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DEVELOPMENT OF LATERAL CONTROL ON AIRCRAFT OPERATING AT HIGH ANGLES OF ATTACK

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ABSTRACT

The concept of tangential wall jet blowing for the control of separated vortical flows is presented. Experimental results for the development of rolling moment about a delta wing for both pre- and post-stall angles of attack with sideslip have been obtained. The unblown vortical flow present on the lee-side of a delta wing at post-stall angle of attack is shown to be sensitive to sideslip and to affect the efficiency of the blowing concept. An extension of the delta wing application to forebody flow control to provide yaw control at post-stall angles of attack is discussed.

SYMBOLS

A_j	slot exit area
b	wing span
c	wing chord
C_L	wing rolling moment coefficient
C_p	pressure coefficient
C_μ	blowing momentum coefficient
m	jet mass flow
q	free stream dynamic pressure
S	wing reference area
x,y	cartesian coordinates
V_j	jet exit velocity
V_∞	free stream velocity
α	angle of attack
α_0	angle of attack prior to roll or yaw perturbation
β	sideslip angle
ρ	free stream density
ϕ	roll angle
ψ	yaw angle
Δp	difference between internal plenum pressure and free stream static

Subscripts

L	left side blowing only
R	right side blowing only

INTRODUCTION

The development of control forces and moments for combat aircraft operating at very high, post-stall angles of attack remains a significant challenge. A recent report from the X-29 flight test program(1) illustrated the complexity of post-stall manoeuvring. The sensitivity to yaw departures at high angles of attack was discussed and the high angle of attack range referred to was from 30° to 50°. The report also described the complexity of the control functions, notably combined rudder and aileron, required at high angle of attack.

Despite this sensitivity, advantages of operating outside the existing angle of attack envelope are anticipated(2) as either point and shoot manoeuvres for WVR engagements or more transient 'agile' manoeuvres with reduced time to turn. Both instances impose extensive regions of asymmetric separated unsteady flow over wings, tail surfaces and fuselage with an accompanying loss of control power from conventional moving surface controls. Compounding the problem are the low dynamic pressure typical of these extreme manoeuvres and the presence of burst vortices over the wing surface. Additional instabilities and non-linearities related to the high angle of attack; nose-slice(3)(4), wing rock(5)(6) etc., may also need to be corrected to avoid vehicle divergence. It is of interest to investigate new mechanisms for the production of pitch, roll and yaw moments such that aircraft can be trimmed at extreme angles of attack or sideslip or that instabilities and non-linearities can be corrected.

For typical current combat aircraft, pitch, roll and yaw control power becomes significantly degraded as the vehicle approaches maximum lift. Pitch and roll control are affected by the separated flow and burst vortices over the wings and tails while rudder surfaces become shielded by the fuselage. For high angles of attack, control effectiveness also reduces with the associated reduction in dynamic pressure. The intention of this paper is to focus on the production of lateral control for post-stall operation.

Previous concepts(7) have included leading edge vortex flaps (LEVF), raked wing tips, apex fences, tiperons, spanwise blowing and other jet augmented devices. In the majority of cases, modest improvements in roll control have been achieved but only over fairly limited angle of attack ranges. For yaw control(8)(9), attention has focused either on thrust vectoring or on manipulation of the forebody vortices by movable strakes/fences or pneumatic devices. Modest improvements in yaw control were identified. It is apparent that control of the induced flow asymmetries and unsteadiness is necessary for safe operation at post-stall conditions.

Recent experimental(10) and numerical(11)(12) investigations into the concept of tangential wall jet flow control for separated vortical flows have demonstrated a capability for both roll and yaw control. This paper will describe some results from the experimental studies and postulate the mechanisms associated with the vortical flow control.

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TANGENTIAL WALL JET BLOWING

The concept of flow control by tangential wall jet blowing is based on the phenomenon of Coanda jet attachment to convex surfaces(13). The high curvature of the surface enhances the entrainment rate of the jet, induces strong suction under the jet and accelerates the transfer of momentum from the jet to the outer flow. This can be used to delay the separation of an outer flow and in some instances produce a global modification of the flow field. An example of the concept is the application of Coanda flow to Circulation Control aerofoils(14). Here the wall jet modifies the location of the rear stagnation point around a bluff trailing edge and controls the circulation of the aerofoil without modification of the angle of attack. The momentum of the jet is the parameter which determines the lift of the aerofoil. Other applications of Coanda wall jets include the control of wind tunnel boundary layers(15), blown trailing edge flaps(16) and the NOTAR helicopter project where a tail boom with tangential wall jet blowing obviates the need for a tail rotor.

