of attack. Thrust vectoring[9] and close coupled canards[10] currently are being investigated as means of providing the nose-down pitching moment that appears necessary for pitch trim

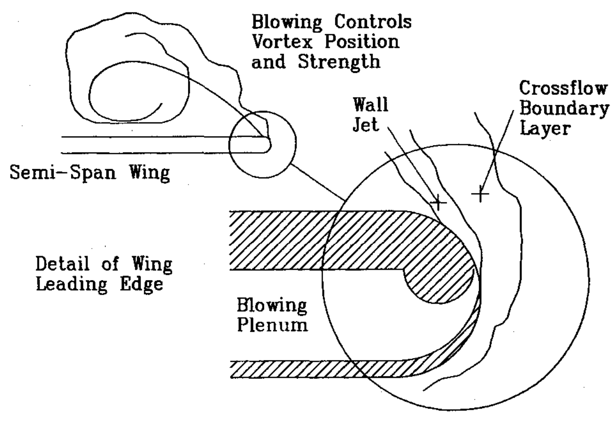

Fig. 1 Tangential leading-edge blowing.

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at high angle of attack.[11] Evaluations of forebody vortex control also are showing promise for developing yaw control at high angles of attack. Previous research on tangential leading-edge blowing[12] as a mechanism for vortex control has illustrated the ability of the device to remain effective to angles of attack well beyond the stall angle but has been restricted to experiments on semispan wings. This paper will present data that show the characteristics of a full-span delta wing with tangential leading-edge blowing applied to both leading edges. The results presented will concentrate on the application of tangential leading-edge blowing as a roll control device. Similar concepts for the production of lateral forces and moments have been developed and will be reported in the near future.

Previous reports have described the concept of tangential leading-edge blowing in some detail. It is suggested that those unfamiliar with the phenomena consult Refs. 12–14 and 16. In summary, direct control of the crossflow separation on a rounded leading-edge delta wing modifies the vortex properties such that vortex equilibrium is maintained (see Fig. 1). Since the interaction with the boundary layer is viscous in nature and results in large changes in the inviscid flow, the interaction is inherently efficient. In addition, no prior knowledge of the vortex condition or location is required in order to affect the vortex. Previous data[13] have shown that tangential leading-edge blowing is also capable of unbursting a previously burst vortex, an effect that has been shown to be analogous to reducing the effective angle of attack of the vortical flow. The concept also has been shown to exhibit little or no hysteresis and to respond quickly to changes in blowing momentum.[14]

The primary objective of this research is to show that tangential leading-edge blowing is capable of resolving or inducing lateral flow asymmetry to produce roll control. This includes operation over a broad range of angles of attack, pre- and poststall, with and without vortex burst. The degree of coupling between the two blown leading edges was of additional importance in resolving the observations from previous experiments conducted on semispan models.

Experiment

Wind Tunnel Model

A sting-mounted, full-span delta wing has been tested in the 0.46-m low-speed wind tunnel at Stanford University. The wing was of constant thickness, approximately 6% at the root chord, and has a 60-deg leading-edge sweep angle (see Fig. 2). Two separate internal plena were used to isolate the blowing supply for each of the leading edges. Leading-edge slots extended over the majority of the leading edge, and the slot width varied linearly from 0.1 mm at the apex to 0.5 mm at the wing tip. This variation produced a linear increment in blowing momentum over the span of the wing, a configuration that previously had been shown to be efficient and simple to interpret. Each plenum was supplied by an independent air source with manual pressure regulation and was monitored by separate pressure transducers. Because of the low flow rates, the internal pressure could be used to calculate the jet momentum directly, assuming the slot exit area was known:

$$C_\mu = 2\,(A_j/S)\,(V_j/V_\infty)^2$$

where

$$V_j{}^2 = 2\,(\Delta p/\rho)$$

A typical wind tunnel freestream speed of 20 m/s was used throughout the experiment, giving a Reynolds number based on the root chord of 4.0×10^5. Some experiments were performed at 40 m/s to determine any first-order effects. These will be discussed in the following section.

The model was mounted on a sting that in turn was supported by two tubes that spanned the tunnel. These tubes were fixed to windows such that rotation of the windows controlled the angle of attack. Angles of attack up to 55 deg were allowable before the structure contacted the tunnel floor. The center of rotation was the centroid of the wing so that any asymmetric blockage effects were minimized. The model support shaft could be rotated, through a worm gear system, from outside the test section to provide roll angles of up to 30 deg. Additionally, ±10 deg of yaw was available, and investigation of the effects of roll and yaw angle will be reported in future papers.

