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Low-Energy Pneumatic Control of Forebody Vortices*

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Motivation

Highly maneuverable combat aircraft and missiles often fly at sufficiently high angles of attack that their slender (usually pointed) forebodies develop asymmetric separated-flow vortex configurations. Management of this vortex (and associated aerodynamic force) asymmetry is essential to controlled flight under such conditions. Furthermore, the ability to generate and suppress this flow asymmetry at will holds promise of serving as a powerful high-angle-of-attack control technique for these vehicles.

Approach

Explore the prospect of employing bluntness, known to suppress the tendency toward flow asymmetry on slender forebodies, jointly with pneumatic vortex manipulation as a system of forebody flow asymmetry control. Evaluate influences of jet location and direction, blowing rate, relative nose bluntness, angle of attack, and state of flow separation feeding the vortices (laminar vs. turbulent).

Effect of Blunting on Side Force for 3.5-Caliber Tangent Ogive

Slender, pointed forebody shapes are well known to develop large side forces and yawing moments at high angles of attack as a consequence of the development of asymmetry of the vortex system formed by flow separation on the leeward side of such bodies. It has been demonstrated that the blunting of such a forebody shape suppresses the tendency of that body to develop asymmetric flow (and corresponding side forces) at high angles of attack. The figure shows the suppression of asymmetric forces achieved by 20% bluntness on the tangent ogive nose (dotted nose shape in plan view). But introduction of slight geometric asymmetry onto the blunted nose (small bump indicated by the spot on the nose in plan view) reintroduces asymmetry of approximately the same magnitude as that of the original (pointed) forebody.

