# Control of Vortical Lift on Delta Wings by Tangential Leading-Edge Blowing

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**An experiment has been performed to examine the feasibility of vortex control by tangential mass injection at the leading edge of a 60 deg delta wing. The initial results indicate that direct control of the primary separation allows significant control of the vortex flow up to angles of attack of 60 deg. At lower angles of attack, the vortical flow may be removed entirely from the surface of the wing, recovering the fully attached flow case. The effects of the mass injection have been shown to be decoupled from the geometric angle of attack, allowing the possibility for controlling lift without changing attitude.**

## Nomenclature

$b$ = wing semispan
$c$ = wing root chord
$C_\ell{}'$ = spanwise sectional rolling moment coefficient
$C_L{}'$ = wing rolling moment coefficient
$C_n$ = spanwise sectional normal force coefficient
$C_N$ = wing normal force coefficient
$C_p$ = pressure coefficient
$C_\mu$ = blowing momentum coefficient
$C_\mu{}^*$ = crossflow blowing momentum coefficient
$h$ = slot height
$V_j$ = jet velocity
$V_\infty$ = freestream velocity
$\alpha_e$ = effective angle of attack
$\alpha_g$ = geometric angle of attack
$\epsilon$ = wing semi apex angle

## Introduction

In recent years, it has become desirable to increase the angle-of-attack envelope of delta wing aircraft as a mechanism for improvement of their maneuverability.[1] Such vehicles rely on the development of strong, stable vortices over the upper surface of the wings to enhance their lifting capability. Typically, these vortices may account for as much as 30% of the total wing lift and they become more important as the angle of attack increases beyond the range of operation of conventional wing systems. At these extreme angles of attack, certain phenomena such as vortex breakdown and asymmetric shedding may produce large periodic excursions in both the lift and rolling moments produced by the delta wing.[2] Naturally, these phenomena are undesirable not only from a control aspect, but also from structural and pilot safety considerations.

These large excursions in angle of attack are typically related to small, highly maneuverable fighter aircraft and may be generally classified as values exceeding the apex angle of the delta wing ($\alpha_g > \epsilon$). A more recent application of equal significance is that of very slender deltas or cone-like bodies where angles of attack exceeding the apex angle may be of the order of only 10–15 deg. Such excursions occur not in highly accelerated flight maneuvers, but during the takeoff and landing phases of proposed vehicles.[3] Clearly, the ability to exert some degree of control over the three-dimensional flowfield at these critical angles of attack is of prime importance to the expansion of their operating envelope.

Some attempt has been made to provide active control of these large overwing vortices through the use of controllable leading-edge flaps.[4,5] These devices appear capable of improving the lift:drag ratio of a given wing, primarily through a drag reduction, but produce only modest improvements in the angle-of-attack envelope. Many attempts have also been made to control the trajectory and evolution of these vortices through spanwise[6] and vortex core[7] blowing. Both the injection of high-momentum fluid into the core of the vortex and the ejection of a thin, high-velocity fluid sheet beneath the vortical flow have been investigated. In some instances, the breakdown of the vortical flow has been successfully delayed and small increases in the angle of attack to stall have been obtained. Many of these techniques rely upon a direct interaction of the device with the global flowfield, which results in a relatively inefficient, inviscid type of interaction. Other aerodynamic concepts have suggested that a far more efficient technique for modification of a global flowfield is by direct interaction with the viscous flows that produce the separated regions.

The concept of circulation control on two-dimensional airfoils has been shown to be a viscous interaction that results in large changes in the global inviscid flowfield.[8] This concept utilizes a thin, high-velocity tangential jet of fluid to control the location of the rear separation points on a rounded trailing-edge airfoil. Gains in lift coefficient of the order of 80 times the injected momentum coefficient have been observed over a wide range of operational conditions. The possibility then exists to consider the use of the circulation control concept as a crossflow plane device to directly control the location of the crossflow separation points and hence the trajectory of the ensuing vortices (see Fig. 1). This, or course, requires the cross section of delta wing to have rounded leading edges in contrast to the usual sharp configurations. To examine the practicality of such a scheme, a wind-tunnel experiment has been performed to examine the lifting characteristics of a conical delta wing with tangential leading-edge blowing.

## Apparatus

### Wind Tunnel

The experiments were performed in the 18×18 in. test section of the Stanford low-speed wind tunnel. The tunnel has a maximum centerline freestream speed of 57 m/s and is capable of continuous operation. Speeds in the range of 20–40 m/s were used throughout this experiment and this variation provided a mechanism for expansion of the range of blowing momentum coefficients that were achievable. Centerline velocities were monitored through a reference static pressure difference from two stations in the contrac-

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tion that had previously been calibrated against a pitot static tube and shown to be free of interference due to the presence of the model.

A continuous operation centrifugal flow compressor was used as the source of compressed air for the blowing. This compressor is capable of delivering a maximum of 450 $ft^3$/min at approximately 2 psi. The mass flow supplied to the model was measured from an in-line venturi meter and by direct measurement of the model internal pressure.

The model was mounted on a rotatable plate in the floor of the test section. Variations in the angle of attack of the model were obtained by rotation of the mounting plate to predetermined locations. The model was mounted offset from the center of rotation so as to minimize asymmetric blockage effects of the wing at high angles of attack.

### Delta Wing Model

To simplify the comparison of the test results with theoretical predictions, it was required that the model be as near conical as possible within the limits of practicality. This required that both exterior and internal dimensions be conical and that the blowing slot height should vary linearly from the apex. Care was also given to the arrangement of a satisfactory jet contraction with the jet exiting as near tangential as possible to the wing surface. These strict limitations led to a design scheme that was dictated by the limitations of the manufacturing capability at Stanford and the construction techniques available.

The overall dimensions of the wing were fixed to produce a 60 deg leading-edge sweep angle and a root chord of 11 in. A semispan configuration was chosen to allow the scale of the model to be increased (relative to a full-span model) and to simplify the ducting required for the blowing air supply.