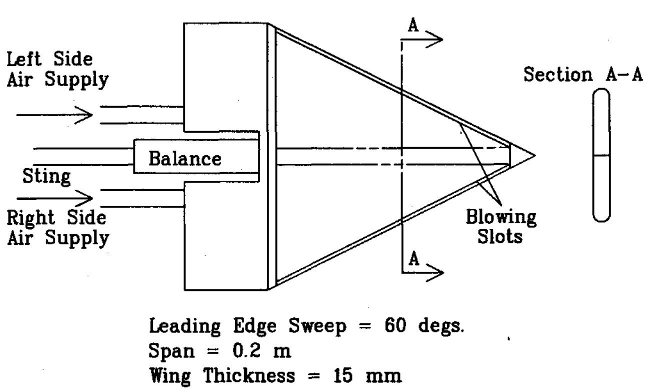

Fig. 2 Schematic of wind tunnel model.

Instrumentation

A single row of pressure tappings was included on the upper surface of the wing at the 35% chord location. The tappings extended 78% of the local semispan on either side of the plane of symmetry, and the surface pressure was monitored by a standard Scanivalve pressure measurement system. The small scale of the model precluded the addition of pressure tappings around the leading edge, and consequently the suction induced by the attached wall jet could not be monitored.

The model was mounted on a simple three-component strain gauge balance giving normal force, pitching, and rolling moment. Care was taken with the alignment of the air inlet hose so as to minimize the effects of induced loads due to pressurization.

Derivation of Results

As just mentioned, the internal pressure in each plenum was used to estimate the blowing momentum, assuming that the slot area was known and that the flow was incompressible.

The sting balance was calibrated with wind off, and an online data acquisition system sampled the output signals and automatically derived the forces and moments. Any residual cross-coupling was accounted for in the balance calibration matrix.

No corrections for tunnel blockage have been applied. At the extreme angles of attack under investigation, the solid blockage could approach 17% of the wind tunnel cross-sectional area. Obviously, this precludes the use of the results in absolute terms and also places the data outside the normal bounds of the approximate correction methods available. However, it is suggested that the trends of the induced effects of tangential leading-edge blowing are representative. Note that all experiments were performed at fixed incidence and, as such, the blockage effect would only impact the initial conditions. The measurements for unblown stall angle, maximum normal force, and pitching moment should be regarded as approximate. The ability to unburst a vortex and to reattach the flow over the entire delta wing for angles of attack up to 55 deg is thought to be sufficiently impressive as to reduce concerns about tunnel boundary effects.

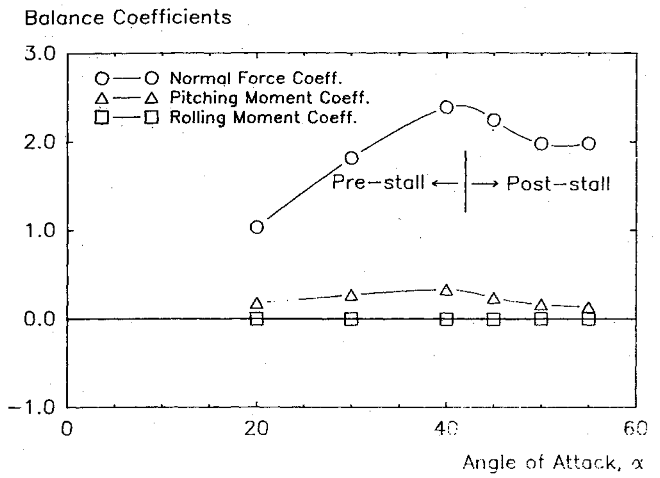

Fig. 3 Unblown force and moment coefficients.

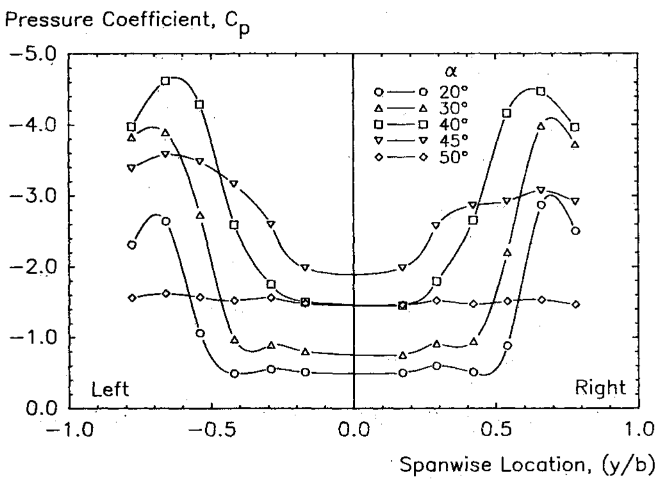

Fig. 4 Unblown spanwise pressure distributions.

