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Forebody Flow Control for Extended High-Angle-of-Attack Maneuvers

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Tangential forebody blowing for the purpose of yaw control has been investigated on a 6% generic fighter model in the 2.1 × 1.5-m low-speed wind tunnel at the University of Bath. Force and moment data were obtained from a sting-mounted, six-component strain gauge balance over an angle-of-attack range of −10 to 120 deg. The tangential blowing slots were incorporated into a vacuum-formed, plastic forebody, which contained two independent plenum chambers. The geometry of the slots was optimized for high-angle-of-attack operation based on results from previous research. Three different forebodies were used to investigate the effects of different azimuthal slot positions. At angles of attack beyond 60 deg, all of the slot locations were shown to produce significant yawing moments, even when compared to conventional yaw control at low angles. This control moment did not decay at the maximum angle of attack tested, which suggests that the envelope of control could be extended farther. The concept remained effective even at conditions where the flow along the longitudinal body axis was reversed. At angles of attack appropriate for normal cruise operation, takeoff, or landing, all slot locations proved effective in producing yawing moments. Consequently, tangential forebody blowing may prove capable of replacing conventional fin and rudder combinations in establishing weathercock stability.

Nomenclature

b = wingspan, 0.66 m
C_l = rolling-moment coefficient, $L/(qSb)$
C_n = yawing-moment coefficient, $N/(qSb)$
C_y = side-force coefficient, $Y/(qS)$
C_z = normal-force coefficient, $Z/(qS)$
C_μ = jet-momentum coefficient, $mV_j/(qS)$, positive to port
d = body diameter
L = rolling moment, positive port wing up
l = length of slot
m = jet mass flow
N = yawing moment, positive nose to starboard
q = freestream dynamic pressure
S = wing reference area
s = wing semispan
V_j = jet exit velocity
x = location of upwind end of jet
Y = side force, positive to starboard
Z = normal force, positive down
α = angle of attack
θ = slot azimuthal angle

Introduction

THE enhancement of maneuverability on a modern fighter aircraft is increasingly important. During an initial contact, the ability to turn quickly (the Herbst maneuver[1]) or point and shoot[2] provides greatly improved kill opportunities. Control is thus required independently of the velocity vector and well into the stalled region, where significant regions of separated and unsteady flow are evident. At angles of attack beyond 60 deg, the control requirements shift from a dependence on pitch and roll control to one on pitch and yaw. There is therefore a strong interest in concepts capable of providing yaw control power into the extreme angle-of-attack range.

At low angles of attack, the forebody vortices are stable and symmetric in position and strength (Fig. 1). At intermediate angles of attack they develop a bistable condition, where one vortex lifts from the surface and strengthens while the other moves closer to the surface and weakens. Similarly, the crossflow separation line of the stronger vortex moves closer to the windward generator, as the separation line of the weaker vortex moves farther away. Small asymmetries in the forebody, differing surface finishes, or disturbances in the airflow may all determine which vortex lifts. Further disturbances, often associated with a change in the angle of attack, can modify which vortex dominates, although the disturbance must overcome the inherent stability of the vortex pattern. It is during this intermediate region that side forces develop,[3] resulting in considerable yawing moments from the long moment arm ahead of the c.g. Coincidentally, conventional yaw-control devices reduce their effectiveness at these angles of attack when the wake from the fuselage and wing produces an area of low dynamic pressure around the control surfaces. Thus, the yaw moment required to trim frequently exceeds that available.

At higher angles of attack periodic vortex shedding occurs, where the vortex pair are no longer stable and the net time-averaged side force is zero. It is this last region that appears to offer the most potential for maneuverability, providing a suitable control system can be developed.

The most logical means of providing lateral stability is to control the source of the problem, the forebody vortex pair, or, more precisely, the forebody crossflow. Several different methods of control have been researched based on this premise.[4,5] Fixed symmetric pairs of strakes mounted on the forebody force the vortex pair to remain symmetric by fixing the line of separation and have been shown to be effective under certain conditions. Deployable strakes or strakes on a rotating

