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Directional Control at High Angles of Attack Using Blowing Through a Chined Forebody

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Directional control through the use of pneumatic blowing was investigated on a generic subscale model with a chined forebody. Pneumatic control was accomplished by blowing through a chine slot in a direction normal to the forebody surface. Comparisons are made with a vertical tail on and off, and with control through conventional rudder deflection. Force and moment data were obtained for various blowing coefficients over an angle-of-attack range from 0 to 75 deg to document the techniques effectiveness. Flow visualization was also conducted in order to obtain qualitative information about the effect on the flowfield. Results indicate that pneumatic blowing through a chined forebody can be an effective technique for generating yaw moments at large angles of attack where conventional control surfaces lose their effectiveness. Yaw moments generated are typically much larger than that obtained by just the jet thrust effect alone since the forebody flowfield is significantly modified from the interaction of the jet with the chine vortices. Directional control capability was found to increase with angle of attack for a given blowing coefficient until a maximum was reached. Further increases in angle of attack result in a rather rapid loss of effectiveness. In addition, the effectiveness of the pneumatic concept was found to be dependent on tail configuration.

Nomenclature

b = wing span
C_l = roll moment coefficient, L/QSb
C_m = pitch moment coefficient, M/QSc
C_N = normal force coefficient, N_F/QS
C_n = yaw moment coefficient, N/QSb
C_Y = side force coefficient, S_F/QS
C_μ = blowing coefficient, $\dot{m}V_j/QS$
c = mean aerodynamic chord
L = roll moment
M = pitch moment
$\dot{m}$ = mass flow rate
N = yaw moment
N_F = normal force
Q = dynamic pressure
S = wing area
S_F = side force
V_j = jet velocity
α = angle of attack
δ_r = rudder deflection angle

Introduction

HIGH angle-of-attack capabilities of aircraft are constantly being expanded in order to improve maneuverability of combat aircraft. The large-scale separated flowfields that are associated with operating at large angles of attack pose a challenge in developing methods by which the aircraft may be controlled. At large angles of attack, vertical tail surfaces lose effectiveness due to the separated wake on the leeward side of the aircraft, resulting in a significant degradation of yaw control. This point is illustrated in Fig. 1, which is a plot of yaw moment coefficient due to rudder deflection, vs angle of attack for the X-29.[1] Note that above an angle of attack of 45 deg, the rudder is almost completely ineffective, which poses a problem, since at the higher angles of attack more control effectiveness is needed to counteract yaw moments due to forebody asymmetries.

A typical modern combat aircraft has a configuration consisting of a relatively rearward c.g. and an associated long slender forebody. The slender forebody of modern aircraft is well-documented to exhibit a vortical flowfield at large angles of attack. The strength of these forebody vortices, along with the relatively large moment arm from the aircraft c.g. combine to create a possible mechanism for yaw moment generation. For example, some aircraft are known to exhibit "nose slice" which is a lateral-directional departure phenomenon initiated by strong yaw moments associated with asymmetry of the forebody vortices. It is logical to assume that control of these vortices, therefore, may result in an effective method to generate yaw moments at large angles of attack.

Experimental and computational investigations have documented success in generating yaw moments through the control of forebody vortices.[1–7] Both mechanical and pneumatic methodologies have been employed with some success. Most of the work, however, focuses primarily on aircraft configurations with conventional forebodies in which separation points are free to move. Consequently, pneumatic efforts have focused on modifying the separating points through energizing or suction in the preseparation boundary layers.

Chined forebodies offer some advantages over conventional forebody cross sections. For example, the relatively strong vortex system emanating from the chine generates additional lift. Associated with the increased lift is an increase in the

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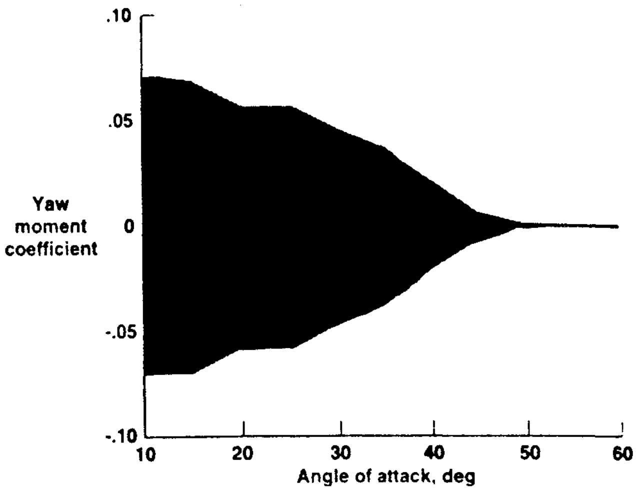


Fig. 1 Yaw moment control capability due to rudder deflection on the X-29A.[1]

nose-up pitching moment and a reduction of the static margin. Also, the fixed separation points assured by the chine offer advantages in terms of directional stability.[7] Studies involving the control of chined forebody vortices are limited in number, although future combat aircraft are likely to utilize the advantages of the chine.