To maintain the requirement for internal conicality, the leading edge of the wing was chosen to be a 4 deg half-angle right circular cone whose axis was offset 26 deg from the model centerline. Two flat plates were chosen to fabricate the remaining upper and lower surfaces of the wing and a cross section normal to the tunnel wall was defined to have parallel upper and lower surfaces. These few simple specifications permitted the entire wing geometry (except the blowing slot), including skin thickness and leading-edge cone tangency points, to be defined.

To define the slot geometry, the slot was designed to be manufactured from two pieces. First, a slot lip was detailed to be constructed by cutting two offset 4 deg half-angle conic cylinders to form a crescent. This was then reduced to the required arc length for attachment to the upper-surface plate. The lower surface of the slot was produced from a 3 deg half-angle right circular cone whose axis had been carefully offset to produce the required slot height-to-span ratio, while maintaining tangency with the lower surface and overall conicality. For simplicity of model fabrication, the slot was not extended over the entire length of the leading edge. Figure 2 illustrates the final model design.

To measure the loads on the wing, a total of 189 pressure tappings were installed on the surfaces of the model in eight separate rows. Rows 1–8 correspond to chordwise locations 18, 27, 36, 45, 54, 63, 72, and 90% of the total root chord. At each row, the tappings were placed on identical conical generators (2.5 deg fanlines from wing root) to simplify the data reduction. A single tapping was placed inside the model to permit measurement of the internal pressure. All of the 0.032 in. tubing used for the pressure tappings was carefully laid out on the inside surfaces of the plenum chamber and secured with adhesive. Care was taken to minimize the effect of the tubes upon the overall internal geometry. The tubes were routed through a bulkhead positioned at the trailing-edge extent of the blowing slot and the plenum was carefully sealed at that point.

The coflowing configuration is defined as that where the jet issues toward the upper surface, i.e., coflowing with the crossflow.

### Instrumentation

The pressure tappings in the model were monitored by a 4 barrel, 48 port Scanivalve pressure measuring system that was controlled by a PDP 11/23 minicomputer. The Scanivalve was equipped with $4 \pm 2.5$ psid pressure transducers that were conditioned to give 10 V response per 1 psi of pressure. The data were sampled automatically, ensemble averaged, and converted to pressure coefficient form for integration. Graphical displays of the individual spanwise pressure distributions was available on-line.

## Results

The loads on the model were derived from integrations of the pressure distributions across the individual spanwise locations assuming a unit span at each location,

$$C_n = \int_0^1 C_p \mathrm{d}(y/b) \qquad (1)$$

A second integration was then performed between rows 2 and 7 (those rows bounded by the chordwise extent of the jet) to evaluate a wing loading coefficient. Account was

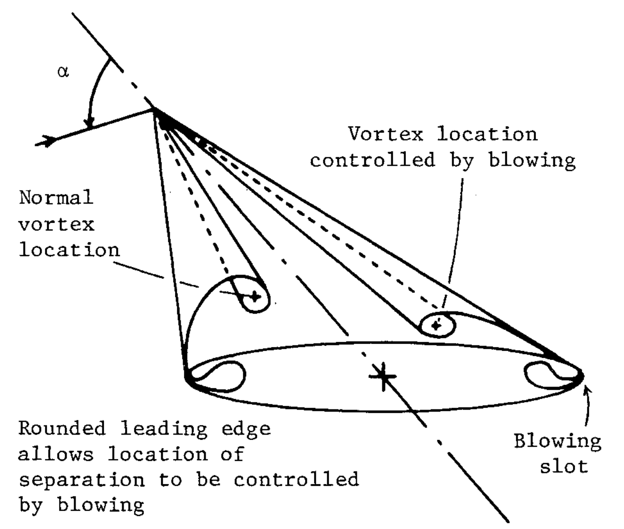


**Fig. 1 Concept of crossflow separation control.**

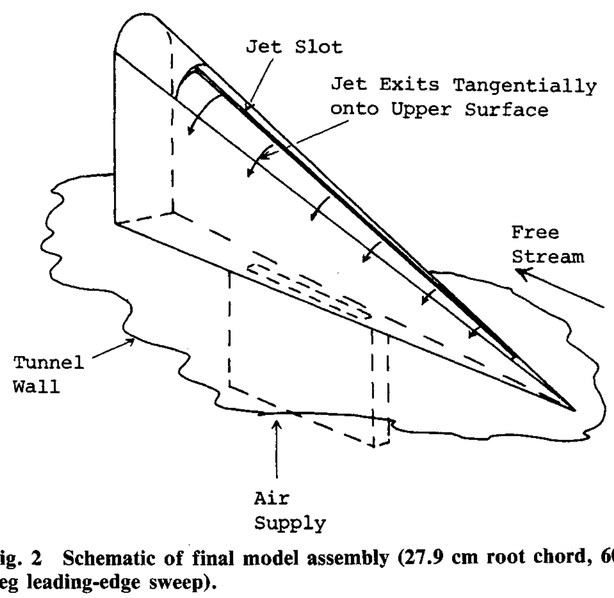


**Fig. 2 Schematic of final model assembly (27.9 cm root chord, 60 deg leading-edge sweep).**

taken of the change in dimension of the span at each row in order to produce a quasiconical normal force coefficient,

$$C_N = \int_{x_1}^{x_2} C_n \cdot b\mathrm{d}x \bigg/ \int_{x_1}^{x_2} b\mathrm{d}x \tag{2}$$

where $b$ is a linear function of $x$.

Rolling moments were calculated for each spanwise row and the rolling moment due to blowing found by subtraction of the unblown result for each angle of attack. It was assumed that the increment in rolling moment represented the full three-dimensional case. This, of course, is a conservative form for rolling moment, since the wind-tunnel wall represents an image vortex system that moves symmetrically with the real vortex.[9] For an actual three-dimensional wing, the position of the opposite vortex would be only slightly modified.