Recently, wall jets have been applied to the control of the crossflow separation on rounded leading edge delta wings(17), figure 1. Instead of modifying the circulation of the wing, the wall jet momentum now controls the strength and location of the lee-side vortex pair such that equilibrium is maintained. Previous results have shown this particular application capable of removing a vortex burst from the wing surface in a process analogous to reducing the "effective" angle of attack of the vortical flow.

Several reports(18)(19) have discussed the attributes of tangential leading edge blowing with particular reference to the steady state and time response characteristics. It is reasonable to summarise the primary effects before proceeding to a discussion of the generation of roll and yaw moments.

When applied to a delta wing, at pre-stall angles of attack, the effect of blowing is to weaken the adjacent vortex and move the core location inboard. The effects are uncoupled such that asymmetrical blowing effects can be determined by simple superposition of the individual effects. The net rolling moments and normal forces are functions of a balance between the reduction of the vortex influence and an increase in the suction loading at the leading edge due to the jet attachment, figure 2.

At post-stall angle of attack, increasing symmetrical leading edge blowing momentum moves the vortex burst points aft. At a given chordwise location, this is perceived as a local increase in the vortex strengths up to a level equivalent to that at maximum lift, unblown. Thereafter the vortices weaken as for the pre-stall angle of attack case. For asymmetric blowing, the vortex properties are strongly coupled up to the maximum vortex strength condition and thereafter are uncoupled, figure 3. The coupling produces a reversal of operation in that right side blowing initially unbursts the left side vortex. This phenomenon has been observed in previous data and the cause remains undetermined.

ROLL CONTROL AT HIGH ANGLE OF ATTACK

To determine the ability of tangential wall jet blowing to provide roll control for high angle of attack operation it is important to evaluate the steady state roll response of a delta wing to asymmetric blowing in the presence of sideslip. Unlike low angle of attack, attached flow cases sideslip imposes asymmetries upon the vortical flow on the lee-side of a delta wing. Experimentally, the sideslip is produced by either yaw or roll about the body axes of the model. For positive roll about the longitudinal body axis, the sideslip angle increases while the angle of attack reduces. Using standard notation:

$$\alpha = \alpha_0 \cos\phi$$

$$\beta = \alpha_0 \sin\phi$$

For positive yaw about the normal body axis, the sideslip angle decreases while the angle of attack increases.

$$\alpha = \tan^{-1}\left(\frac{\tan\alpha_0}{\cos\psi}\right)$$

$$\beta = -\psi$$

These combinations may produce non-linear changes in the vortex structure over a delta wing, particularly when a vortex burst is present over the upper surface. The individual effects are difficult to isolate.

Experiment

Details of the experiment are given in reference 10. A 60° sweep full span delta wing was sting mounted in the Stanford University, 0.46m, low speed wind tunnel, figure 4. The mounting system allowed angles of attack to 55°, yaw angles of +/-10° and roll angles up to 30°. Individual blowing plenums supplied a tangential blowing slot on each wing leading edge. Separate control systems permitted asymmetric steady state blowing to be applied and a 3-component strain gauge balance provided normal force, pitching and rolling moment. A single row of pressure tappings located at approximately 35% chord provided information regarding the upper surface pressure distributions. Due to space limitations, these tappings could not be extended around the leading edge to measure the leading edge suction peak. The majority of the results were obtained for free stream speeds between 20 and 40 m/s.

The blowing momentum coefficient, C_μ is defined as the non-dimensional form of the jet momentum.

$$C_\mu = \frac{mV_j}{qS}$$

With the simplifying assumptions of incompressible flow and the local exit static pressure equal to free stream static, this becomes:

$$C_\mu = 2\,\frac{A_j}{S}\left(\frac{V_j}{V_\infty}\right)^2$$

where

$$V_j^2 = 2\,\frac{\Delta p}{\rho}$$

Pre-stall Roll Control

It is convenient to initially examine the roll behaviour at pre-stall angles of attack where the effects of asymmetric blowing are uncoupled. Figure 5 shows the roll response of the wing to asymmetric blowing and the appropriate sideslip and incidence angles are given in Table 1. It is apparent that at pre-stall angles of attack, leading edge blowing is only capable of trimming a delta wing to roll angles of approximately 7°. At higher roll angles, only restoring moments can be produced. This limitation, presumably induced by the vortex asymmetry due to sideslip, is worthy of investigation.