Results and Discussion

Previous research on tangential leading-edge blowing has concentrated on identification of the associated phenomena and investigation of the unsteady response characteristics. To that end, the concept has been shown to exhibit capabilities beyond that of any other control device. Results, both experimental[12] and computational,[13] showing the ability of the concept to control the position and strength of a vortex at prestall angles of attack and to reattach the flow completely to the wing root have been previously published. At poststall angles of attack, observations about the ability of tangential leading-edge blowing to unburst a vortex and to restore stable, well-organized flow over the wing also have been obtained.

Unfortunately, all of the previous experimental data were taken from semispan models that were mounted on a wind tunnel sidewall. As such, the implied symmetry made interpretation of the results, with particular respect to rolling moment, subjective at best. The presence of a relatively thick sidewall boundary layer also had been identified as a source of uncertainty. The present experiment resolves those questions by examination of tangential leading-edge blowing on a full-span delta wing with independent blowing control available on each leading edge.

While measurement of the overall unblown forces and moments is affected by the proximity of the tunnel boundaries, it is of some use in defining the pre- and poststall boundaries. Figure 3 shows the balance results with no leading-edge blowing, and it appears that the stall point is located at approximately 40-deg angle of attack. The break in the pitching moment curve occurs at this same point and signifies the vortex burst point reaching the wing apex. Comparison with previous data for wings of similar sweep would suggest that the stall point has been delayed. This may be attributed to the effect of the tunnel boundaries upon the longitudinal pressure gradients on the wing that in turn affect the vortex burst phenomenon. The pressure distributions for the unblown data are given in Fig. 4. Notice the peak in the vortex influence at 40 deg with the peak suction reduced as incidence is further increased. It is significant also to note the asymmetry that becomes apparent only at 50-deg angle of attack and beyond.

Before focusing on the results for rolling moment, it is of interest to review the effects of tangential leading-edge blowing on both the normal force and the pitching moment. Figures 5 and 6 present data for the normal force variation as a function of blowing momentum for both the symmetric and asymmetric blowing cases. In general, the results are quite comparable, suggesting that simple superposition of the asymmetric results to produce the symmetric result is applicable. The exception appears to be the poststall data where the rate of increase of the normal force is significantly greater for the symmetrically blown configuration. This eventually will be shown to be related to a strong cross-coupling between the individual

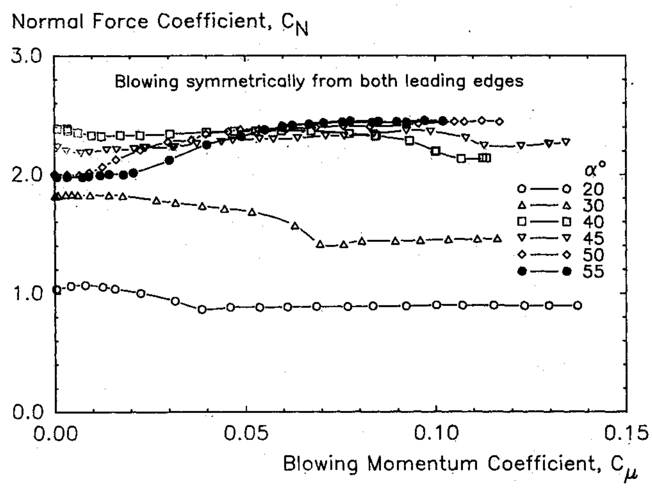

Fig. 5 Normal force coefficient for symmetric leading-edge blowing.