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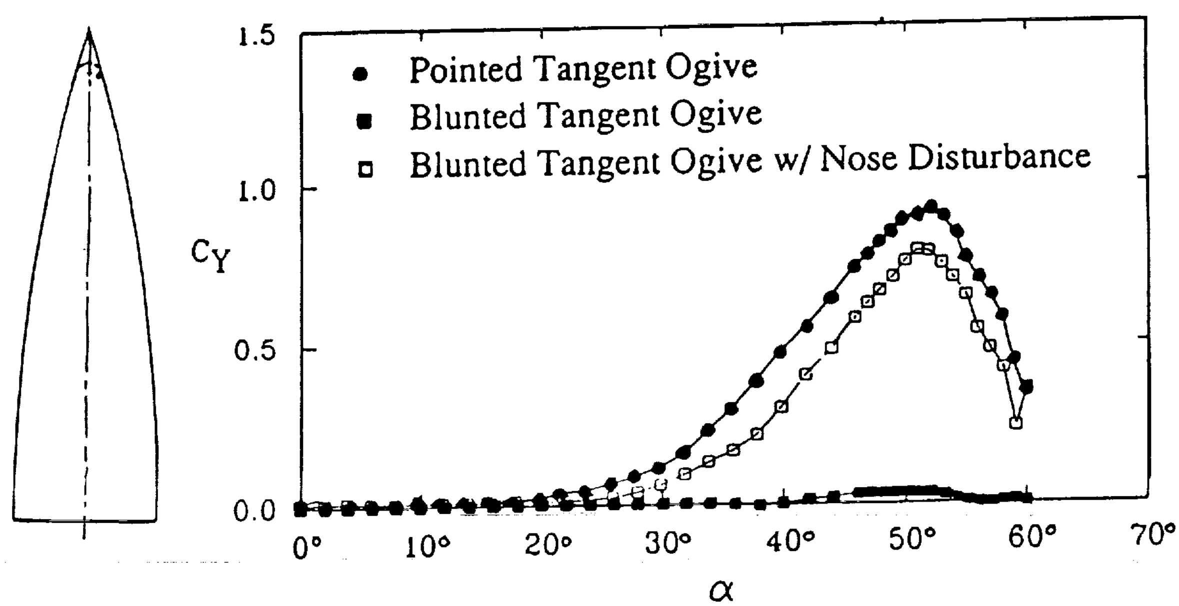
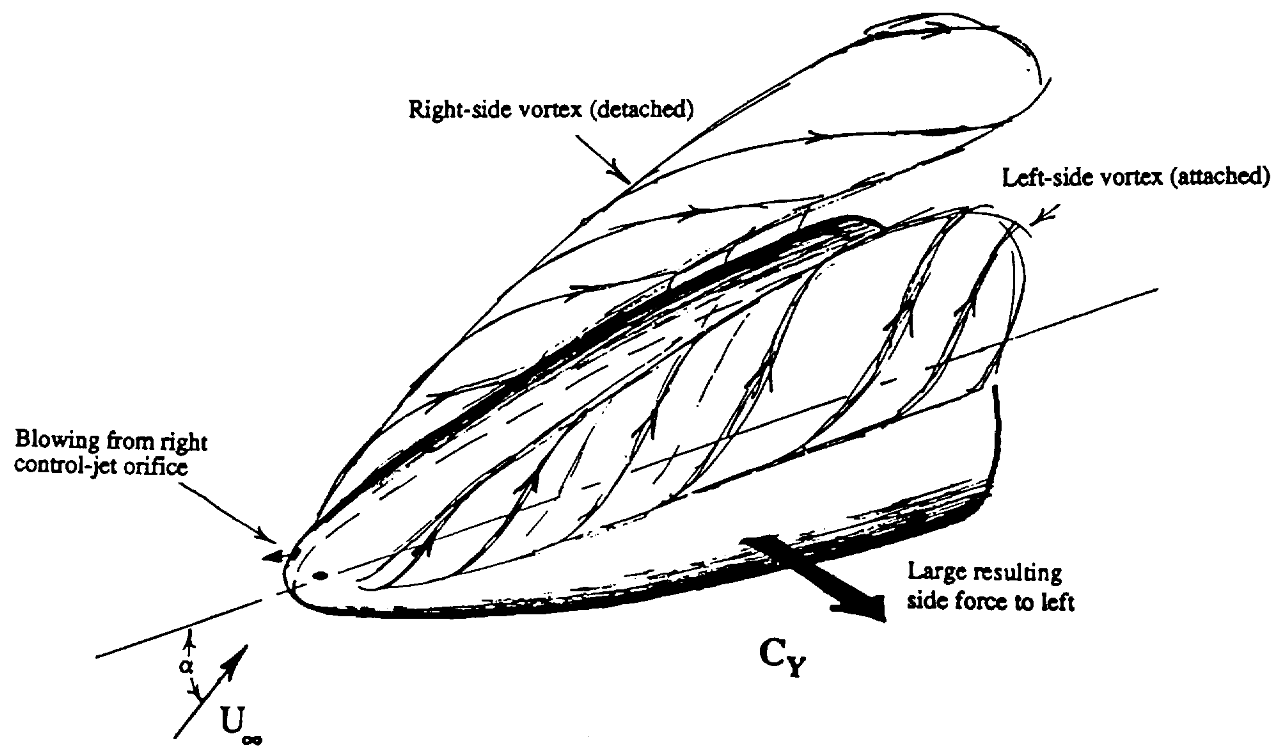


Nose Jets for Side Force Control

The foregoing leads to the concept of combining nose blunting (to suppress flow asymmetry) with blowing through small, symmetrically positioned nose jets to introduce flow perturbation leading to controllable side forces. As suggested by the sketch, the local displacement effect of slight blowing through a jet on the right side of the nose would promote detachment of the separated-flow vortex on the right side of the forebody, leading to a leftward side force. (Here and elsewhere, right and left are intended in the sense of the view forward over the forebody nose.)



Forward-Blowing Nose Jet Configuration on 20% Blunt, 3.5-Caliber Tangent Ogive

The model forebody studied experimentally (at low speed) was a 3.5-caliber tangent ogive having a base diameter, D, of 7.62 cm. For the bulk of this study, the nose of the body was hemispherically blunted to a radius that was 20% of the base radius. Several control-jet configurations were evaluated; in all cases, jet orifices were located axially at the point of tangency of the hemispherical nose and the tangent ogive surface. Azimuthally, the jets were usually positioned at ±135° from the windward meridian. The figure is a photograph of the nose of this model configured with flush, forward-facing jet orifices.