Consider figure 6, which shows pressure distributions for right side blowing at various roll angles. Since the roll response was symmetric for either right or left blowing, we need only consider one side, simplifying the interpretation of the flow. Furthermore, if the flow is uncoupled, then the phenomena should be isolated on the side which is blown, i.e. the right side in this instance. Figure 5 showed that as the roll angle was increased, the blowing was capable of producing larger restoring moments, i.e. dC_L/dC_μ decreases. To understand this, the various contributions to roll must be identified.

For pre-stall conditions, blowing weakens the adjacent vortex influence and provides a strong leading edge suction. For rolling moment, these two effects oppose each other as depicted in figure 7. It is seen that increasing sideslip relocates the right side vortex inboard without modification of the strength, effectively reducing the vortex contribution to rolling moment. Thus, as blowing is applied, the vortex is weakened and the leading edge contribution becomes dominant producing a net negative rolling moment. The enhanced vortex burst on the windward side must also contribute to a reduction in the vortex contribution to roll.

These results are from sting balance measurements and therefore include the effects of vortex burst over the trailing edge of the wing. The interaction between sideslip and burst location is complex and not subject to simple interpretation.

It is well known that vortex influence reduces as the trailing edge is approached, while the jet induced leading edge suction presumably varies with the local C_μ. Therefore, since the jet momentum increases linearly from the wing apex to the tip, one would expect the stronger leading edge suction near the wing tip to become more dominant as the angle of attack approaches stall. The sensitivity to the balance between leading edge suction and vortex influence suggests that the resulting moment could be sensitive to geometry. For example, a smaller leading edge radius or different sweep angles would affect the balance between the two contributions.

Post-stall Roll Control

Figure 8 illustrates the control reversal which has been identified between pre- and post-stall angles of attack. Coupling between the leading edge vortices has been found to be responsible and therefore is important in the production of rolling moment under sideslip conditions.

The effects of sideslip are that the windward wing vortex burst moves forward in response to positive sideslip (positive roll)(20). At high post-stall angles of attack where the burst point is already at the apex, it appears that the effect is rather to 'unburst' the leeward side vortex, figure 9. It is conceivable that this effect is a function of the rounded leading edges of the present model. As sideslip is increased, the crossflow separation on the upwind leading edge may be delayed, not unlike the effect of the wall jet blowing. Since it has been observed that weak blowing unbursts the opposite side vortex, then possibly the sideslip angle has a similar effect. Further experiments are needed for clarification, the phenomenon does however, aid interpretation of the rolling moment response to blowing with sideslip. It may be that asymmetric blowing should be considered as producing an "effective" sideslip angle, analogous to the "effective" angle of attack for symmetric blowing.

Figure 10 summarises the rolling moment obtained at 50° angle of attack, post-stall. The symmetry around no blowing is again apparent and so discussion will be concentrated on right side blowing only. It is of interest to note the reversal which appears between -10° and -20° roll for right side blowing. Consider the pressure distributions for the various roll angles shown as figure 11. This reversal can be attributed to the recovery of the right side vortex influence due to sideslip as shown in figure 9.

		Roll Angle					Yaw Angle		
α_0		-20°	-10°	0°	10°	20°	-10°	0°	10°
30°	α	28.19	29.54	30.00	29.54	28.19	30.38	30	30.38
	β	-10.26	-5.21	0.00	5.21	10.26	10.00	0.00	-10.00
50°	α	46.98	49.24	50.00	49.24	46.98	50.43	50.00	50.43
	β	-17.10	-8.68	0.00	8.68	17.10	10.00	0.00	-10.00

Table 1: Sideslip and Incidence for Combinations of Yaw, Roll and Incidence.

At post-stall angles of attack, the two primary sources of roll in the low blowing region of figure 10 are the increasing influence of the leading edge vortices. Leading edge suction is also a factor but not until the adjacent vortex has been unburst.