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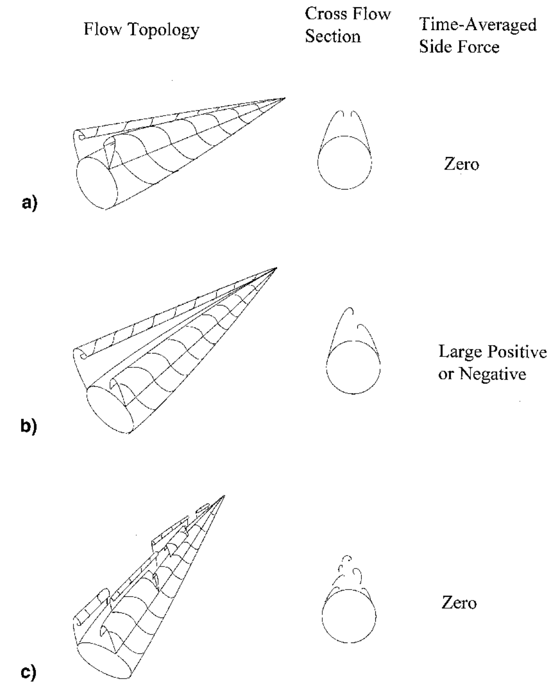

Fig. 1 Flowfield regimes for a slender body at incidence. Angle-of-attack ranges = a) 0–20, b) 20–60, and c) 60–90 deg.

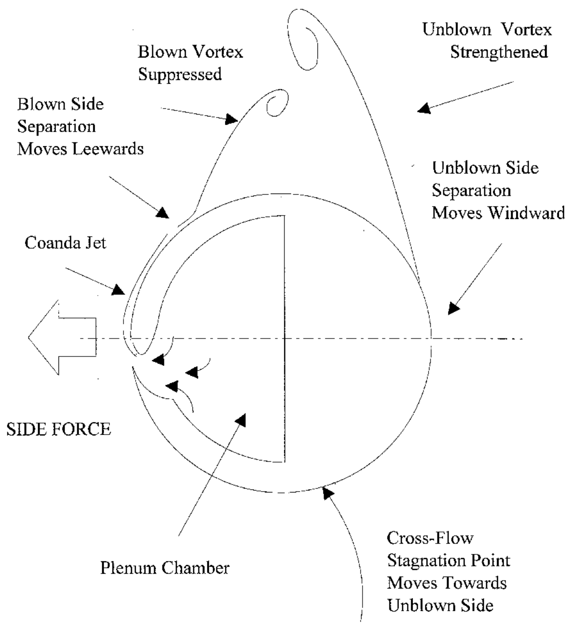

Fig. 2 Fluid mechanism for tangential forebody blowing.

nose cone enable the direction of the vortex asymmetry to be controlled. Discrete jet blowing in a forward, reverse, or normal direction can manipulate the vortex core and control the direction of the asymmetry. They do, however, require prior knowledge of the vortex position to effect high gain control. The term *tangential*, when applied to these concepts, should not be confused with the present application. Because no wall jet exists, a more correct term is *parallel*.

Each of these control methods relies on vortex manipulation to produce the forces and moments. As yet, they have not been shown to be effective in the angle-of-attack range dominated by periodic vortex shedding. It is unlikely that they would continue to function when the axial flow was reversed, i.e., at angles of attack greater than 90 deg.

Thrust vectoring has demonstrated an ability to combat the unstable side forces and yawing moments produced by vortex asymmetry. Programs such as the FA-18 HARV, X-31, F-16 MATV, and YF-22 (Refs. 6–10) have investigated the use of such a control device. However, the extra weight of the engine installation, and potential installation problems posed by aircraft with low observability characteristics, may restrict its success.

Previous research[11] identified tangential forebody blowing (TFB) as a possible solution to the problems. The forebody vortices generally influence only the pressures on the upper surface, and their ability to produce a significant side force is limited. However, they do create a bistable situation that gives rise to differential areas of attached flow on the surface of the forebody, and it is the resulting pressure distribution over the entire forebody that produces the strong side force and yawing moment. Manipulation of the lines of separation results in not only control of the direction of asymmetry but also yaw control between the two extremes of the vortex pattern. TFB can alter the azimuthal position of the local separation line during asymmetric vortex production and can also suppress separation and flow unsteadiness during periodic vortex shedding, thus providing control over both regions. The effectiveness of such a device is unlikely to be affected by reversals in the body-axis flow direction.