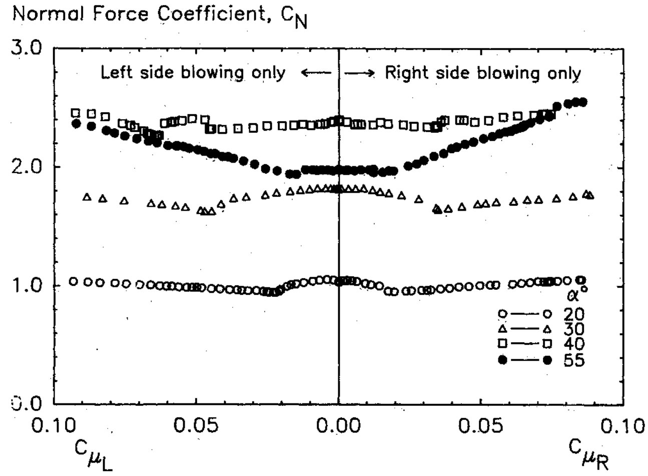

Fig. 6 Normal force coefficient for asymmetric leading-edge blowing.

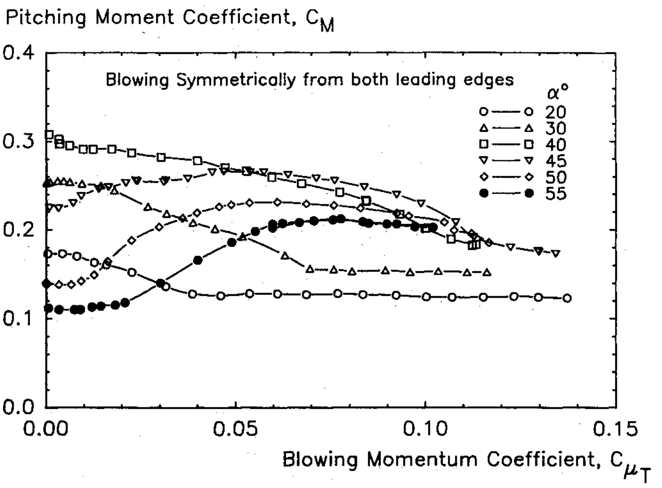

Fig. 7 Pitching moment coefficient for symmetric leading-edge blowing.

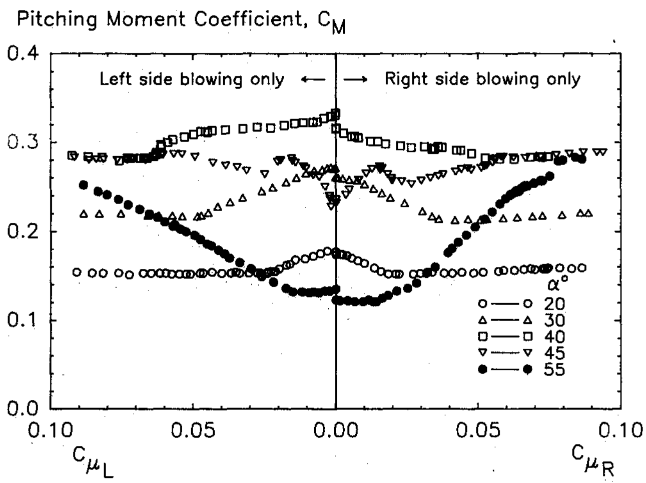

Fig. 8 Pitching moment coefficient for asymmetric leading-edge blowing.

vortex flows, which is only apparent at poststall angles of attack. It also will be noted that at prestall the total normal force reduces with increasing blowing, whereas at poststall the normal force increases. The poststall behavior is related to the unbursting of the vortices and the consequent increase in the vortex influence on the upper surface. Pressure distributions that are discussed later in the paper with reference to rolling moment clearly show these effects. Examination of pressure distributions at a single location may be misleading when referred to as unbursting the vortex. It has been observed that increasing blowing strength at poststall angles of attack moves the vortex burst point aft. Therefore, at any measurement location in the vicinity of the vortex, the effect is one of a gradually decreasing surface pressure.

The points at which the normal force curves reach a nearly constant value are also of significance. For prestall angles of attack, they signify the points at which the flow has been fully reattached across the upper surface of the wing. Note that this is demonstrated even at 40- and 45-deg angle of attack. For poststall angles of attack, the plateau that is reached is indicative of the flow being completely unburst. Again, evidence of this is given in the context of the discussion of rolling moment production.

As might be expected, the results for the pitching moment coefficient, shown in Figs. 7 and 8, follow trends that are consistent with the previous observations. The one exception would be to note that for the asymmetrical blowing case at poststall angles of attack, the pitching moment rises to a higher value compared to the symmetric case. The reason for this is not immediately obvious but again may be due to the strong cross-coupling between the vortex flows at these conditions. For the prestall case, it is interesting to note that the reduction in pitching moment for the asymmetric case is approximately one-half that of the symmetric case. This again would imply that, for prestall conditions, simple superposition of the effects is appropriate. It should be remembered that all of these results represent steady-state time-averaged data and therefore do not indicate the modification of the unsteady vortex-induced loads by tangential leading-edge blowing.