Additional details of the experimental setup and effort can be found in Roos, F.W. and Magness, C.L., "Bluntness and Blowing for Flowfield Asymmetry Control on Slender Forebodies," AIAA Paper No. 93-3409, August 1993.

Mass-Flowrate Coefficient

Blowing rates are all defined in terms of a mass-flowrate coefficient, $C_{\dot{m}}$, rather than a momentum coefficient, C_{μ}, to emphasize the fact that it is the displacement effect of the jet flow, rather than any momentum-related entrainment and/or energizing effect, that is responsible for the phenomena demonstrated here.

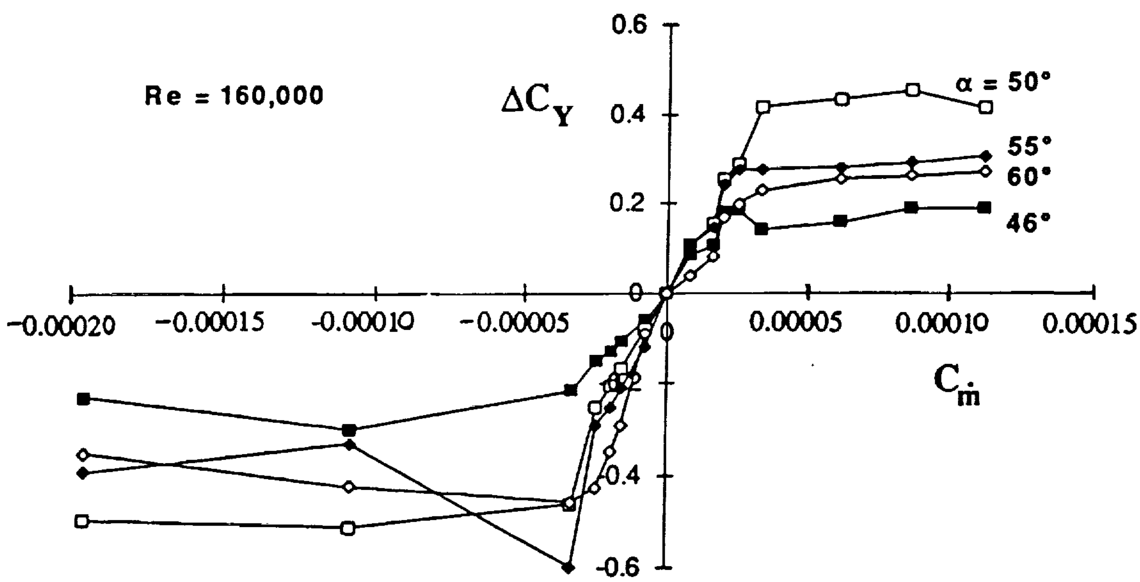
$$C_{\dot{m}} = \dot{m}_j / \rho_\infty U_\infty A$$