Ely[8,9] conducted a study in which the blowing concept was investigated with a chined forebody. Concepts investigated included port blowing and slot blowing through the chine. Parametrics included slot location and blowing angle. It was found that the most effective configuration was the forwardmost slot location, and a blowing direction that was normal to the forebody. The results from Ely were used to choose a blowing configuration for the present investigation.

The primary objective of the research was to investigate the characteristics of pneumatic control on a chined forebody to generate yaw moments. Several aspects of the technique were addressed:

1) The angle-of-attack envelope of effectiveness.

2) The extent of coupling between the desired yaw control, and the remaining degrees of freedom (DOF).

3) The interaction with a vertical tail surface.

In order to address these points, an aircraft and chine configuration had to be chosen. The aircraft geometry was chosen to be generic in nature, with a wing representative of modern combat aircraft.

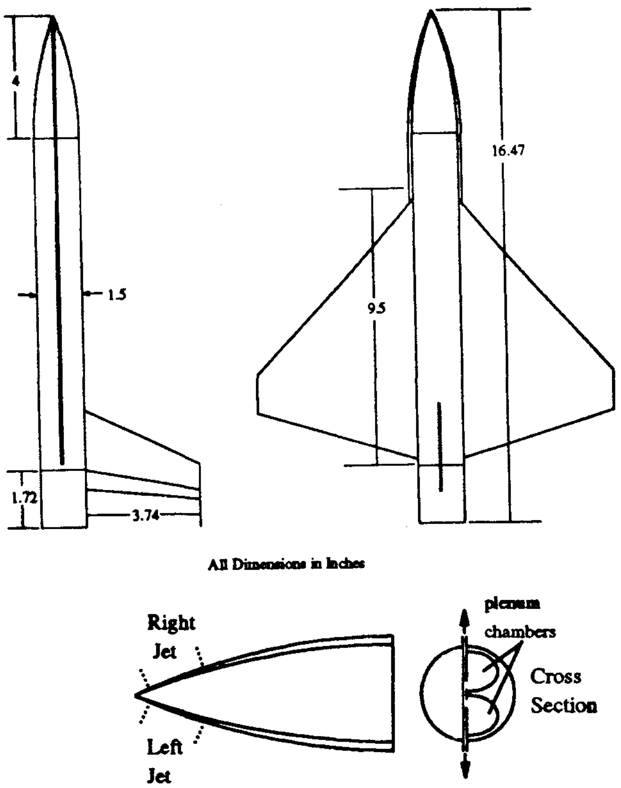
Although the capability for an investigation of variations in chine slot location and dimension existed, a nominal chine slot was chosen based on results from Ely.[8,9]

Experimental Apparatus

All experiments in the study were conducted in the University of Notre Dame Low Speed Wind Tunnels. These tunnels have a test section cross section of 2 ft by 2 ft. The apparatus consisted of a motion control system, a five-component internal force balance, and the model with pneumatic apparatus. Reynolds number for all tests was 3.0×10^5 based on wing root chord.

Model

The model used in the study incorporated a chined tangent ogive forebody, a clipped diamond wing with 50-deg leading-edge sweep, beveled 45 deg on each edge, and a single removable vertical tail. Fineness ratio for the forebody was 2.67. Rationale for model choice was to have a generic configuration with a wing that is representative of future combat aircraft. A planform and side view of the model may be seen in Fig. 2 along with geometry data. The chine is 0.03 in. thick,



	Wing	Vert. Tail
Span	11.25	3.74
Area	60.47	7.73
Taper Ratio	0.131	0.438
Root Chord	9.5	2.87
L.E. Sweep	50°	28°

Fig. 2 Model geometry.

and is one-twelfth the dimension of the local forebody diameter. Blowing slots are on both sides of the model forebody chine beginning 0.25 in. from the nose and are 1 in. long. Slot thickness is a nominal 0.01 in. The blowing slots are fed by two independent plenum chambers located in the forebody. The forebody separates into two halves, and by changing the chine plate, a wide range of slot configurations may be tested. The plenum chambers are each connected via flexible tubing to a flow meter, filtration system, and pressure source. Blowing of each of the two slots may be operated independently or simultaneously.