The blowing momentum coefficient for a *conical* blown delta wing in the absence of compressibility is defined as

$$C_\mu = 2 \cdot \left(\frac{V_j^2}{V_\infty^2}\right)\left(\frac{h}{b}\right) \tag{3}$$

The jet velocity was determined from the measurement of the internal pressure of the model and the isentropic flow equations. The value of the slot height-to-span ratio was measured at several chordwise stations and an average of 0.0046 based on twice the span of the half-model was calculated. Although every precaution was taken to ensure slot conicality, some nonlinearity was apparent in the slot dimension. The slot gap was slightly larger toward the trailing edge of the model and this could be observed in the subsequent pressure measurements and surface oil flow photographs. The value of 0.0046 used throughout this experiment was judged to be conservative and represented a value toward the trailing edge of the slot.

An example of the overall effect of coflowing leading-edge blowing is shown in Fig. 3 for constant increments of blowing strength. It is immediately apparent that increments in both the angle of attack at maximum normal force and the maximum normal force coefficient may be realized. The unblown result has been compared with those from Kuchemann,[10] which summarized the data from previous experiments on sharp leading-edge wings. Both the linear lift contribution and the total normal force are shown for comparison. The effect of the rounded leading edge and the increasing thickness of the wing appears to be consistent with previous observations. The total normal force being approximately 60% of that produced by an equivalent sharp leading-edge delta wing.

Figure 4 illustrates the primary effect of the leading-edge blowing upon the vortical flow. At 40 deg angle of attack without blowing, the upper-surface flow exhibits the qualities associated with a separated stagnant bubble. With the addition of a small amount of blowing, the primary separation is delayed and the resulting vortical flow interacts with the wing surface, producing the familiar vortical flow pressure signature. The corresponding increase in local normal force and rolling moment is obvious. No discernible differences in the lower-surface pressure distribution were measured as a function of blowing strength.

The effect of the blowing upon the longitudinal load distribution is given as Fig. 5. If the flow were truly conical, the force coefficient, as defined, would be constant, independent of chordwise location. Obviously, this is not the case. As the level of blowing increases, the load on the wing increases faster toward the apex of the wing until the condition of maximum total normal force is reached. From then on, further increases in blowing strength result in reducing loads toward the apex of the wing. Pressure distributions at other

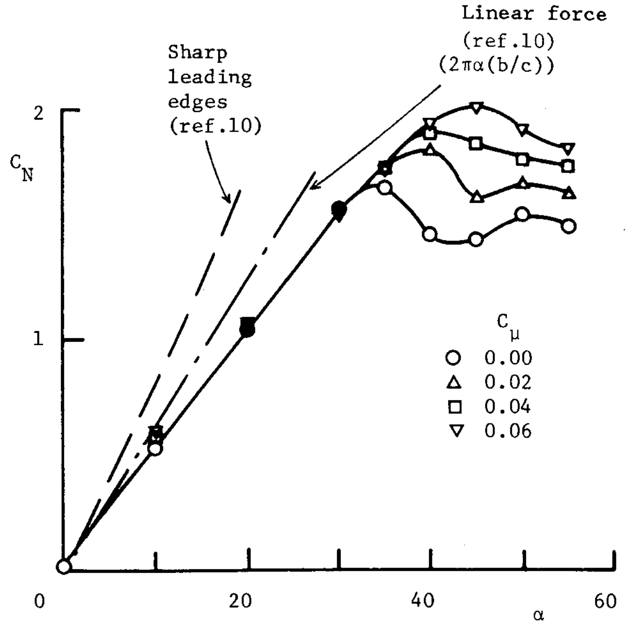


**Fig. 3 Effect of leading-edge blowing on normal force.**

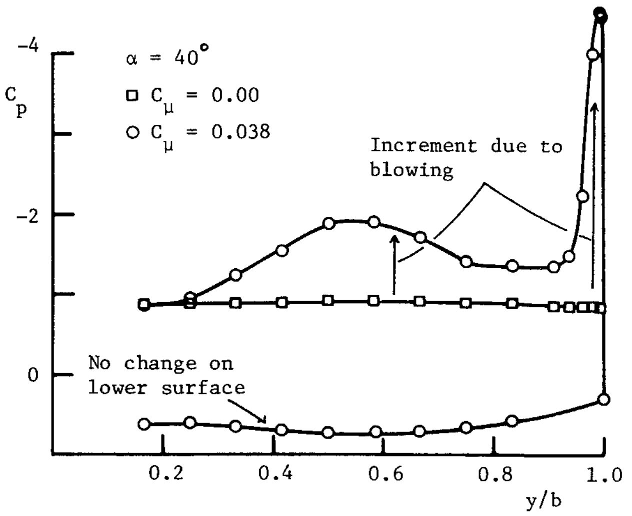


**Fig. 4 Effect of leading-edge blowing on the spanwise pressure distribution at high angles of attack.**

angles of attack have indicated that conicality ceased to be observable beyond 15 deg. However, flow visualization suggested that the separation lines remained conical until almost 30 deg angle of attack. This experience suggests that experimenters should carefully check both surface pressures and surface streamlines when testing for conicality.