The primary objective of this research is to demonstrate the ability of tangential leading-edge blowing to provide roll control at very high angles of attack. By implication this means only considering asymmetric blowing conditions, and all of the following data will be of that form.

Figure 9 shows the overall results for rolling moment coefficient generated by either left or right leading-edge blowing as a function of angle of attack, as measured by the sting-mounted strain gauge balance. It is obvious that, apart from the symmetry around zero blowing, there are sign reversals and discontinuities in the results. At low angles of attack (20 and 30 deg) blowing on the right leading edge produces a negative (right wing up) rolling moment. As the angle of attack increases to poststall values, for modest blowing rates the sign of

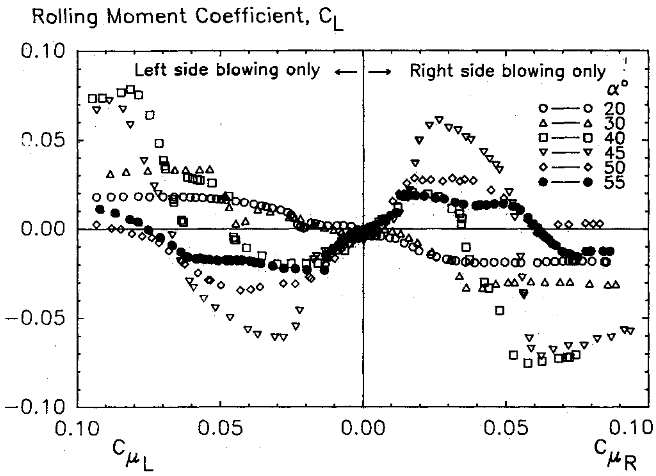

Fig. 9 Rolling moment coefficient for asymmetric leading-edge blowing.

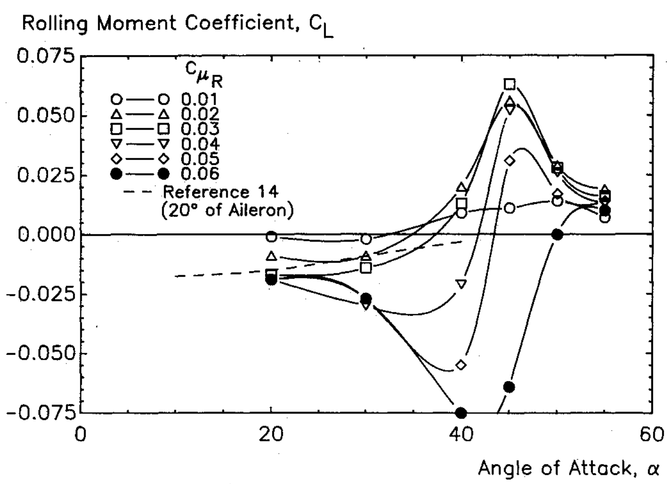

Fig. 10 Rolling moment control effectiveness at high angle of attack.

the rolling moment reverses, which implies that right-wing blowing produces a positive (right wing down) moment. This result is contrary to what might be expected and will be discussed in more detail in subsequent sections. These results are clarified in Fig. 10 where the rolling moment is presented for fixed blowing rates as a function of angle of attack. If this concept is to be adopted, then clearly the reasons for this control reversal must be understood. It is clear that tangential leading-edge blowing has the potential to produce rolling moments that far exceed those produced by conventional moving surface devices. The data used for comparison was acquired from a wind tunnel model similar to a YF-16.[15] Unfortunately, no data for a comparable 60-deg sweep delta wing was available.

Some insight can be gained from examination of the pressure distributions at pre- and poststall angles of attack. Figure 11 shows the measured pressure distributions for 30-deg angle of attack for a range of blowing momentum. For this condition, blowing on the left leading edge modifies the left side vortex with little impact on the right side flow. As the blowing is increased so the vortex influence reduces and in the limit, the condition of fully reattached flow on the wing upper surface is achieved. It might be expected that a left wing down moment (negative) is produced, but examination of Fig. 9 shows that for left side blowing at 30-deg angle of attack, the rolling moment was positive (right wing down). Wood et al.[16] showed that for prestall angles of attack, there were two contributions to rolling moment: one from the vortex and one from the leading-edge suction induced by the Coanda wall jet. Because of the small scale of the present model, pressure tappings could only be placed in the vicinity of the vortex flow. Therefore, it has to be assumed that the contribution from the leading-edge wall jet suction must in part offset that due to the reduced vortex influence. It also must be recognized that the burst point would have been relocated over the rearward portion of the wing; however, the complexity of the interactions for burst vortices precludes any conclusion about the precise contribution to roll. To what extent the net result of this balance is geometrically dependent is not known, but it is certainly an area for further investigation. The slight increase in the vortex suction peak for very weak blowing momentum is not without significance. For this angle of attack, the vortex burst is probably just aft of this chordwise measurement station. Consequently, the slight aft movement of the vortex burst caused by this weak blowing allows the vortex to strengthen and increase the local suction peak.