Force and Moment Measurement

An internal five-component balance is mounted inside the model and attached to a yoke-mounted sting. Virtual moment center for the balance was located 3.57 in. from the rear of the model. Moment data have been shifted from the measurement center to a nominal c.g. location of 25% mean aerodynamic chord (mac) to be more representative of an actual configuration. Shifting the data in this manner, however, increases the uncertainty in the data due to the combination of two measured quantities, but it is necessary to obtain an indication of the relative effectiveness of the technique. Angle-of-attack adjustment is made by varying yoke angle with the motion control system discussed in Ref. 10.

Results

Angle of attack was varied for each test from -10 to 75 deg. Reynolds number for the tests was 3.0×10^5 based on root chord. The model was tested with a vertical tail on and off, and with and without a chine on the forebody to investigate characteristics of each.

Chine Effectiveness

The baseline model with no vertical tail was tested with and without the chine and blowing off. This was to establish the effect of the chine on the force and moment characteristics of the configuration. Data are nondimensionalized by wing area since the total area of the chine is insignificant compared to S.

Figures 3a and 3b illustrate the difference in normal force and pitching moment for the chine and no-chine cases. The chine had a minimal effect on the normal force, even at the larger angles of attack. Pitching moment, however, is affected by the addition of the chine with a resulting nose-up change in the moment. This would indicate forward movement in the c.p. due to the chine configuration.

The greatest aerodynamic benefit of the chined forebody is illustrated in Figs. 4a and 4b. For the smooth forebody configuration, large zero-sideslip side forces and yaw moments are generated due to an asymmetry in the forebody flow at large angles of attack. For this particular configuration, susceptibility to these asymmetries is significant above angles of attack of approximately 45 deg. This zero-sideslip asymmetry has been well-documented for smooth forebodies and is a mechanism for nose-slice since the yaw moment created will typically overwhelm the capability of the vertical tail that is operating in the separated wake. Examples of this phenomenon can be seen in work by Ng and Malcolm,[2] and may be partially due to asymmetry in the forebody separation points. When the chine is added the zero-sideslip asymmetry is almost completely eliminated with a corresponding reduction in the directional divergence potential. This effect has also been documented by Norris and Lan,[7] who theorize that the elimination of asymmetry by fixing separation points is due to an increase in the lateral separation of the vortices, thereby decreasing interaction.

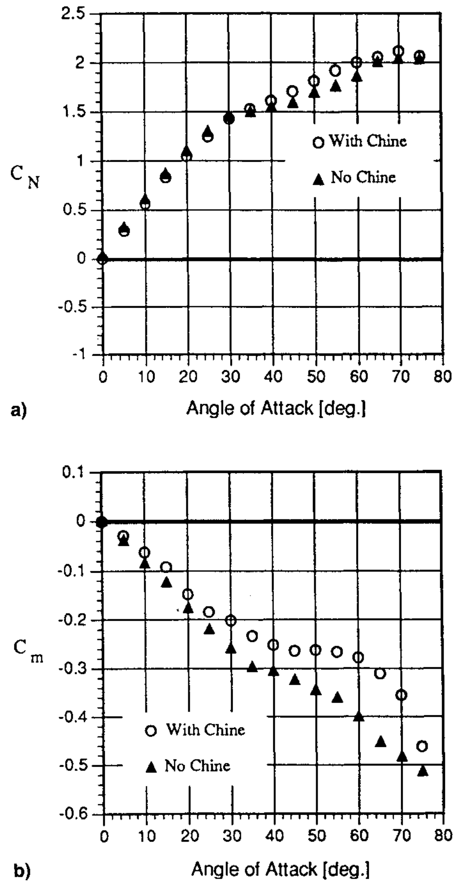


Fig. 3 Comparisons of conventional and chined forebody configurations (longitudinal): a) normal force and b) pitching moment.

Pneumatic Blowing, Tail Off

After establishing the effectiveness of the chine over the smooth forebody, the effectiveness of pneumatic blowing through the chine for control was investigated. Since separation points are fixed with the chine, the goal is to favorably control the position and strengths of the forebody vortices by adding momentum into the shear layer. Blowing was generated asymmetrically (one side on, one side off) for five different blowing coefficients over the entire angle-of-attack range tested. This was done for both right and left sides to assure that the results were not directionally dependent. Also, symmetric blowing was investigated.