Figure 6 illustrates the calculated rolling moment induced as a function of jet blowing momentum. Only results for high angles of attack are shown, since at low angles of attack the rolling moments due to changes in the spanwise pressure distributions tend to cancel. As is shown, the values obtained are easily one order of magnitude higher than those for more conventional deflected surface controls. The results obtained at 35 deg exhibit some reversal of the moment for low blowing momentum. This phenomenon is thought to be due to the small spanwise movement of the primary separation point for weak blowing. The resulting reduction in the vortex-induced suction is significant and the small surface extent of the suction under the jet is insufficient to counteract the imposed moment. This problem may be alleviated by a small movement of the slot location closer to the normal crossflow separation point. A more detailed

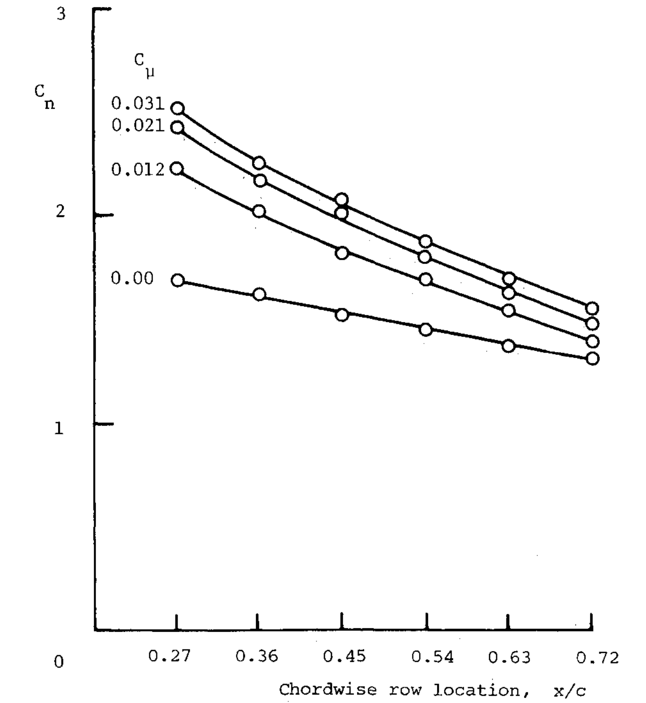


**Fig. 5 Effect of leading-edge blowing on the longitudinal load distribution.**

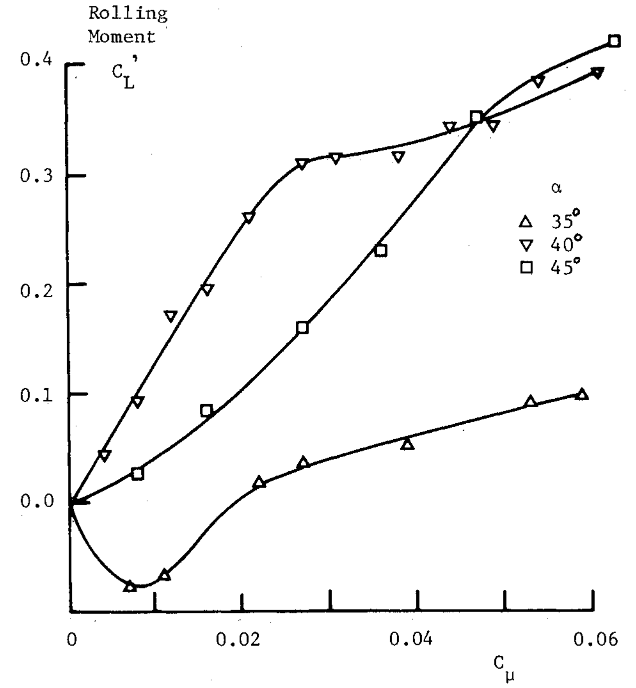


**Fig. 6 Rolling moment generated by leading-edge blowing at high angles of attack.**

presentation of the results has been given by Wood and Roberts.[11]

## Discussion

It is immediately obvious from the summary of results presented that coflowing, tangential, leading-edge blowing is capable of exerting significant control on the flowfield over a delta wing at high angles of attack. A more detailed interpretation of the experimental data has yielded an even more fundamental result regarding the nature of the flow control.

The normal force developed by a conventional delta wing consists of two distinct contributions: a linear portion representing the attached flow lift and a nonlinear portion representing the vortical lift. Such a combination may be represented as[9]

$$C_N = 2\pi k_1 \alpha_g \left(\frac{b}{c}\right) + k_2 \left(\frac{\alpha_g}{b/c}\right)^{k_3} \left(\frac{b}{c}\right)^2 \qquad (4)$$

where $k_1$, $k_2$, and $k_3$ are constants. Note that this form applies only to angles of attack *below* stall.

It was assumed that some equivalent formulation would exist for the present configuration. Examination of the spanwise pressure distributions reveals the nature of the interaction between the tangential jet and the outer flow.

At angles of attack less than those corresponding to the original unblown maximum normal force coefficient, the introduction of blowing appears to weaken the vortical flow, as shown in Fig. 7. The vortex strength decreases and its location moves closer to the surface. This may be deduced simply from consideration of the model of a point vortex next to a flat plate. The peak suction imposed upon the plate is an indication of the strength and the "half-width" of the pressure signature an indication of the distance of the vortex from the surface. For sufficiently strong blowing, the vortical flow disappears completely and the flow resembles the attached flow configuration, also known as the R.T. Jones or linear lift solution. The fact that the overall normal force changes only slightly is due to the offsetting effects of the increased leading-edge suction and the reduced vortex influence. As previously stated, there was no measurable effect of the blowing strength on the lower-surface pressure distribution.