The application of TFB is a demonstration of Coanda jet attachment to convex surfaces (Fig. 2). The surface curvature increases the rate of fluid entrainment from the external boundary layer and will accelerate the transfer of momentum from the jet to this external fluid. The result is a suppression of the separation of the external flow. In the case of TFB, the separation of fluid is suppressed on the blown side of the forebody, weakening the associated vortex. The opposing vortex lifts from the leeward surface and strengthens to maintain the equilibrium of the vortex pattern. This requires an earlier separation of the flow on the unblown side and a movement of the stagnation point toward the unblown side, representing a form of circulation in the crossflow plane. The major source of yawing moment has been shown to be the modified area of attached flow rather than the modified vortex influence.

The intention of this paper is to demonstrate yaw control up to a 120-deg angle of attack using a slot optimized for the periodic vortex shedding region. Wind-tunnel results will also be scaled to provide typical data for full-scale applications.

Experiment

All tests where conducted in the 2.1×1.5-m low-speed wind tunnel at the University of Bath. The model was supported from the sidewall of the test section by a pantograph rig passing through contoured slots in the tunnel wall, which incorporated foam seals. The model was a 6% generic fighter aircraft (Fig. 3) and was sting mounted, wings vertical, which made unnecessary a calibration allowance for changes in the weight vector from a changing angle of attack. This arrangement also aligned the longitudinal axis of the model with the major dimension of the working section, thereby minimizing blockage. A six-component balance was housed inside the model and connected the model to the sting. The pantograph support system was modified by the addition of a cranked arm to provide an angle-of-attack range of -30 to $+120$ deg, although this was not continuous during a single run. Vents in the test section walls provided a static pressure equal to atmospheric, and the Reynolds number was held constant at 1.5×10^6/m. The balance was calibrated in situ and exhibited only minor amounts of cross-coupling, which were corrected for in the acquisition software.

The forebodies, all tangent ogives with a fineness ratio of four, were constructed of vacuum-formed plastic components and assembled to create two plenum chambers, each containing an optimized slot. Small screws set back from the slot lip provided fine-tuning of the slot height and support to maintain the height constant under differential pressure load without significant disruption of the jet attachment. In total, three fore-

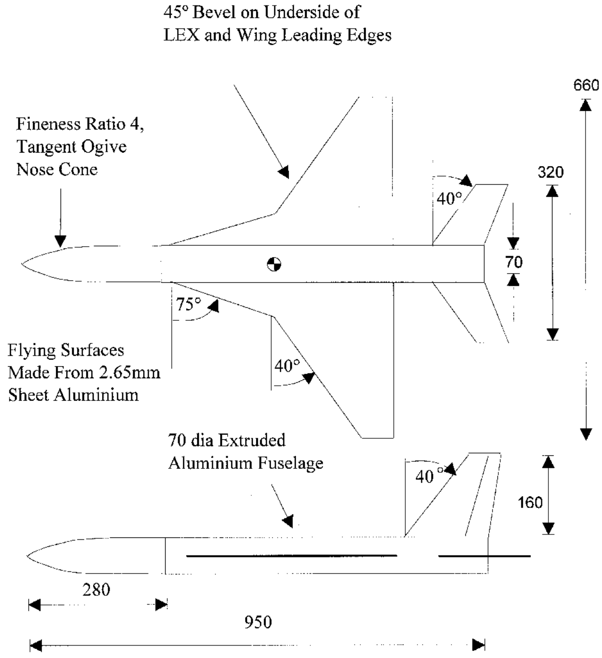

Fig. 3 Basic wind-tunnel model (dimensions in mm).

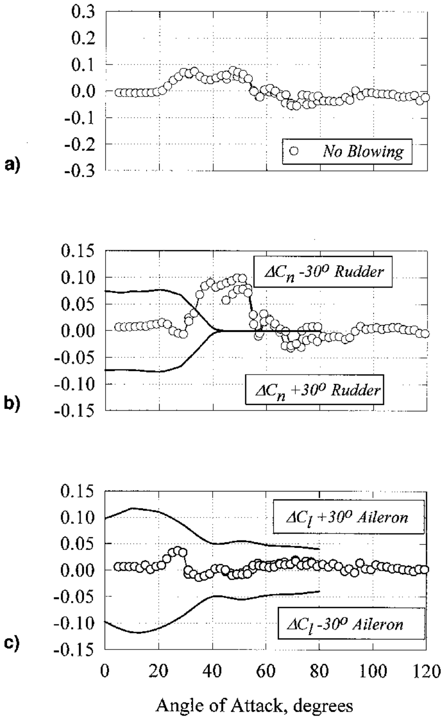

Fig. 4 Baseline characteristics for 90-deg slots: a) C_y, b) C_n, and c) C_l.