Typical results illustrating the effectiveness of pneumatic blowing on yaw moment can be seen in Fig. 5. The data shown is for left-side blowing. At the lower angles of attack (0 deg $\leq \alpha \leq$ 20 deg) the yaw moment is roughly constant. As

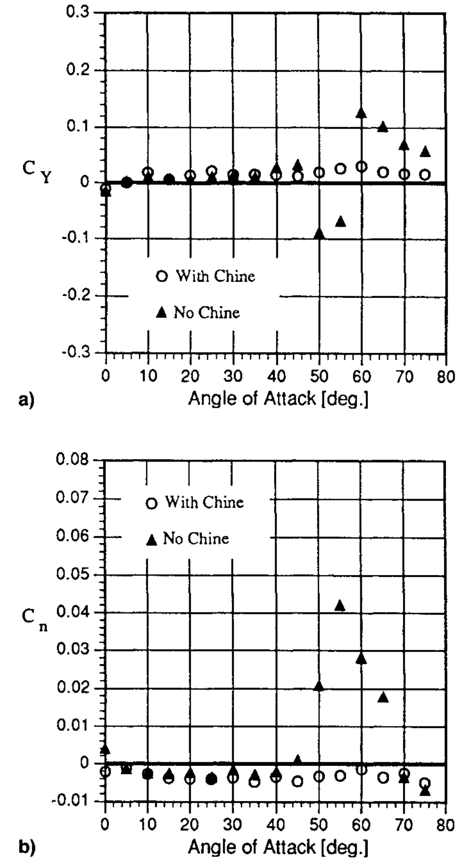


Fig. 4 Comparisons of conventional and chined forebody configurations (lateral): a) side force and b) yaw moment.

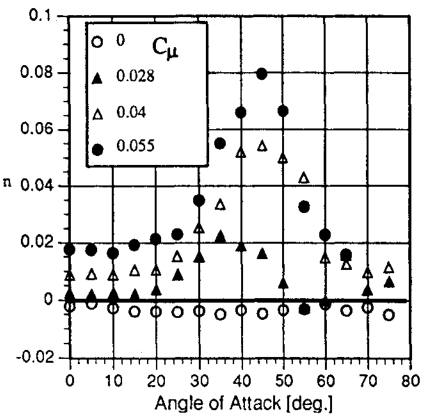


Fig. 5 Effectiveness of pneumatic blowing on yaw moment.

expected, increasing the blowing coefficient increases the yaw moment. As angle of attack is increased further, the generated yaw moment increases significantly until a maximum is reached. It was noticed that for the lower blowing coefficients the maximum C_n was reached at lower angles of attack. Further increases in angle of attack in all cases result in a dramatic loss in effectiveness until C_n converged to the value seen at the lower angles of attack.

Figure 6 illustrates the reasonable symmetry obtained in yaw moment for left and right blowing. Shown are the results for the maximum blowing coefficient tested ($C_\mu = 0.055$), although results are consistent for all five blowing rates tested. Note again that for the smaller angles of attack the generated moment is constant. Included in the figure are dashed lines showing the yaw moment coefficient obtained at the same blowing rate, but at zero freestream velocity. This corresponds to the yaw moment generated by ejecting momentum out of the chine or the "jet thrust" effect. It can be clearly observed that up to angles of attack of approximately 15–20 deg, the control yaw moment is mainly due to this effect alone. As angle of attack is increased further, a favorable interaction between the pneumatic jet and the separated forebody flowfield results in a synergy that significantly increases yaw moment capability as angle of attack is increased. For this particular case, the control effectiveness increased by over a factor of 4 beyond the jet effect alone. Beyond some critical angle of attack, however, further increases in α result in a loss of effectiveness. This behavior was also noted by Ely.[8] Ultimately, at the very large angles of attack, the yaw moment again converges to the value of the jet thrust moment. Although it could not be confirmed, flow visualization suggests that the loss in effectiveness is due to the presence of vortex breakdown.

It is not clear whether or not the loss in pneumatic control effectiveness beyond a critical angle of attack is unique to the chined forebody. Tests on a smooth, conventional forebody using slot and jet blowing by Ng and Malcolm[4] suggest that effectiveness is also reduced once a certain angle of attack is reached. Direct comparison, however, is not realistic due to the difference in forebody shape and fineness ratio.

Of particular interest when investigating alternative control methodologies is the coupling between the desired force or moment, and those resulting in the other DOF. Since data were taken in each case for five DOF (only axial force was not available), this coupling could be evaluated. Figures 7a and 7b show the effect of the pneumatic blowing on the additional lateral DOF; roll and side force. Side force generation is significant and in some cases may be larger than that generated by a rudder producing an equivalent yaw moment. The force is also in the same direction as that provided by a rudder for a given yaw moment. Behavior with α is similar to that exhibited by C_n in which a maximum is reached, and then C_Y falls off with further increases in angle of attack. One notable difference is that in the range of 0–20 deg, where C_n was relatively constant and near the jet effect value, C_Y increases with α. This would seem to imply that as α increases, vortical interaction with the jet provides an increasing side force, however, the lateral c.p. must move aft until approximately 20 deg. It is not clear at which angle-of-attack value vortices begin to form on the forebody. The roll moment due to blowing is largest beyond angles of attack of 20 deg. The behavior is unsteady in the time history due to the large scale and unsteady separation of the wing flowfield.