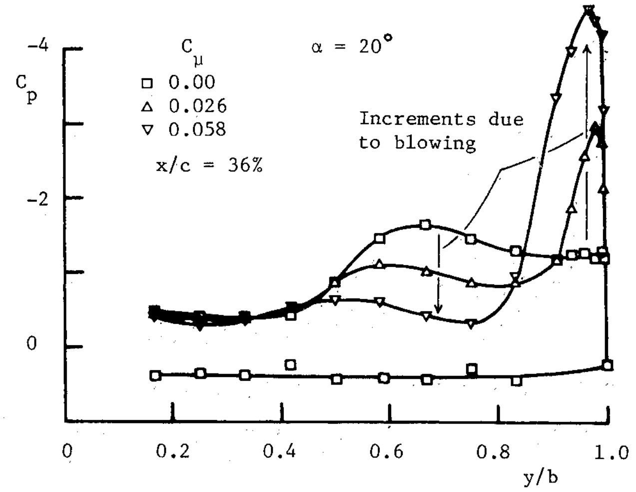


**Fig. 7 Effect of leading-edge blowing on the spanwise pressure distribution at moderate angles of attack.**

Figure 8 shows results for angles of attack that are typically greater than the original unblown maximum normal force condition. Here, the unblown pressure distribution suggests a stagnant, separated flow over the upper surface and the introduction of blowing merely reduces the pressure within that "bubble." This, however, is consistent with the changing location of the primary separation point and the reducing pressure reflects the modification of the crossflow boundary-layer separation condition. Eventually, the trajectory of the free shear layer is deflected sufficiently to permit interaction with the upper surface of the wing and a stable well-defined vortex reappears on the upper surface. This is clearly shown by the appearance of the familiar pressure signature under the vortex. For these cases, significant increases in normal force are evident. Over the range of angles of attack studied, some similarity in the effects of the addition of blowing were observed. For example, the pressure

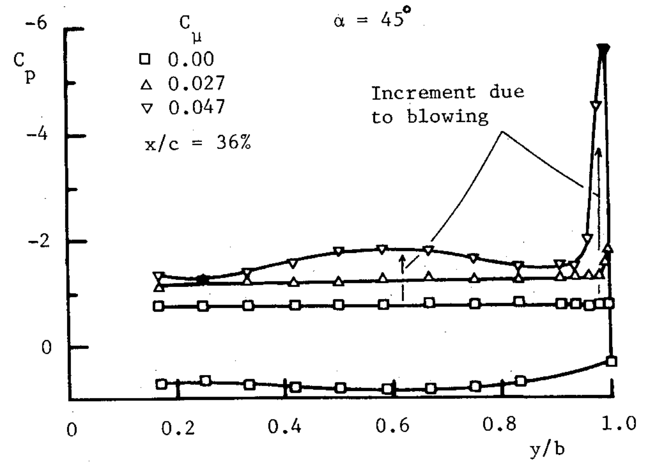


**Fig. 8 Effect of leading-edge blowing on the spanwise pressure distribution at high angles of attack.**

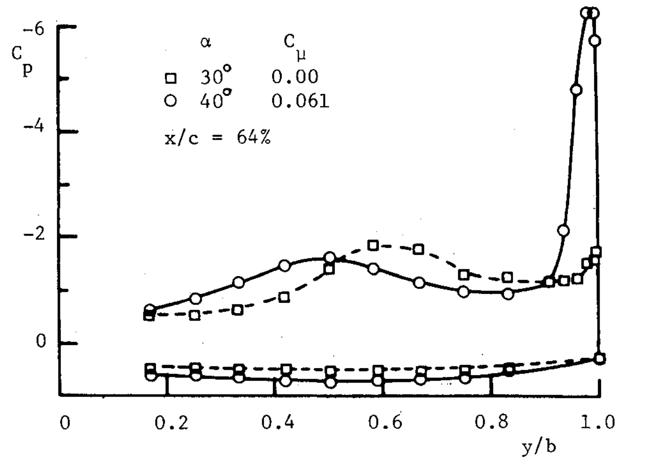


**Fig. 9 Similarity of the vortical flow with/without leading-edge blowing.**

distribution measured at 30 deg angle of attack without blowing resembled that measured at 40 deg with blowing; see Fig. 9. Some lateral translation is observed, but otherwise the vortical flow appears similar. Additional correlations were noted for the positions of the secondary separation lines with and without blowing at different angles of attack.

For two-dimensional circulation control airfoils, the lift due to blowing is decoupled from the lift due to incidence over a significant portion of their operational envelope. Therefore, due to the similarity of the concepts, it was hypothesized that the vortex lift due to blowing was decoupled from the attached flow lift due to incidence. If such a concept could be confirmed, then this would imply that normal force could be modulated independent of angle-of-attack changes. Figure 10 clarifies the concept. Consider that the effect of blowing is to produce a vortical flowfield corresponding to some other effective angle of attack. The change in angle of attack is negative, as indicated by the shift in the primary separation point that was observed as blowing strength was increased. An equivalent form of the equation for normal force that applies to the blown configuration may then be postulated to be

$$C_N = 2\pi k_1 \alpha_g \left(\frac{b}{c}\right) + f(\alpha_e)\left(\frac{b}{c}\right)^2 \tag{5}$$

The function $f(\alpha_e)$ would be of similar form to the nonlinear term in Eq. (4). In Eq. (5), the effective angle of attack may be represented by a simple linear equation as a function of the blowing strength,

$$\alpha_e = \alpha_g + \frac{\partial\alpha}{\partial C_\mu}\Delta C_\mu \tag{6}$$

where $\partial\alpha/\partial C_\mu$ is negative.

This equation may be confirmed from examination of the blowing momentum coefficient required for maximum normal force at a number of different angles of attack. Figure 11 shows the development of the normal force as a function of blowing strength and angle of attack. From this type of data, Fig. 12 may be deduced. The values shown for angles of attack in excess of 50 deg were obtained from extrapolation of results from other experiments on the same model. Clearly, if Eq. (6) were correct, the results would form a straight line indicating a constant value for the partial derivative. Since the jet is directly interacting with the crossflow boundary layer, a more appropriate form of the