bodies were constructed, providing different slot azimuthal positions, each with equal slot lengths and axial positions. The values for these parameters were identified from the results of previous work.[11] It was shown that, for control in regions of high vortex asymmetry, short slots near the forebody apex were most efficient, while for control at higher angles of attack, short slots further aft were acceptable. This may be an advantage for full-scale applications to maintain constant dielectric properties ahead of any avionics mounted in the forebody.

The forebodies were located on a Perspex® bulkhead that contained the pressurized air supply inlets and two pressure tappings. Two blowing supply tubes were connected to a single air supply, external to the test section, and this allowed a controlled volume flow rate to be applied independently to each plenum chamber. These tubes were only minimally constrained at the base of the sting to ensure that they did not produce any forces or moments on the model when the angle of attack was altered.

The output from the six-component balance, the pressure transducers attached to the static pressure tappings, a rig position potentiometer, and a micromanometer were all sampled at 1000 Hz using a single personal computer-based data acquisition system. The results were presented in graphical form in real time. Prior to each test, the slot areas were calibrated as a function of the flow rate; hence, the overall mass flow could be related to the plenum pressure. Providing the slot stiffness remains constant, the jet momentum can be calculated as a function of the plenum pressure. A nondimensional C_μ was used to measure the amount of blowing applied. Unlike equivalent mass flow parameters, momentum provides the best collapse of force and moment data that include variations in slot geometry and freestream conditions.

Results and Discussion

Unblown Tests

The 90-deg slot configuration can be used as an example, as all the forebodies have the same fineness ratio and tangent ogive shape. The side-force, yawing-moment, and rolling-moment characteristics for this forebody were measured and exhibited three stages of vortical flow development between 0 and 120 deg (Fig. 4). Both side force and yawing moment are related and therefore follow similar patterns. Up to about 20 deg, the vortex pair are equal in strength and symmetric in position, producing no side force, yawing moment, or rolling moment. Between 20 and approximately 55 deg, the steady vortex asymmetry produces large side forces and yawing moments, although, unlike in previous research, the force and moment do not reverse between 40 and 55 deg. Note that the sensitivity of this flow regime is highlighted by the fact that each of the forebodies produced dramatically different unblown responses in this angle-of-attack range. This is not unexpected, as previous research has shown the sign of the asymmetry to be dependent on the roll orientation of circular forebodies.[12] It should also be noted that the intent of this paper is to provide control beyond this angle-of-attack range.

Above 55 deg, periodic vortex shedding begins and the time-averaged side force and yawing moment both return to zero. The yawing moment data also show the extent of the lateral control provided by a rudder deflection of ± 30 deg. The maximum yawing moment coefficient is approximately 0.07, but this rapidly decays and reduces to zero by 45 deg. The steady lateral asymmetry, or nose slice, exceeds the control power of the rudder at 33 deg and reaches a maximum yawing moment coefficient of 0.10 at 50 deg.

The rolling moment essentially remains at zero except for an angle-of-attack range of 10 deg centered at 25 deg, where a large positive rolling moment is evident. This is ascribed to an interaction between the forebody vortex pair and the leading edge extension (LEX) vortices (Fig. 5). The asymmetric forebody vortices influence the LEX vortex burst points, producing an asymmetric pressure distribution on the upper surface of the wings, resulting in a rolling moment. This phenomenon is planform-dependent, is well within the control power of the ailerons, and has been shown to diminish for more conventional delta wing planforms.

When the baseline yawing moment coefficients are compared for each forebody as a function of slot azimuth angle (Fig. 6), the magnitude of the steady asymmetry is the same and occurs at similar angles of attack. The sign of the asymmetric yawing moment for the forebody with the 90-deg slots is positive, but it is negative for the remaining two forebodies, despite the fact that all of the models are essentially the same.