Downstream behavior of the modified forebody vortices suggests a reason for the coupling with the roll DOF. Flow visualization results clearly show significant movement of the vortices when blowing is applied. Downstream of the chine, not only is the vortex affected on the blowing side, but the opposite side vortex as well. In fact, under certain blowing conditions, fluid from the opposite side of the jet would be drawn across the forebody and interact with the opposite vortex. Farther downstream, significant interactions of the chine vortices with the wing were observed. The interactions were strongly dependent on the blowing configuration and rate. The flow asymmetries observed on the wing due to asymmetric blowing were most likely the reason for the roll moment coupling.

The effect of asymmetrical pneumatic blowing on the longitudinal DOFs can be seen in Figs. 8a and 8b. Normal force variation is relatively insignificant as illustrated in Fig. 8a. Pitching moment variation is also relatively small, however, as angle of attack is increased beyond 40 deg, the variation in pitch moment increases. This behavior begins relatively near the maximum blowing effectiveness angle of attack, be-

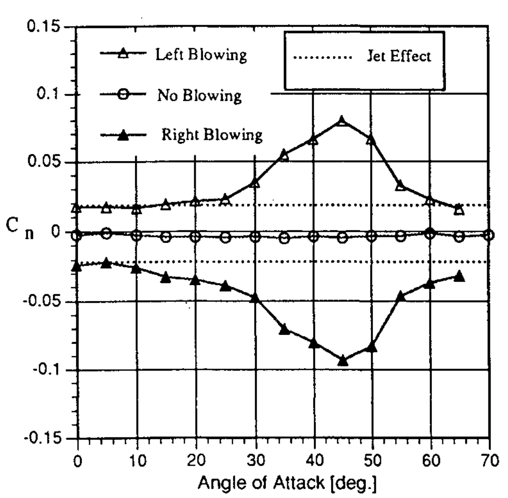


Fig. 6 Comparison of right and left side blowing with jet effect (C_μ = 0.055).

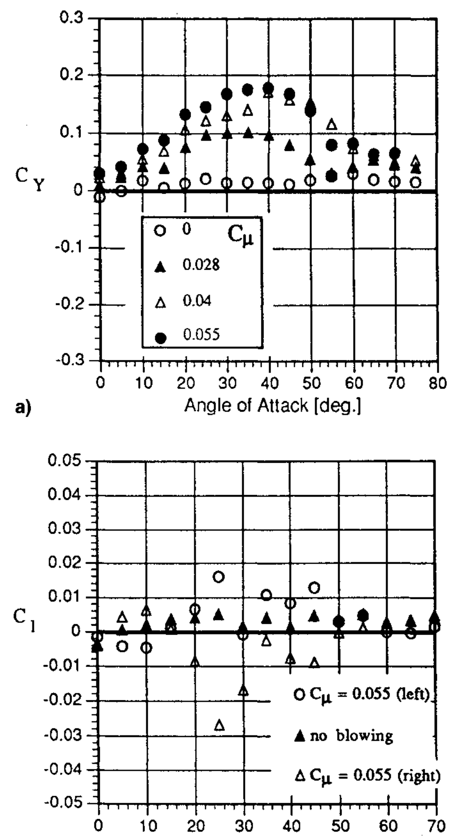


Fig. 7 Coupling of pneumatic yaw control with lateral DOF: a) side force and b) roll moment.