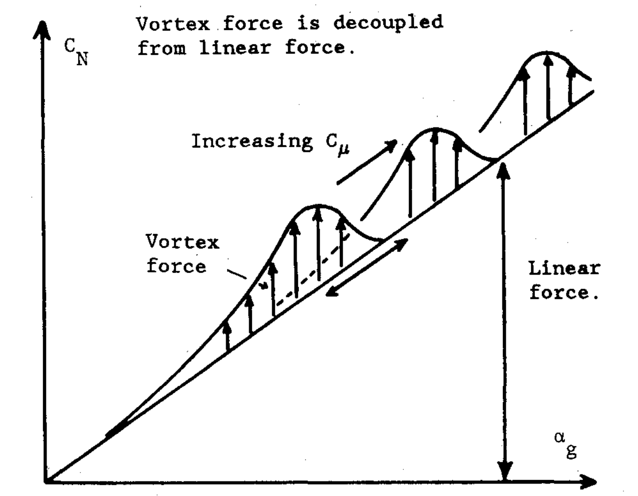


**Fig. 10 Concept of decoupled linear and nonlinear lift contributions.**

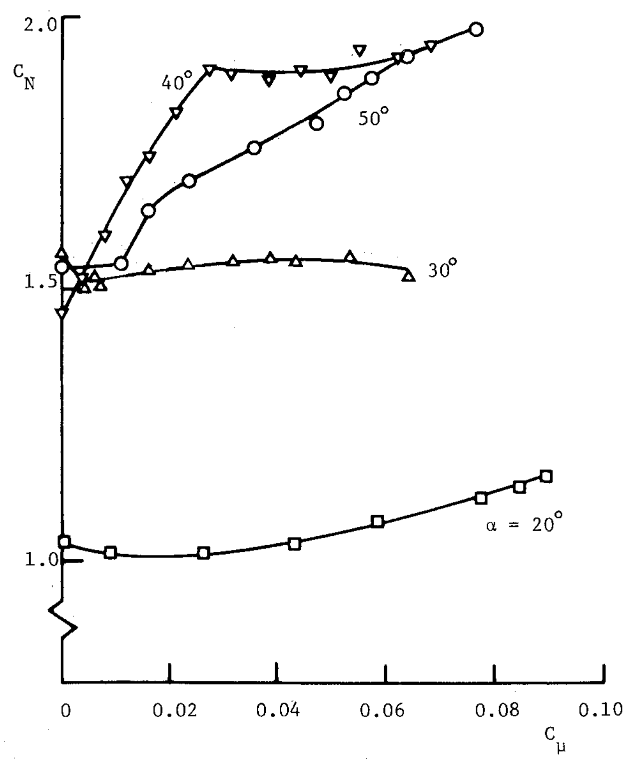


**Fig. 11 Generation of wing normal force by leading-edge blowing.**

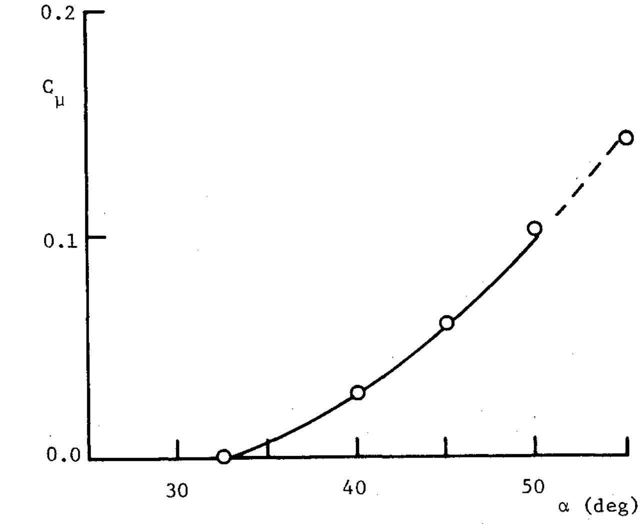


Fig. 12 Leading-edge blowing required for maximum normal force.

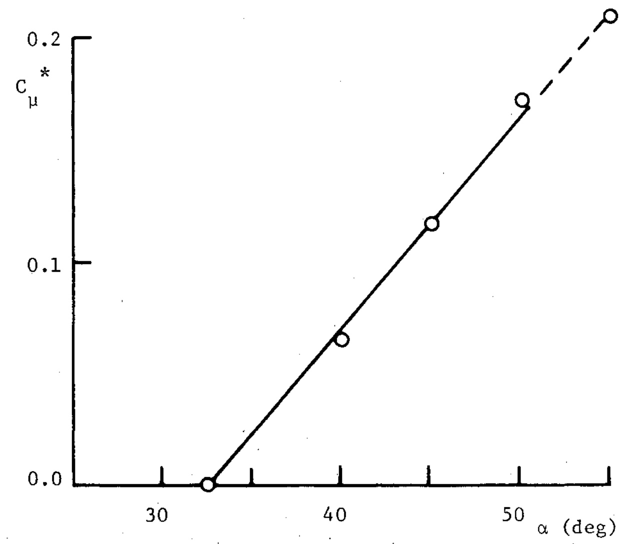


Fig. 13 Leading-edge blowing required for maximum normal force relative to crossflow velocity.

jet momentum coefficient may be

$$C_\mu^* = 2\left(\frac{h}{2b}\right)\left(\frac{V_j}{V_\infty \sin\alpha_g}\right)^2 \tag{7}$$

$C_\mu^*$ may now be substituted into Eq. (6). Figure 13 illustrates the resulting relationship for the blowing coefficient at the maximum normal force points. This form of the blowing coefficient appears to collapse the data much more satisfactorily and a value for $\partial\alpha/\partial C_\mu^*$ of $-95$ deg is obtained. Thus, it may be suggested that a crossflow blowing momentum coefficient is the important scaling parameter for the coflowing leading-edge blowing configuration. This also implies that such a system would operate at high-subsonic Mach numbers and even into the supersonic regime for modest angles of attack, a significant advantage over most conventional blowing schemes.