$\dot{m}_j$ = mass flowrate of control jet

A = planform area of 3.5 caliber tangent ogive

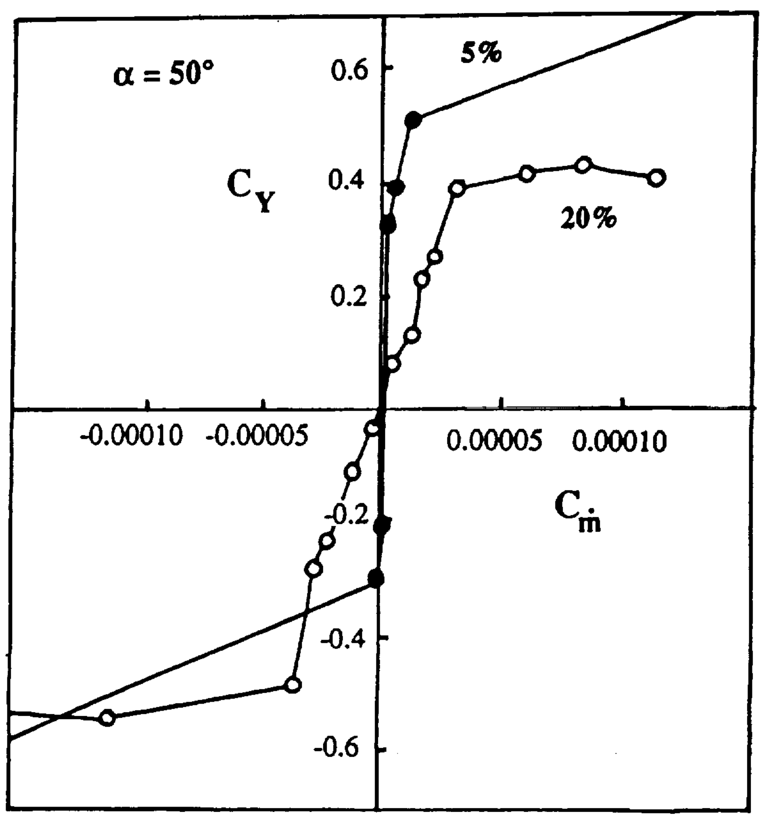
Side-Force Control via Forward-Blowing Jets on Blunt Tangent Ogive (Laminar Separation)

Cross-plotting ΔC_Y vs. blowing rate (+ for right jet, - for left jet) for several angles of attack shows the basic characteristics of the low-energy pneumatic control. Within a range about $C_{\dot{m}} = 0$, the effect of blowing is proportional, up to limiting levels of ΔC_Y (with different maxima for each α).



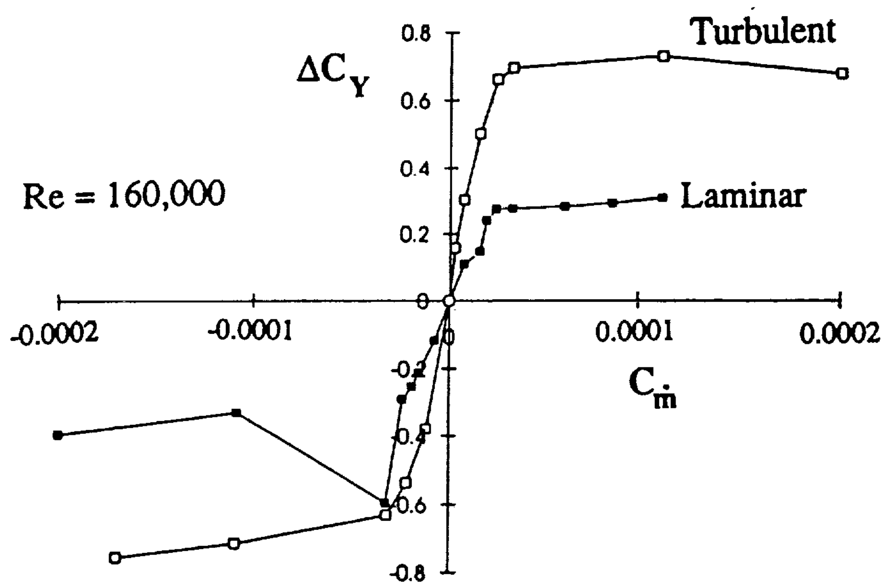
Influence of Bluntness Ratio on Blowing Effectiveness (Laminar Separation)

Limited studies were conducted with a 5%-blunted forebody, also equipped with forward-blowing jet orifices. C_Y vs. $C_{\dot{m}}$ results were similar to those for the 20%-blunted body, although it appears that the less-blunt shape is more sensitive to blowing rate. This is evident in the figure, which compares blowing-effectiveness curves for the two blunted forebodies at the same angle of attack ($\alpha = 50°$).