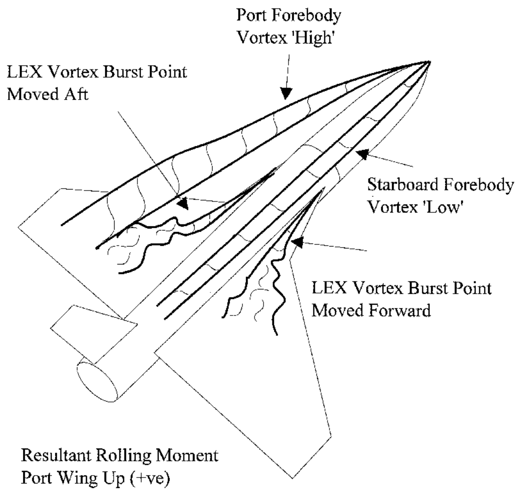

Fig. 5 LEX and forebody vortex coupling.

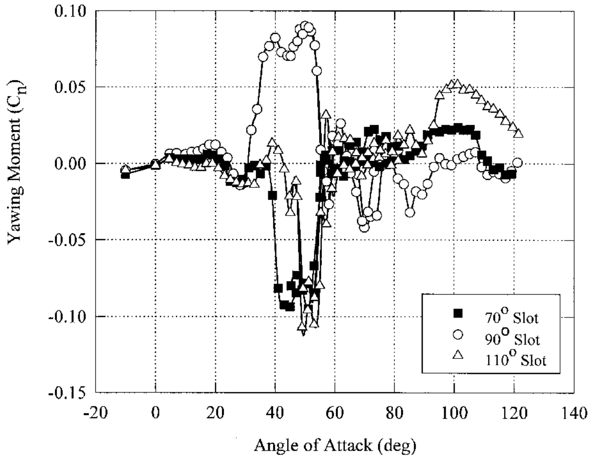

Fig. 6 Unblown yaw response.

This demonstrates the susceptibility of the vortical pattern to small disturbances produced on any individual model. The 110-deg slotted forebody also features a slight delay in reaching maximum asymmetry and a nonzero yawing moment at high angles of attack. The latter is caused by a slight roll misalignment of the model for this test, which resulted in a nonzero sideslip angle (which reaches a maximum at 90 deg), and a component of the normal force acting in the direction of the side force.

Blown Tests

The effect of blowing on side force, normal force, rolling moment, and yawing moment was measured over a range of angles of attack (Fig. 7). As with the baseline data, the side force and yawing moment response are coupled. The normal force is unaffected by blowing, because the degree to which the jet remains attached over the top surface of the forebody is limited (and is dependent primarily on the slot length), and any resulting force is insignificant when compared to the normal force created by the wings. The rolling moment is modified by blowing, suggesting that the location of the LEX vortex burst point is coupled to the forebody flow. A reversal occurs at 30 deg for constant blowing momentum, although blowing has no effect on the rolling moment above 45 deg.

Considering the yawing moment in more detail (Fig. 8) and using the forebody with 90-deg slots as an example, the three regions of vortical flow are clear. At low angles of attack, constant blowing produced a rapidly increasing yawing moment in the symmetric vortex range, whereas blowing on the alternate side provided an equal but opposite response. Between 25 and 65 deg, the steady vortex asymmetry is dominant, and blowing is unable to completely damp out the vortex-induced yawing moment. Because the slot has been optimized for high-angle-of-attack operation, the extent of the slot is too small and too far aft to completely reverse the vortex asymmetry. At high angles of attack in the periodic vortex shedding region, the unblown response produces only very slight changes in yawing moment, and these are easily controlled by a very small amount of blowing. The response to increasing blowing appears to be symmetric and varies little as angle of attack increases.