A further interesting result from Eq. (6) is that one may define the blowing required to achieve fully attached flow over the wing for any angle of attack. This condition is obtained when the effective angle of attack is set to zero, i.e., no vortex lift. The resulting equation is

$$(C_\mu)_{\text{attached}} = -\frac{\alpha_g}{\partial\alpha/\partial C_\mu^*}\cdot \sin^2\alpha_g \tag{8}$$

Figure 14 illustrates the predicted blowing coefficient for attached flow and is compared with results from the present experiments. The agreement is most satisfactory. The experimental data are represented as a band to encompass the range of values deduced allowing for the nonconicality of the flow. The weaker trailing-edge flow required less blowing momentum to reattach the flow compared to the leading edge. Also, difficulty was encountered in actually defining the blowing coefficient where the vortical flow ceased to exist, due to the discrete spacing of the data points. The results are shown for the blowing coefficient relative to the freestream velocity, not the crossflow velocity, since this was the form originally adopted for the experiment. Thus, the hypothesis has been correlated for both the points of maximum normal force and the conditions for obtaining fully attached flow over the wing upper surface.

More recently, a detailed flow visualization study has begun and some initial results are shown in Figs. 15–19. Apart from the movement of the primary and secondary separation lines, one can also see the presence of the vortical flow established on the upper surface. At higher blowing levels, it is also apparent that the jet flow is not completely

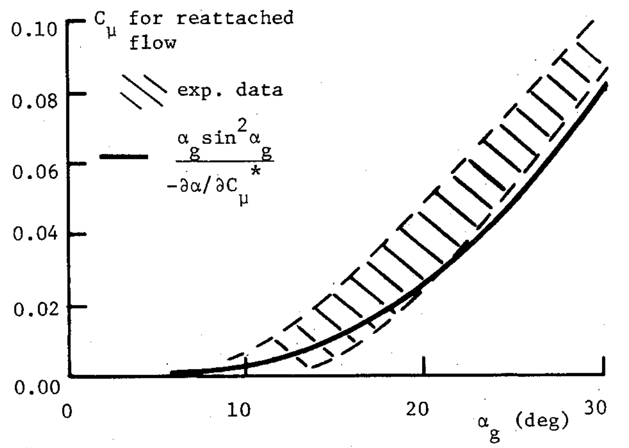


Fig. 14 Leading-edge blowing required for reattached flow.

conical and that the end effects are quite severe. The extremely high curvature of the leading edge causes high levels of vorticity to be shed from the ends of the jet and these rapidly concentrate to form vortices. This effect was especially important at angles of attack over 55 deg and suggests that longer models that would reduce end effects are required to evaluate the performance at higher angles. To illustrate this problem, Fig. 20 shows the chordwise normal force distributions that were measured at 60 deg angle of attack. As the blowing was increased, the majority of the lift increment appeared toward the trailing edge of the wing, reflecting the presence of a large vortex shed from the finite end of the jet. At the highest blowing rate, however, the flowfield "flip-flops" to an apex-loaded form similar to that seen at lower angles of attack. The main wing vortical flow had been re-established and the trajectory of the shed vortex redirected. Thus, it appears that the basic flow mechanism still persists at very high angles of attack with sufficient blowing momentum.

A measure of the efficiency of this blowing scheme may be to examine the rate of change of the effective angle of attack with blowing momentum coefficient ($\partial\alpha/\partial C_\mu^*$). This has a parallel in circulation control of lift augmentation ($\partial C_\ell/\partial C_\mu$). Experimental and numerical studies should be performed to examine the effects of such parameters as leading-edge radius, extent and size of the slot, and direct control of transient phenomena. It has been well documented in the field of circulation control that smaller slot heights are more efficient in terms of momentum