For right side blowing only, the contributions to roll may be schematically represented as in figure 12. The positive left vortex contribution is significantly reduced as the effective sideslip angle 'unbursts' the vortex; noting that unburst vortices tend to be uncoupled. Except for large negative sideslip, the right side roll contribution is small until the left side vortex is unburst, it then produces a negative contribution to roll. At large negative sideslip, the opposite vortex is already nearly fully unburst and therefore, the negative contribution from the adjacent vortex occurs for much lower blowing rates. The combined effect of these phenomena may be summarised as in figure 13 which schematically represents the sum of the right and left vortex influences as a function of sideslip (roll) angle. The trends appear similar to those measured.

Yaw and roll results may be directly compared at similar sideslip angles. Although not an exact correlation, the results given in figure 14 do show the common form of the moment response to asymmetric blowing. The successful application of this concept requires the identification of the vortex coupling mechanism and the verification of its existence for actual vehicle configurations.

YAW CONTROL AT HIGH ANGLE OF ATTACK

The production of yaw moment at high angle of attack remains of equal importance to the development of agile combat aircraft with post-stall manoeuvre capability. Devices which could overcome the phenomena associated with the long forebodies typical of combat aircraft, without compromising performance, would be desirable. It would appear that the forebody is an obvious choice for the placement of control devices due to the long moment arm ahead of the centre of gravity.

The effectiveness of tangential wall jet blowing applied to the control of separated flows over delta wings prompts the proposal for a similar control device for aircraft forebody flow control, figure 15. The primary intention being to control the forebody vortices to provide yaw control and/or correct the vortex asymmetries associated with nose-slice and wing rock. This concept was recently investigated computationally by Tavella et.al.(13).

By extrapolation from the wing data, expected blowing rates, based on similar velocity ratios but smaller slot areas, would be an order of magnitude less than those quoted for wing vortex control. No prior knowledge of the vortex location is required to effect control, providing the slot is positioned in the vicinity of the crossflow separation. Thus, either an asymmetric vortex pair could be made symmetric, or vice versa. Forebody vortices typically remain unburst to quite high angles of attack with the implication that control laws could be simply derived based on uncoupled tangential blowing effects. Pitch control may also be available through symmetric blowing.

It may be possible to modify the cross-section of the forebody to minimise the effect of cross-flow Reynolds number and sideslip on the separation location. Data from circulation control experiments showed that while tangential blowing remains effective if the slot is poorly positioned relative to the flow separation, the efficiency may be reduced and non-linearities introduced.

The convective time lags which could lengthen the response time to such a control device should be relatively short since, at high angle of attack, the forebody vortices depart the body in the vicinity of the canopy and thereafter cease to interact with the aircraft surface. Malcolm et.al.(10) observed that the majority of the yawing moment induced by vortex control was experienced on the forebody as opposed to the remainder of the fuselage and tail surfaces.

The simplicity, speed of response and minimal weight penalty of such an installation make forebody vortex control by tangential wall jet blowing an attractive proposition for further research. It is hoped to report experimental results on the effectiveness of such a device in the near future at which time further discussion of the potential of the device would be appropriate. It is anticipated that those results would support the general observations reported by Tavella et. al.(13).

CONCLUSIONS

Experimental results suggest that tangential wall jet blowing is an effective mechanism for controlling separated flows including either burst or unburst vortices. At high sideslip angles, the induced asymmetry of the separated flow reduces the ability of the wall jet blowing to provide positive and negative roll control. Large restoring rolling moments may be generated over a range of pre- and post-stall angles of attack to control vehicle divergence.

The geometry of the wing may affect the balance of vortex and leading edge roll contributions, pre-stall. The strong coupling of the burst vortices, post-stall, induces control reversals compared to pre-stall which would be undesirable and is therefore an area for further research. Numerical studies by other researchers support the proposal that tangential wall jet blowing could provide yaw control through manipulation of the forebody vortices.

ACKNOWLEDGEMENTS

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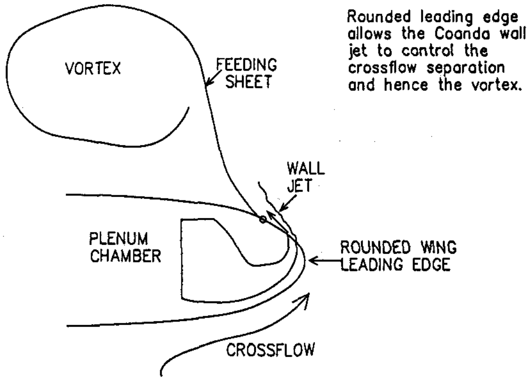


Rounded leading edge allows the Coanda wall jet to control the crossflow separation and hence the vortex.