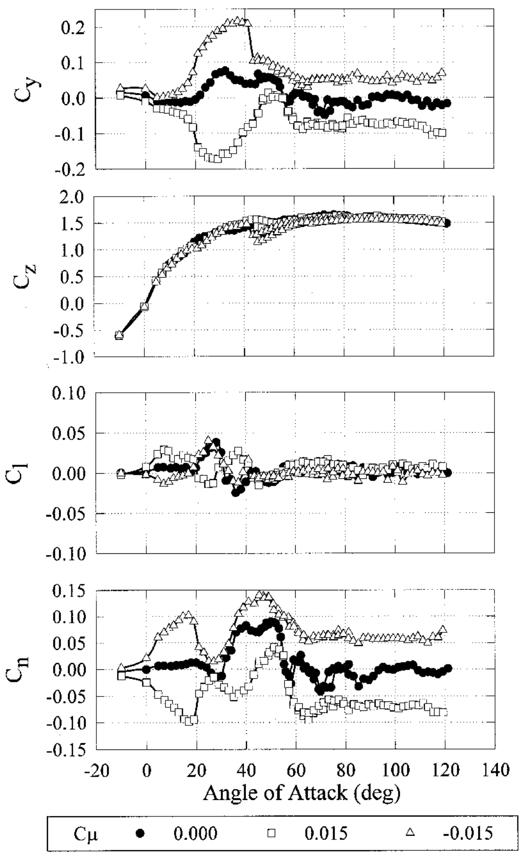

Fig. 7 Force and moment data for θ = 90 deg.

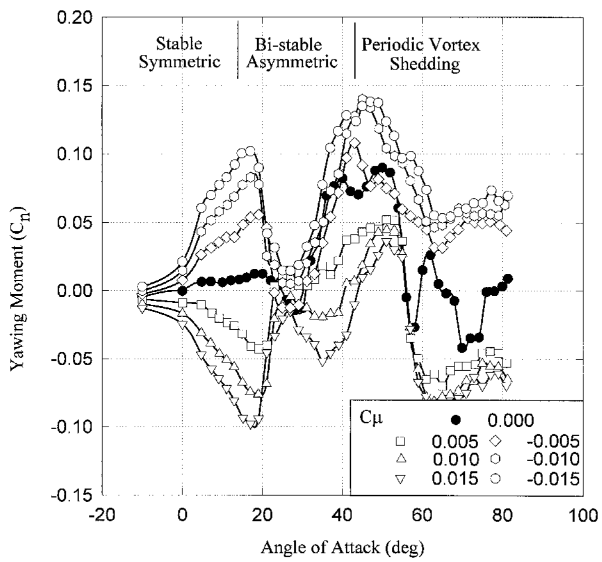

Fig. 8 Yawing moment response to incremental blowing for θ = 90 deg.

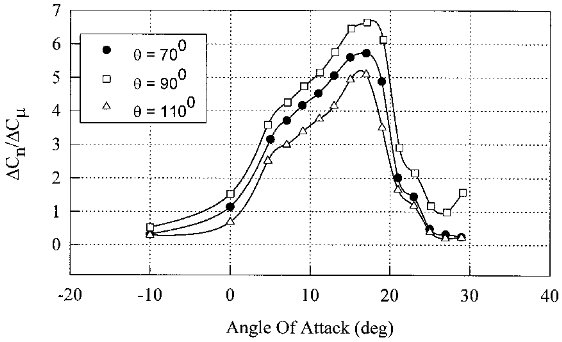

Fig. 9 Control gain at low angles of attack.

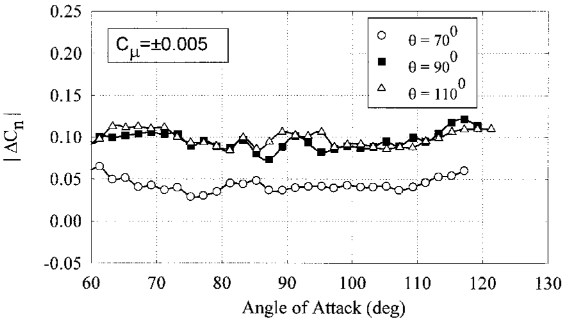

Fig. 10 Yaw control modulus at high angles of attack.

The low-angle-of-attack response to blowing was investigated as a function of the three slot azimuthal locations (Fig. 9). The 90-deg slot location provided the highest control gain and the maximum control power at a 0-deg angle of attack. The overall response is a complex function of the advantages of improved projected side area under the jet attachment and the disadvantages of having a jet exit removed from the boundary-layer separation.

In the high-angle-of-attack region, where periodic vortex shedding occurs, the dependence of the yawing moment on slot azimuthal location was investigated (Fig. 10). Similar to the 90-deg slot case, the use of blowing produced a response that was almost constant as angle of attack increased between 60 and 120 deg, regardless of the irregularities in the baseline characteristics. Because the mechanism for yawing moment generation is the attached flow under the jet, it is only weakly affected by the crossflow velocity. Hence, it is expected that the yawing moment is likely to be generated to angles of attack beyond 120 deg. The maximum yaw control produced by the 70-deg slot is somewhat less than the other two. In a manner similar to low angles of attack, the control gain is determined by the relative locations of the slot and the crossflow boundary-layer separations. If the slots are too close to the windward generator, then energy is needlessly absorbed prior to the wall jet, delaying separation. If the slot is too far from the windward generator, past the flow separation point, then energy must be expended in first modifying the external flow prior to the jet exerting full control. The fact that adequate control is available over a 40-deg range of slot locations suggests that the effects of sideslip or yaw rate on yawing moment gain would be small.