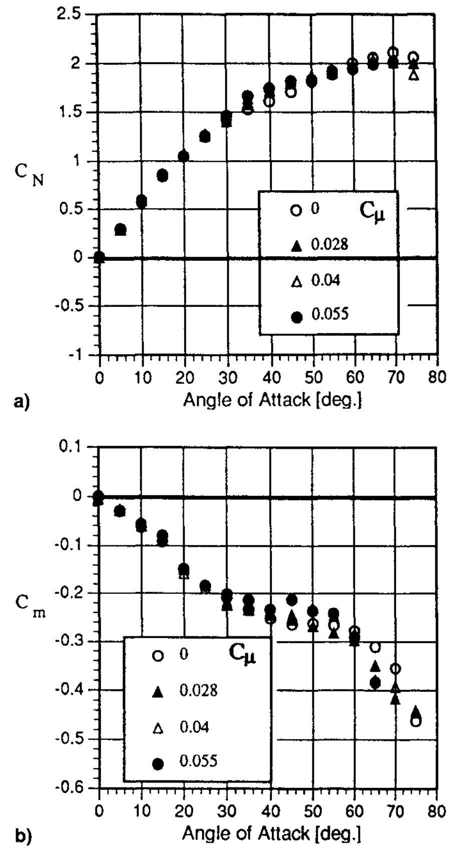


Fig. 8 Coupling of pneumatic yaw control with longitudinal DOF: a) normal force and b) pitching moment.

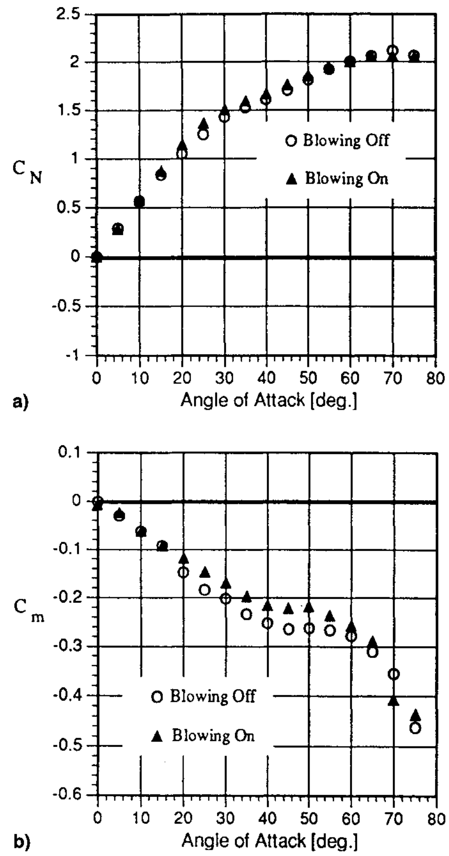


Fig. 9 Symmetric blowing effect on longitudinal characteristics (C_μ = 0.028): a) normal force and b) pitching moment.

yond which breakdown is thought to greatly effect the forebody flowfield. These results indicated that the lateral and longitudinal DOFs are effectively decoupled when considering the pneumatic generation of yawing moments. This is much the same situation as for conventional yaw control with a vertical tail and rudder. This is a desirable characteristic since little compensation has to be made in pitch moment or angle of attack when commanding a directional control response. Strong lateral and longitudinal coupling in response to a control input is undesirable since the response is nonintuitive to the pilot. Compensation to coupling would have to be implemented in a flight control computer to maintain adequate handling qualities.

The effect of symmetric blowing on longitudinal characteristics was also investigated. This was done in order to investigate the capability of the system in providing an additional increment in lift or in pitch moment. This capability would allow for increased performance for short periods of time while higher lift forces are needed. Figures 9a and 9b illustrate the changes in normal force and pitching moment while symmetric blowing at a moderate blowing coefficient. The moderate value was chosen since blowing at this rate through both chines required as much air as blowing at the maximum blowing coefficient on one side only. It can be seen that the effect on normal force is again minimal, especially at the lower and higher angles of attack. Pitch moment is marginally affected over the angle-of-attack range 20–60 deg. Increasing blowing coefficient caused nose-up pitch moment changes. It is not clear whether or not the pitch moment change is due to the interaction of the modified flow with the main wing or due to the changes in the forebody flowfield itself. Further surface pressure measurements would have to be conducted to resolve this issue.

Pneumatic Blowing, Tail On

The complete set of experiments were also conducted on the model with a single vertical tail attached. The vertical tail was scaled to represent that which could be found on a modern combat aircraft. These experiments were conducted to ascertain the extent to which the modified forebody flowfield would interact with a vertical surface. This aspect of the pneumatic blowing concept was not found in the literature, however, it was expected that a vertical surface could change the characteristics of the control effectiveness depending on the configuration. The tail also had a 25% rudder that could be deflected 30 deg for comparisons in control effectiveness.

Figures 10a and 10b are comparisons of side force and yaw moment for three different blowing coefficients in the tail-on and tail-off configurations. Significant differences can be seen between the two configurations in both side force and yaw moment. For the zero-blowing coefficient case, a small offset in side force was noticed for both configurations, but the difference was small. With respect to yaw moment, however, a more significant difference is seen and the moments are in different directions. With the tail on, the yaw moment offset does become more significant when angle of attack is increased to 30 deg. For a moderate blowing coefficient, the difference between the two configurations in both side force and yaw moment appears to be almost a shift in magnitude, with the tail-on configuration producing more side force. At the maximum blowing coefficient tested, very noticeable differences were also obtained, however, the difference is more complicated. Side force for the tail-on configuration resulted in a narrower but higher peak in side force. Yaw moment difference was most significant in that with the tail on, a double peak characteristic was seen in the yaw moment plot.