The primary observation from Fig. 11 is that blowing asymmetrically at prestall angles of attack is an uncoupled phenomenon. Blowing on the left side does not significantly affect the right side flow and vice versa.

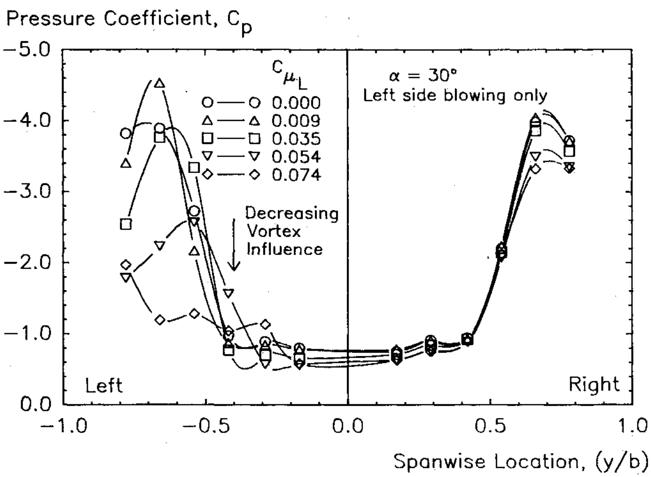

Fig. 11 Spanwise pressure distributions for asymmetric blowing, prestall.

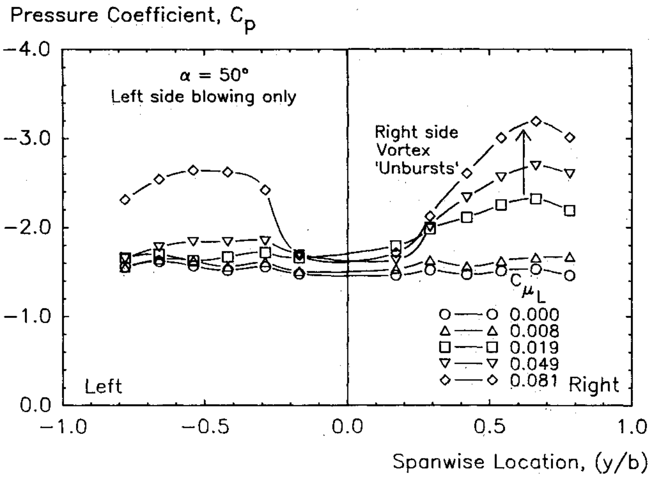

Fig. 12 Spanwise pressure distributions for asymmetric blowing, poststall.

Consider now Fig. 12, which shows the rolling moment response to asymmetric blowing for a post-stall (50-deg) angle of attack. The form of the data is consistent with Fig. 11 in that the blowing is applied to the left leading edge only. Notice though that for all but the highest blowing momentum shown, the effects are concentrated on the right side of the wing. Also notice that instead of reducing the vortex influence on the right side, it is actually enhanced. The distribution varies from one that is flat, showing no vortex influence, to one where a stable, organized vortical flow is present. Obviously, a number of effects of tangential leading edge blowing are present.

First, tangential leading-edge blowing clearly is capable of unbursting a burst vortical flow, as evidenced by the increasing vortex influence. Second, the left and right vortical flows are very strongly coupled. Blowing on the left leading edge appears to unburst the right side vortex first and the left side vortex second.

For this poststall case, it is somewhat easier to correlate the pressure distribution with the balance measured rolling moment. From Fig. 9, left side blowing at 50 deg would produce a negative (left wing down) rolling moment at all but the highest blowing rates. The pressure distributions shown in Fig. 12 would tend to correlate well with this observation. Indeed, the rolling moment that can be approximated from the pressure distribution agrees well with that measured on the balance. Wood and Roberts[12] showed that for the poststall case where a vortex has been unburst there is no additional leading-edge suction effect until after the burst point has passed aft of the measurement location. This implies that the limited amount of pressure information has captured the majority of the moment-inducing modifications.