Figure 1: The Control of Crossflow Separation by Tangential Wall Jet Blowing.

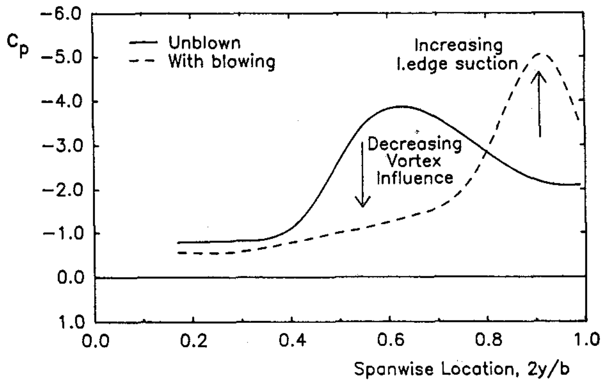


Figure 2: Rolling Moment Contribution Induced by Blowing at Pre-stall Angle of Attack.

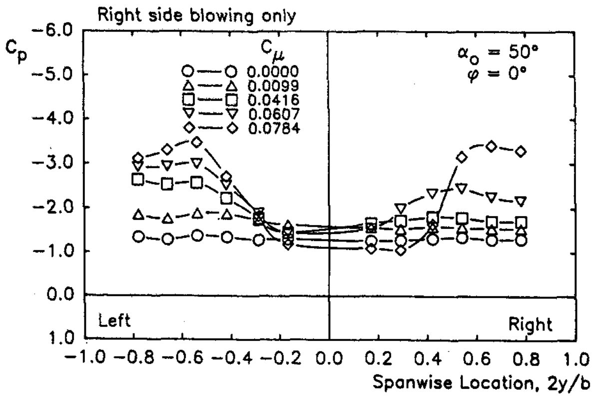


Figure 3: Vortex Coupling at Post-stall Angle of Attack.

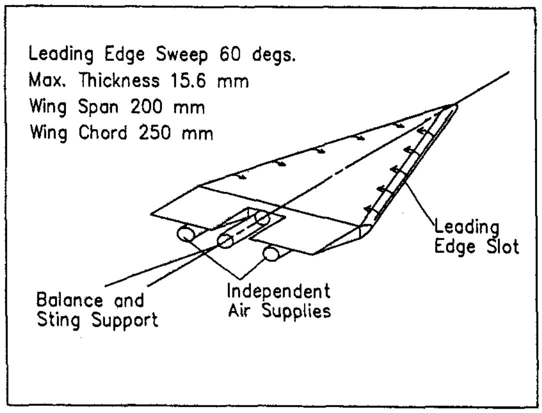


Figure 4: Delta Wing Model with Tangential Leading Edge Blowing.

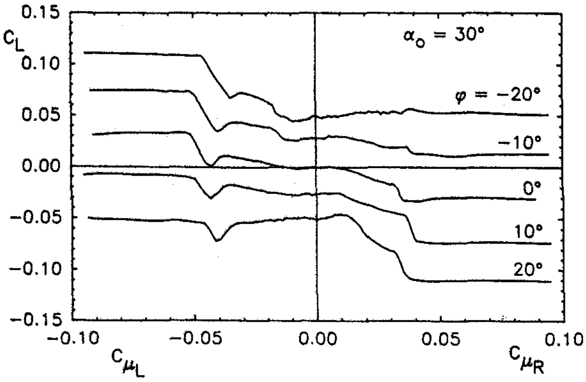


Figure 5: Rolling Moment due to Asymmetric Blowing at Pre-stall Angle of Attack.