The comparisons between the tail-on and tail-off configurations illustrates an important point in that it is clear that the effectiveness of the pneumatic blowing concept is configuration-dependent. In the present configuration, the effectiveness on the pneumatic concept was found to be dependent not only on the tail configuration, but also the combination of tail configuration and blowing coefficient. The differences

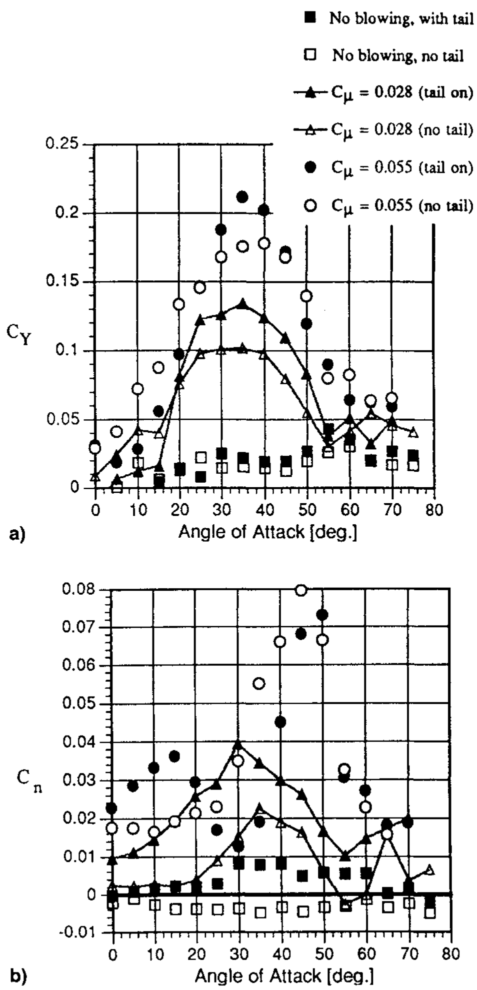


Fig. 10 Comparison of blowing effectiveness for vertical tail-on and tail-off cases: a) side force and b) yaw moment.

in the two configurations tested are very likely due to the large-scale, unsteady separation of the main wing interacting with the forebody flowfield and the vertical tail. As mentioned previously, the sensitivity of the chine vortices interaction with the wing flowfield was sensitive to the blowing configuration and rate. Additionally, vortex breakdown that is affected by the downstream tail configuration and blowing rate must be considered. Although the characteristics of vortex breakdown subject to tail configuration and blowing were not quantified in this study, the vortex breakdown interaction with the tail is expected to have a significant effect on the yaw moment and side force generated. For these reasons, it would be reasonable to assume that the characteristics of the directional moment generation, and associated coupling with other DOF may be different for a twin-tail configuration. Additionally, the sensitivity of the flowfield and the resulting moments would suggest that a specific configuration should itself be tested before any conclusions could be made about the effectiveness of the chosen blowing method.

Comparison of the pneumatic blowing concept was also compared to the effectiveness of a conventional rudder. The rudder compromised 25% of the local chord of the vertical tail. Deflection of the surface for the tests was 30 deg. Figure 11a is a comparison of yaw moment due to rudder deflection with chine blowing and no vertical tail. It can be clearly seen that rudder effectiveness remains constant up to an angle of attack of approximately 25 deg. Beyond this, the effectiveness is rapidly lost. Above angles of attack of 40 deg, vertical tail effectiveness is almost completely lost. This is consistent with the observations on actual aircraft such as the X-29 discussed in the introduction. This behavior clearly illustrates the need