Blowing Control

To illustrate the relative effects of different blowing rates more clearly, the yawing moment response from increasing blowing rates at discrete angles of attack for the 90-deg slot position is re-examined (Fig. 11). At low angles the control gain is very linear and increases with angle of attack. However, at 30 and 50 deg, there is a large sign change centered at zero blowing, symmetric about the zero yawing-moment axis. This is coincident with the occurrence of the forebody vortex asymmetry. The magnitude of the asymmetry is affected by the forebody planform, and it is important that these results are attributed to the fineness ratio (l/d = 4) and shape (circular cross section) of the present model. It is expected that a modified planform with reduced l/d would alleviate the majority of the observed control reversals at the expense of some control gain. The modifications may well include a lower fineness ratio and a blunted nose, both of which have been shown to be effective in reducing the angle-of-attack range and reducing the magnitude of the asymmetry.

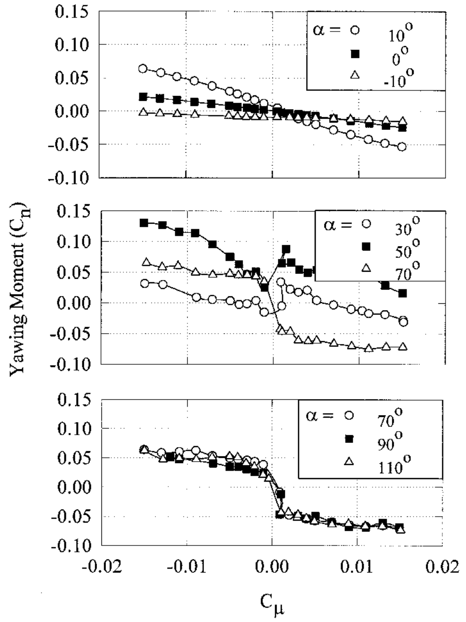

Fig. 11 Effect of blowing rate on yawing moment for θ = 90 deg, at discrete angles of attack.

By 70 deg, the forebody flow is periodic and the jet is providing stable attached flow. The control gain at very low blowing rates is high, which implies that the 90-deg slot is significantly modifying the fluctuating separation lines associated with this angle-of-attack range. At higher blowing rates the gain reduces but remains linear above blowing rates of 0.002. This type of response is the highest angle of attack tested.

The variation of yawing moment as a function of the slot azimuthal location was investigated for high angles of attack (Fig. 12). The eventual slopes of the curves are the same and remain linear at higher blowing rates. For the 70-deg slotted forebody, this linearity continues down to zero blowing. However, both the 90- and 110-deg slots produce a sharp jump between unblown and a jet momentum coefficient of 0.001 at all angles of attack of 70 deg and greater. Accepting that the zero offset in the baseline yawing moment was because of a roll misalignment of the 110-deg slot test, both the 90- and 110-deg slots act in a similar manner.

The crossflow separation line and the delay induced by blowing can be identified in Fig. 13, which is a photograph of surface flow visualization of the forebody with 90-deg slots at a 90-deg angle of attack. The suggestion that the yawing moment is generated by the attached flow under the jet rather than the vortex influence is clearly supported.