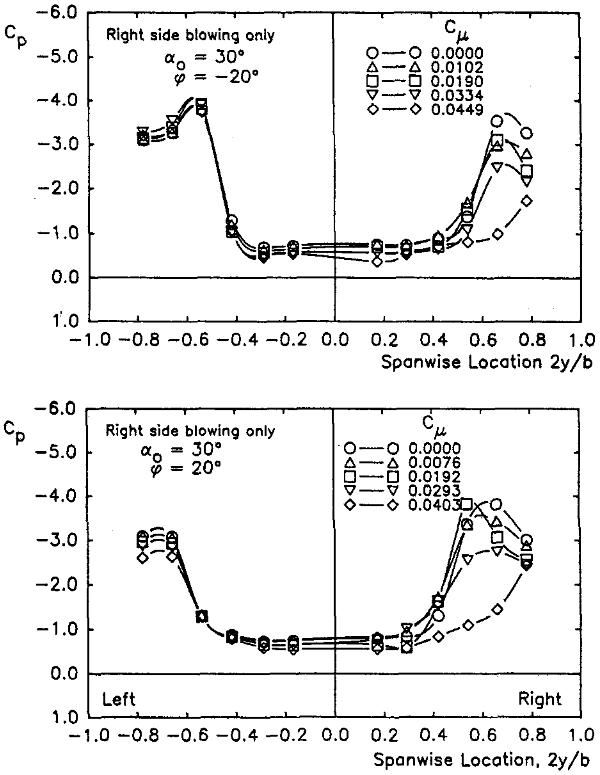


Figure 6: Pressure Distributions at Pre-stall angle of attack for:
(a) -20° and (b) +20° roll.

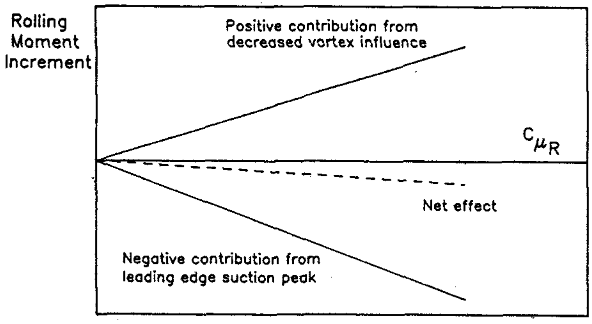


Figure 7: Sources of Rolling Moment, Pre-stall.

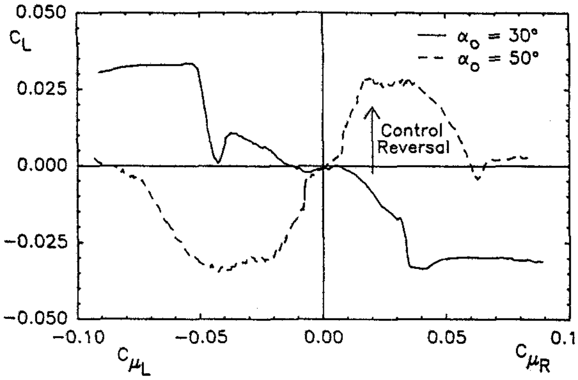


Figure 8: Control Reversal due to Vortex Coupling at Post-stall Angle of Attack.

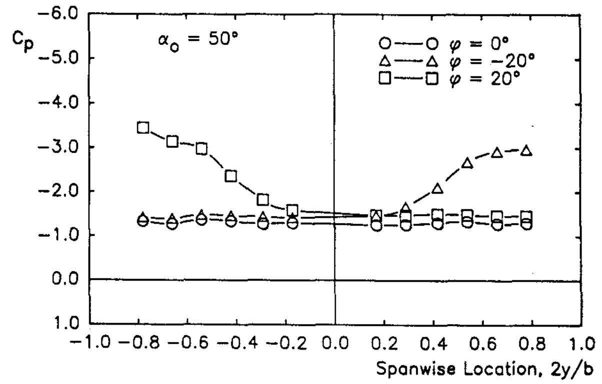


Figure 9: Effect of Sideslip on Unblown Vortex Strength at Post-stall Angle of Attack.