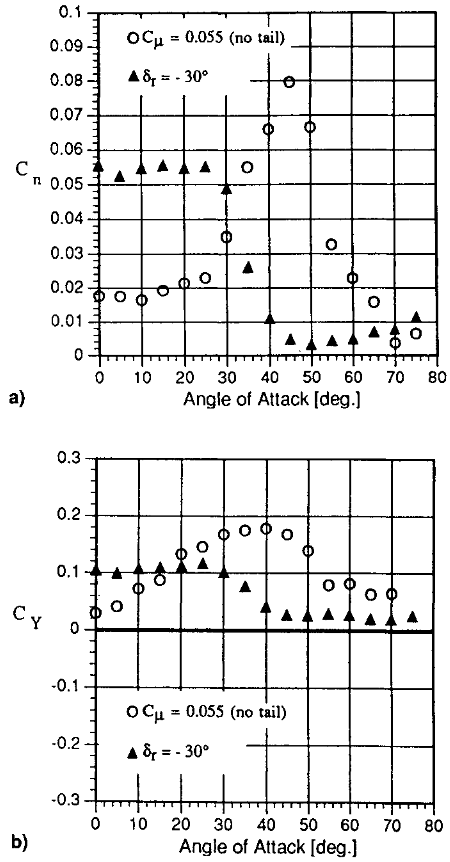


Fig. 11 Comparison of rudder effectiveness and pneumatic control: a) yaw moment and b) side force.

for alternative yaw control devices for controllable flight at large angles of attack. In contrast, the effectiveness of the blowing technique for maximum blowing coefficient tested and no vertical tail is also shown. As mentioned previously, the effectiveness grows with angle of attack until a maximum is reached; in this case 45 deg. Further increases in angle of attack result in a decrease in effectiveness. The fact that the blowing technique is most effective at angles of attack beyond the capabilities of the rudder suggests that a combination of the two concepts on an aircraft could almost double the angle-of-attack controllability envelope. Tests using symmetric blowing and rudder deflection revealed a small increase in rudder effectiveness.

Figure 11b shows the resultant side force for each type of control. As expected, the behavior is consistent with that seen in yaw moment. For the rudder, the side force drops off above an angle of attack of 25 deg, whereas, the side force generated by the blowing technique increases until 40-deg angle of attack.

Full-Scale Feasibility

The results from the investigation clearly demonstrated the favorable yaw control capability of pneumatic blowing on a subscale, chined model. A question arises, however, as to the feasibility of this technique when scaled to a full-scale flight vehicle. For the blowing coefficients shown to significantly affect yaw moment in this study, equivalent full-scale jet velocities would be supersonic. In order to maintain subsonic velocities, the geometric similarity of the slot dimensions would have to be violated. This point has also been made by Boalbey et al.[9] who suggest increasing jet temperature in order to increase the sonic velocity. Extrapolation of the subscale data to full-scale vehicles should be considered in light of the trade-off between geometric and Mach number similarity. This point becomes more significant in the chined forebody configuration in which it appears, in comparison to the smooth forebody configuration, that larger blowing coefficients are needed in order to generate significant control authority in yaw. This is most likely due to the fact that in the smooth forebody configuration, pneumatic control affects separation location, which has a large effect on the symmetry of the forebody vortices, whereas the chined forebody blowing concept attempts to modify vortex strength and position directly since separation is fixed.

Another point of consideration regarding extending the results to a full-scale configuration is Reynolds number. Although Reynolds number will not play a significant role in the generation of the chine vortex due to the sharp separation locations, there may be more significant secondary separation effects on the forebody above the chine. Also, one of the factors that plays a role in the location and symmetry of vortex breakdown is Reynolds number. This should be considered, since as mentioned previously, vortex breakdown will affect the interaction of the chine vortex flow with the main wing and any vertical surface.

Conclusions

The effectiveness of pneumatic blowing for directional control on a chined forebody at high angle of attack was investigated experimentally. The results indicate that the method is capable of producing significant yaw moments at high angles of attack with a resulting minimal control coupling with the other DOFs. The effectiveness of the technique was found to increase with angle of attack until a maximum is reached, at which point further increases in angle of attack reduced control effectiveness. Increments in yaw moment were found to be a maximum four times higher than that produced by a jet alone, indicating favorable interaction with the forebody flowfield. The loss in control effectiveness at higher angles of attack is thought to be due to the forward movement of forebody vortex breakdown with angle of attack.

The effect of a vertical tail on the control scheme was also investigated. It was shown that the pneumatic control technique was tail-configuration-dependent. In general, the vertical tail increased the effectiveness of the blowing, however, this can only be substantiated for the single vertical tail tested. Flow visualization results suggest that there are strong interactions between the modified forebody flowfield, the separated wing flow, and the vertical tail. It can be assumed that different tail geometries will interact with the separated flow of the wing and modified forebody flows in different ways. It would seem wise, therefore, to investigate the configuration dependencies of the technique before it could be implemented in a design. The single vertical tail technique, however, did not affect the overall characteristics of the pneumatic control angle-of-attack envelope. It was also shown that in certain cases, that directional controllability envelope could be almost doubled with the addition of the pneumatic blowing technique to a conventional rudder system.

Acknowledgments

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