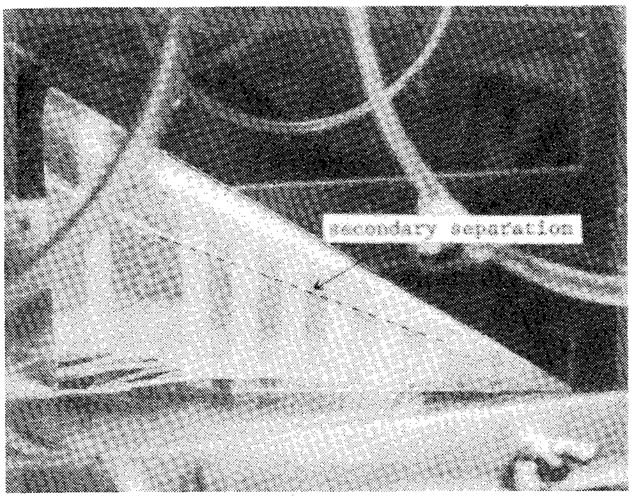


**Fig. 15 Surface oil flow visualization, $\alpha = 20$ deg, $C_\mu = 0.0$.**

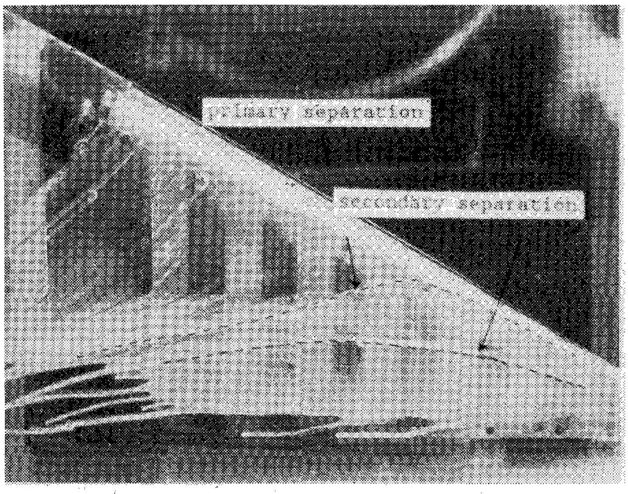


**Fig. 16 Surface oil flow visualization, $\alpha = 20$ deg, $C_\mu \approx 0.06$.**

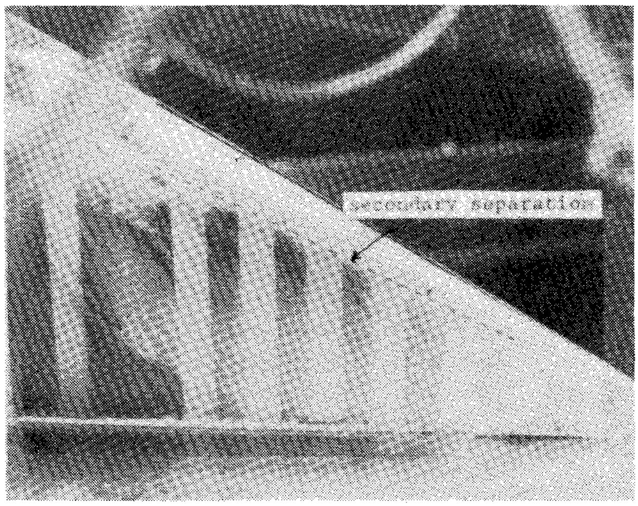


**Fig. 17 Surface oil flow visualization, $\alpha = 30$ deg, $C_\mu = 0.0$.**

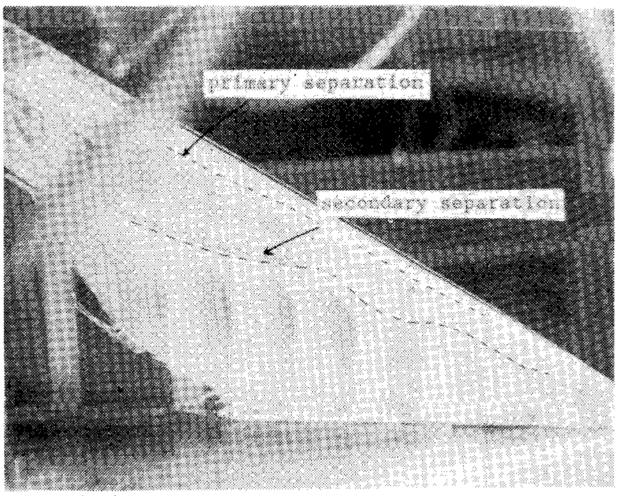


**Fig. 18 Surface oil flow visualization, $\alpha = 30$ deg, $C_\mu \approx 0.05$.**

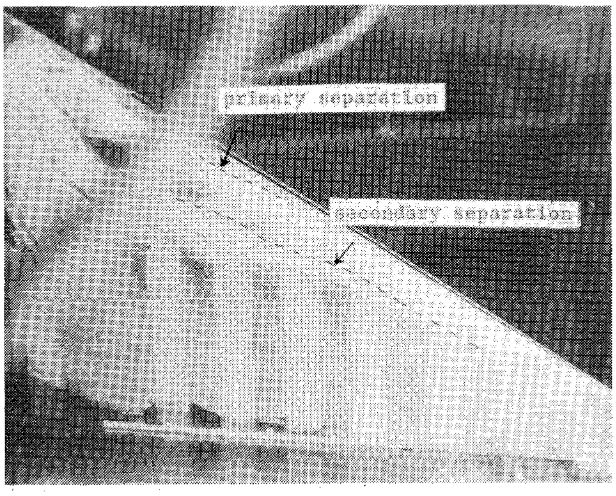


**Fig. 19 Surface oil flow visualization, $\alpha = 40$ deg, $C_\mu \approx 0.05$.**

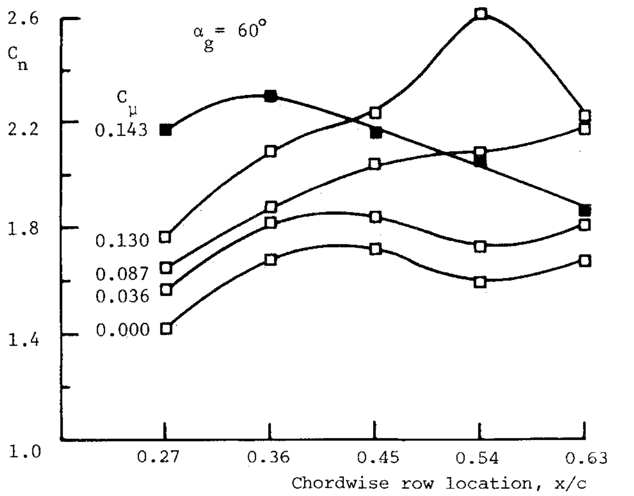


**Fig. 20 Effect of leading-edge blowing on the longitudinal load distributions at very high angles of attack.**

transfer; therefore, some improvement in the efficiency of the present configuration may be possible through the use of a reduced slot height. The current value of $h/b = 0.0046$ is at least double that of a typical circulation control airfoil when comparing the chord of a two-dimensional airfoil to the span of a delta wing.

The present leading-edge blowing scheme has shown itself to be extremely powerful in controlling the vortical flow above a delta wing at high angles of attack. An optimized system may be capable of high-frequency modulation of the vortex strength and location, thereby avoiding transient control phenomena at high angles of attack or on very slender bodies. The incorporation of a leading-edge slot and a rounded leading edge on a delta wing should not degrade the unblown performance and also may be beneficial to avoid problems of aerodynamic heating at high Mach numbers.

## Conclusions

Initial results indicate that the coflowing, tangential leading-edge mass injection was capable of extending the regime of stable, controlled vortical flow over the upper surface of a delta wing by approximately 30 deg angle of attack for modest blowing requirements. Increases in maximum normal force coefficient of approximately 30% were achieved and significant rolling moments produced at angles of attack of 35–60 deg.

The concept clearly exhibited a decoupling of the two lift components, linear and nonlinear. This suggests that such a scheme may be a practical solution for changing normal force without changing attitude, for the production of control moments at extremely high angles of attack (both steady and transient), and for increasing the *L/D* of very slender cone-like bodies at modest angles of attack. The decoupling of the lift components was shown to depend upon the crossflow blowing momentum coefficient, suggesting that operation at speeds in excess of Mach 1 should be possible.

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