Scaling to a Full-Size Aircraft

For the purpose of this example, an average maneuver is chosen to take place at 10,000 ft altitude and $0.3M$ flight speed. From Fig. 11, a C_μ of 0.002 would produce a yawing moment coefficient of 0.05 at high angles of attack, compared with 0.077 for a 30-deg rudder deflection at α = 10 deg. If a 1.5-m slot was incorporated into the forebody of an F-16, set back approximately 0.5 m from the apex of the forebody, it would

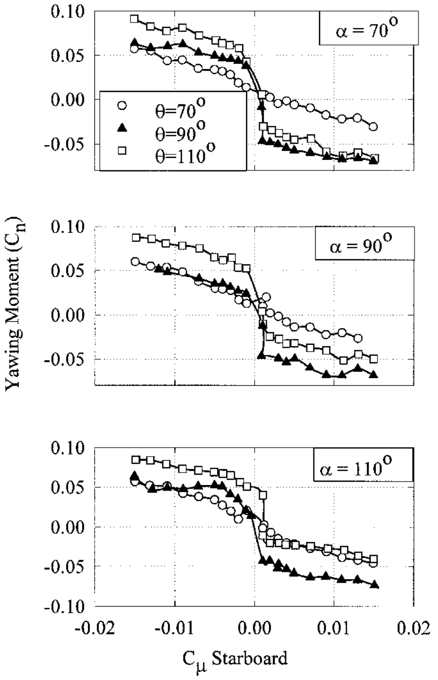

Fig. 12 Effect of blowing rate and slot azimuthal location on yawing moment at high angles of attack.

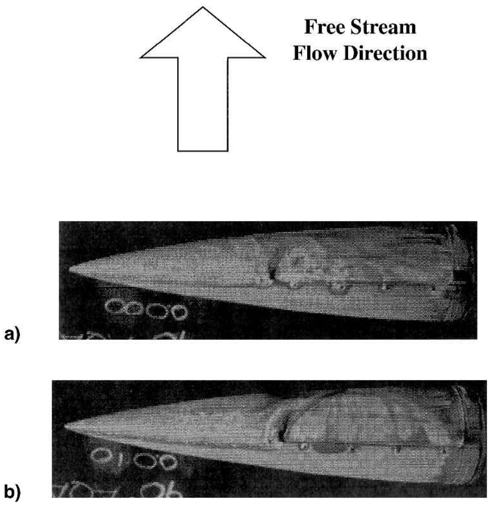

Fig. 13 Surface flow visualization at 90-deg angle of attack, θ = 90-deg port slot shown: a) unblown and b) port blowing.

require 0.9% of the total available mass flow of the engine for a blowing momentum of 0.002. This is approximately half of the available bleed mass flow. Scaling from the test model, such a slot would be 3.3 mm high with a jet exit velocity of 0.9*M*.

At low angles, the maximum yawing moment coefficient at a blowing rate of 0.01 is 0.025. This could provide a nondimensional lateral stability coefficient (yawing moment caused by sideslip) of 0.143, assuming a sideslip angle of 10 deg, as compared with 0.074 for the full-scale aircraft. However, this requires a jet exit velocity of 1.43*M*.

Such scaling does not account for the jet exit velocity being supersonic, and, unlike the wind-tunnel tests, the surface flow is likely to be turbulent. Some correction would thus be required for compressibility and the delayed separation. Note that, if the engine mass flow scales with thrust, then the blowing levels quoted earlier would represent a loss in forward thrust equivalent to approximately 14 deg of thrust vectoring.

Conclusions

The tests undertaken reconfirmed the presence of large lateral instabilities in the region of steady vortex asymmetry, exacerbated by the high fineness ratio of the forebodies. Such instabilities could not be countered by a conventional rudder beyond a 25-deg angle of attack.

The tangentially blown forebody slot configurations tested at a jet momentum coefficient of 0.01 were capable of providing limited yaw control at 0 deg, which rapidly increased to exceed the control of the rudder by α = 18 deg for all slot positions. Control by these slots, limited in length and set back from the apex of the forebody, was unable to completely reverse the bistable vortex pattern in the steady asymmetric region.

At angles of attack between 60 and 120 deg, the slots exerted approximately 65% of the maximum yaw control that a conventional rudder was able to provide at low angles. This control was almost constant with increasing angle of attack and appeared to be capable of extension to higher angles. The concept appears to function equally well independent of the direction of the axial flow along the fuselage. This is a particularly unique feature.

When comparing different slot azimuthal positions at high angles of attack, the only noticeable difference was a jump in gain at very low blowing rates for the 90- and 110-deg slots. This resulted in greater yaw control but reduced the predictability and controllability of the system. At slightly higher blowing rates the gain leveled out to equal that of the 70-deg slot.

When scaled to a full-scale aircraft, only modest amounts of momentum (approximately half the available bleed mass flow) are required to produce significant yaw control at high angles of attack and a surprising amount of control at low angles.

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