Comparison of Forward-Blowing-Jet Effectiveness with Laminar and Turbulent Separation, 20%-Blunt Tangent Ogive

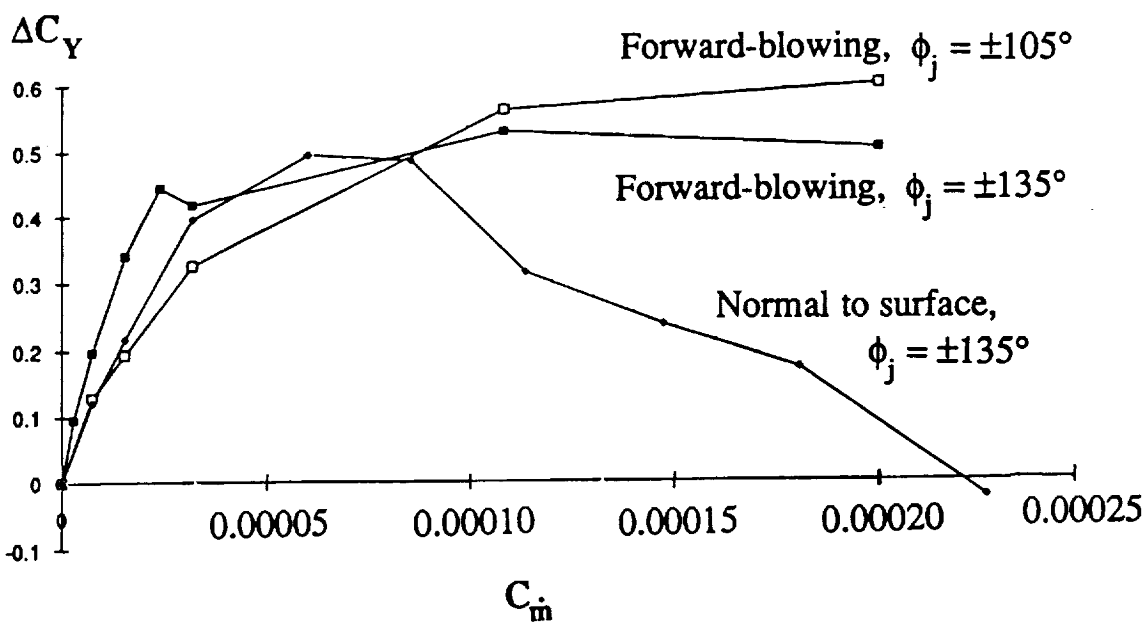
The sensitivity of pneumatic-vortex-control results to the state (laminar or turbulent) of the separating forebody boundary layers was explored via experiments conducted with longitudinal grit strips employed to trip the crossflow boundary layer before separation. Further details concerning the tripping are given in Roos and Magness. The figure compares ΔC_Y vs. $C_{\dot{m}}$ curves at $\alpha = 55°$ with laminar and turbulent separation. At this α, the pneumatic-control effectiveness is clearly much greater when the separation is turbulent. This kind of variation emphasizes the importance of properly simulating the anticipated (full-scale) type of boundary-layer separation when attempting to evaluate unconventional flow-control methodologies.