The primary result of the present research is the recognition that the vortical flow at poststall conditions is cross-coupled. It is this phenomenon that produces the reversal of the rolling moment produced by blowing as the angle of attack increases past the stall point. Therefore, it is important to the development of control laws for vehicle application to understand the factors affecting the cross-coupling. The observation that for unburst vortices the flow is uncoupled suggests that it is the sensitivity of the burst phenomenon that is the key to the moment reversal.

There are many factors that could influence the cross-coupling. Previous papers have highlighted the concept of vortex flow equilibrium as an important factor in the success of tangential leading-edge blowing. Both leading-edge separation point locations and the forces on the vortices and their

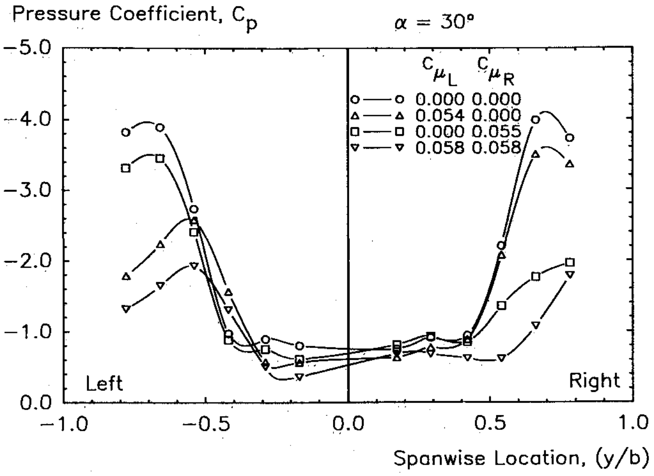

Fig. 13 Spanwise pressure distributions for asymmetric and symmetric blowing, prestall.

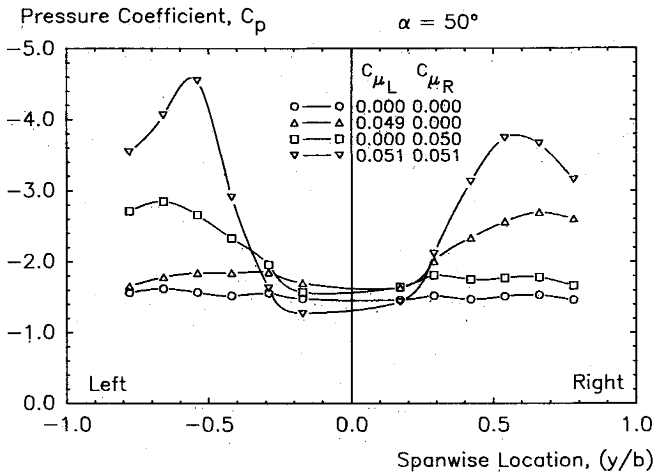

Fig. 14 Spanwise pressure distributions for asymmetric and symmetric blowing, poststall.

feeding sheets must be in a force-free condition. For the prestall, uncoupled case, it would appear that only the local crossflow equilibrium is important. Therefore, changes in one leading-edge condition have only a small effect on the opposite flow by virtue of the relative distance between the vortical flows.

For the poststall case, laser light sheet flow visualization confirmed the nature of the cross-coupling, and the premature unbursting of the vortex on the opposite side could be observed. Even with visual evidence of the phenomenon, the cause was uncertain. It was noticed though that the plane of symmetry between the two vortical flows was shifted toward the vortex on the opposite side. A possibility is that this shift of the plane of symmetry produces an effective increase in the sweep angle of the opposite side leading-edge flow. If this were the case, then it could be expected for the vortex burst on that side to be moved aft. The limited amount of data available on this phenomenon precludes a definitive statement of the cause for the cross-coupling at this stage. If the concept is to be successfully (and simply) applied to new aircraft for high angle of attack control, then the source needs to be identified. Further research is required to determine whether the inclusion of a fuselage, which is of the same scale as the vortical flow, influences the poststall coupling.

Further evidence of the vortical flow coupling at poststall angles of attack is shown in Figs. 13 and 14. These figures illustrate the results obtained both pre- and poststall for the cases where the leading edges are blown first individually and then simultaneously. Observe, for the poststall case (Fig. 14) simultaneous blowing produces far greater modification of the flow than the individual asymmetric blowing cases combined. In contrast, the prestall case shows that the effects of symmetric blowing could be predicted as the sum of the asymmetric results.