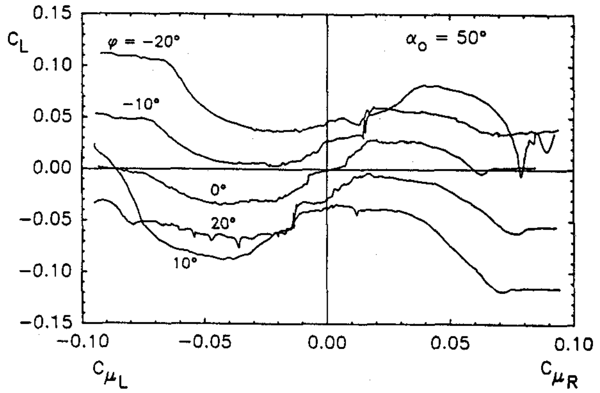
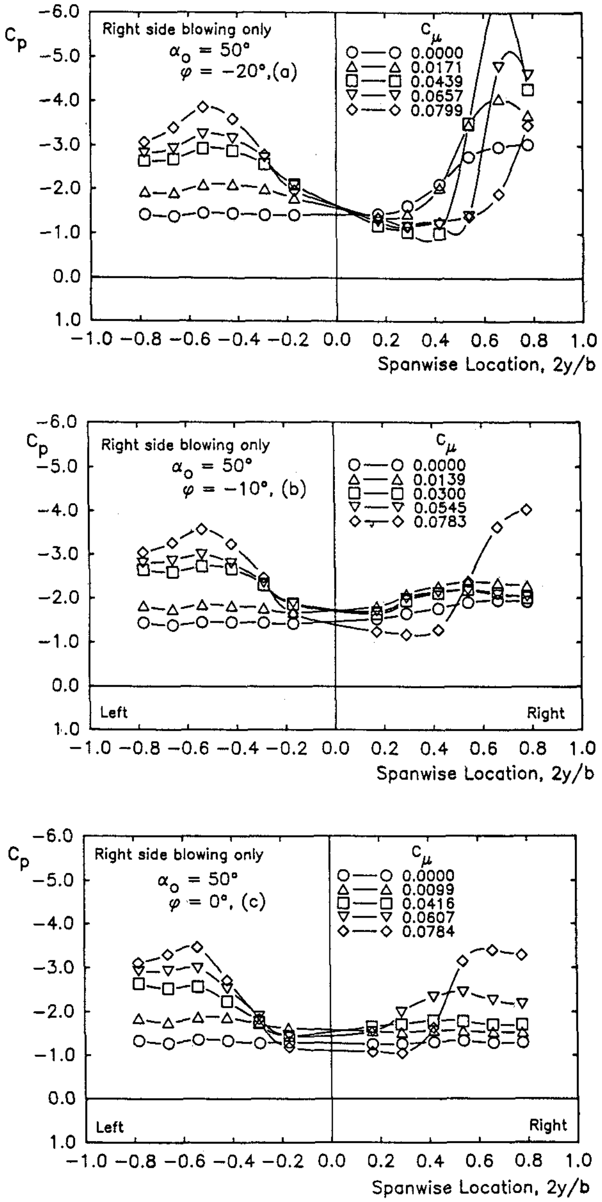


Figure 10: Rolling Moment due to Asymmetric Blowing at Post-stall Angle of Attack.



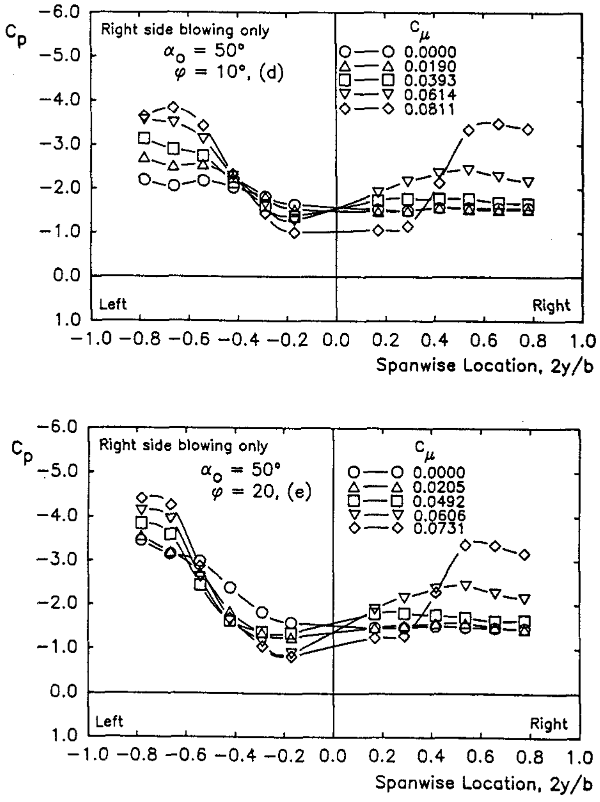


Figure 11: Pressure Distributions at Post-stall Angle of Attack for:
(a) -20° (b) -10° (c) 0° (d) 10° and (e) 20° roll.