Questions have been raised about any possible Reynolds number effects on the effectiveness of tangential leading-edge blowing. There is no doubt that variation of the Reynolds number will modify the position of the cross-flow separation on the rounded leading edge of the wing. However, provided that the initial unblown separation location is known and that the blowing slot is positioned accordingly, the effect should be small. The separated vortical flow is generally regarded as inviscid apart from regions of secondary flow. Confirmation of this hypothesis is given in Fig. 15, where the rolling-moment coefficient generated by asymmetric blowing at both pre- and poststall angle of attack is shown for two different Reynolds numbers. The maximum Reynolds number was limited by the experimental facilities available and is an area for further investigation. The general agreement is excellent suggesting that it is the jet momentum that is the primary parameter for definition of the effects of tangential leading-edge blowing.

Estimating the blowing requirements for full-scale applications reduces, not to considerations of the Reynolds number, but to means of generating the momentum coefficients. Considering that the likely source of the blowing air would be the HP compressor, the installation is likely to be mass-flow limited rather than pressure-ratio limited. A figure of 15 kg/s of bleed flow would not be unrealistic and would correspond to approximately 10–15% of thrust. Previously it has been recognized that smaller slots are slightly more efficient. Therefore, it would be necessary to reduce the slot area at maximum mass flow until a pressure ratio limit is encountered. The parameters at this condition then would determine the maximum momentum coefficient available.

This paper has considered the application of tangential leading-edge blowing to the control of vortical flows over delta wings. In that respect, the concept has proven to be effective over a wide range of conditions and offers a degree of flow control unobtainable by other existing means. In more general terms, thin, highly curved wall jets could be used to advantage to control separated flows in a variety of situations of benefit to aircraft maneuvering at high angles of attack. Application of tangential slot blowing on leading-edge extensions to control LEX/main wing interactions or on aircraft

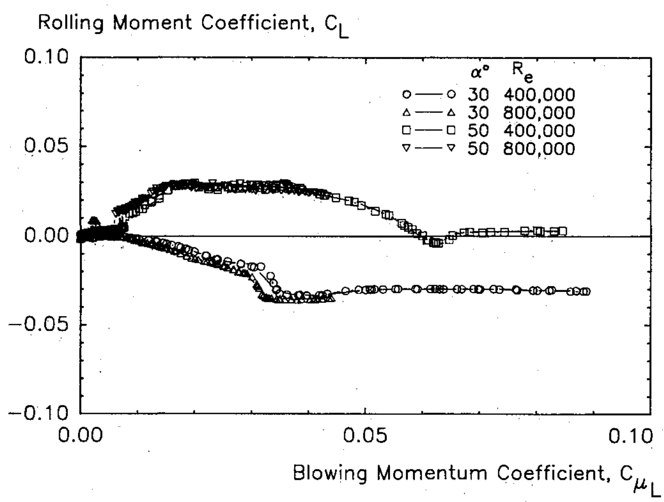

Fig. 15 Effect of Reynolds number on rolling moment for asymmetric blowing.

forebodies to provide lateral control through vortex manipulation would appear to be examples of possible exploitation. Active control of vortex-induced unsteady loads on vertical tail surfaces by feedback control to the blowing control system also may be of interest. As aircraft maneuver envelopes are extended and control requirements in all axes extend beyond the range of existing mechanisms, then the ability to control flow separation efficiently by tangential blowing may become an increasingly viable alternative.

Conclusions

The concept of tangential leading-edge blowing has been applied to a full-span delta wing tunnel model. Results indicate that the concept is capable of controlling the vortical flow over the wing to very high angles of attack. Not only can burst vortices be unburst, but asymmetric flows can be induced or produced. The implication is that substantial rolling moments may be produced at conditions where other control devices cease to be effective.

The effects of asymmetric leading-edge blowing have been shown to be uncoupled at prestall angles of attack such that the overall forces and moments for symmetric blowing can be deduced by superposition of asymmetric cases.

For poststall conditions, the response of the vortical flowfield is strongly coupled for asymmetric blowing. The mechanism for this coupling is not clear but is linked to the presence of burst vortices over the wing upper surface. The coupling produces a control moment reversal that is undesirable for vehicle application. The reversal may well be linked with the generic form of the present wind tunnel model and the absence of a fuselage.

Acknowledgment

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