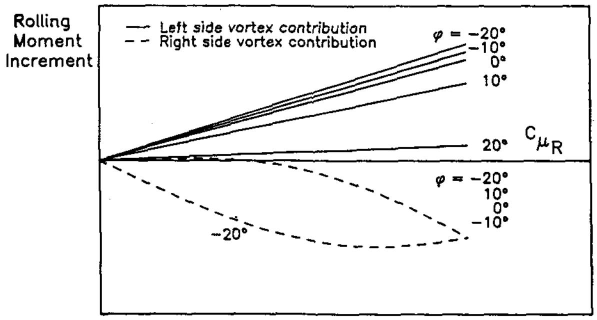


Figure 12: Sources of Rolling Moment, Post-stall.

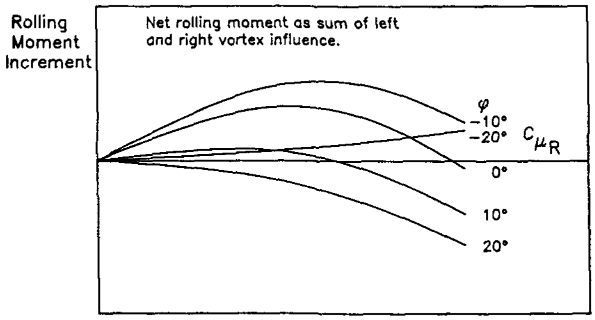

Net rolling moment as sum of left and right vortex influence.

Figure 13: Net Rolling Moment due to Asymmetric Blowing at Post-stall Angle of Attack.

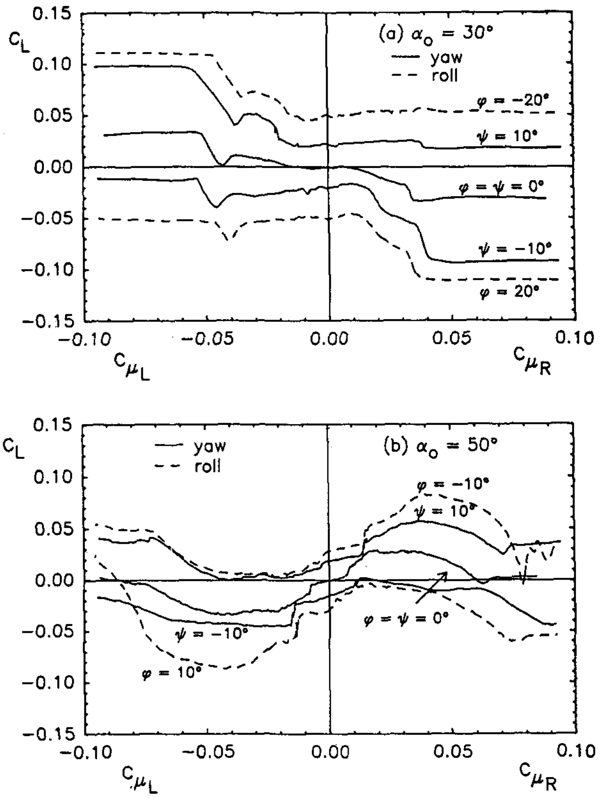
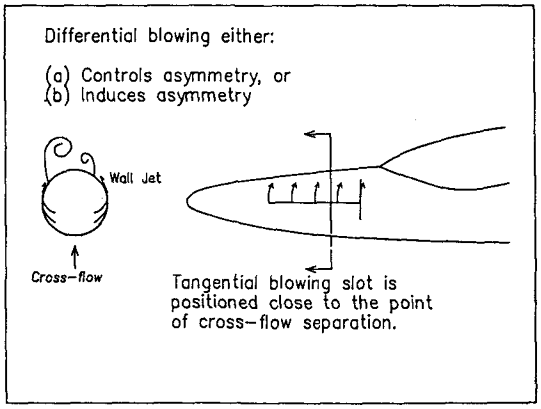


Figure 14: Comparison of Rolling Moment due to Roll and Yaw for: (a)Pre-stall and (b) Post-stall.


Differential blowing either:

(a) Controls asymmetry, or
(b) Induces asymmetry

Tangential blowing slot is positioned close to the point of cross-flow separation.

Figure 15: Tangential Wall Jet Blowing Applied to an Aircraft Forebody.