Effectiveness of Various Jet Configurations on 20%-Blunted Tangent Ogive

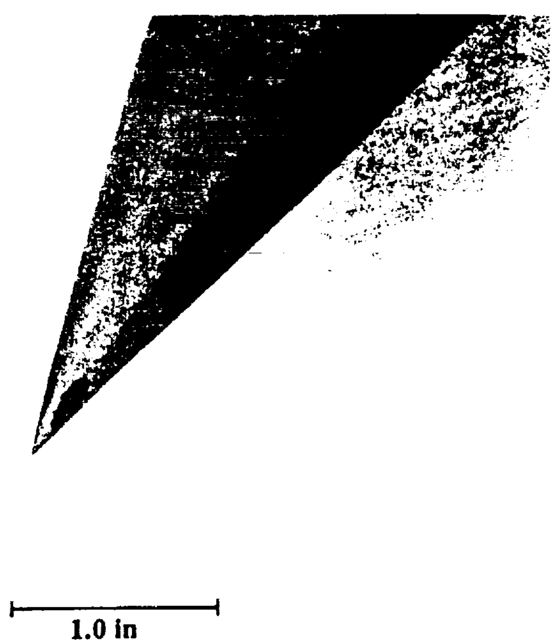
Turbulent Separation, $\alpha = 50°$

Several pneumatic-control jet configurations were studied with turbulent flow separation on the 20%-blunted tangent ogive. Blowing-flow-control effectiveness is compared for three jet configurations, all with fully turbulent separation, at $\alpha = 50°$ in the figure. The forward-blowing jets at $\phi_j = \pm 135°$ produce the strongest response at low $C_{\dot{m}}$, whereas the forward-blowing jets at $\phi_j = \pm 105°$ appear to yield the greatest overall ΔC_Y. The jets issuing normal to the surface evidently reach an "overblowing" condition.



Forward-Blowing Control-Jet Orifices at Nose of 3.5-Caliber Tangent Ogive

Limited studies have been conducted of the forward-blowing concept applied to the basic 3.5-caliber (pointed) tangent ogive forebody shape. The flush, forward-facing control-jet-orifice configuration at the pointed nose is shown in the figure.



Forward-Blowing Results for Pointed Tangent Ogive (Laminar Separation)

The no-blowing flow asymmetry shown in the previous figure is readily reversed at moderate mass flow, as this cross-plot of C_Y vs. $C_{\dot{m}}$ indicates.

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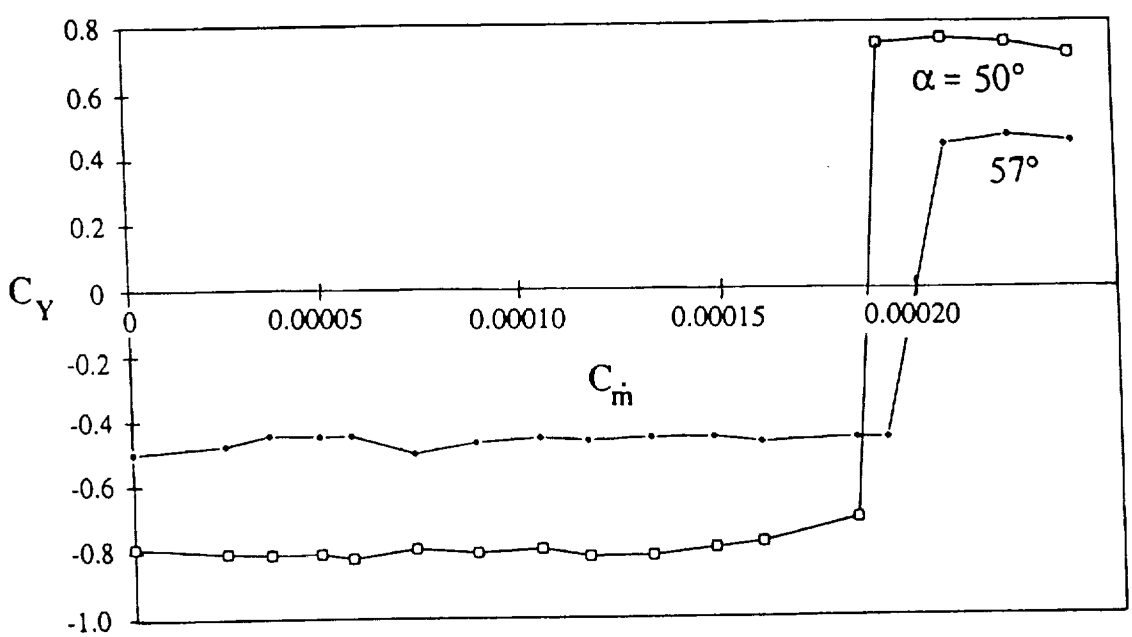
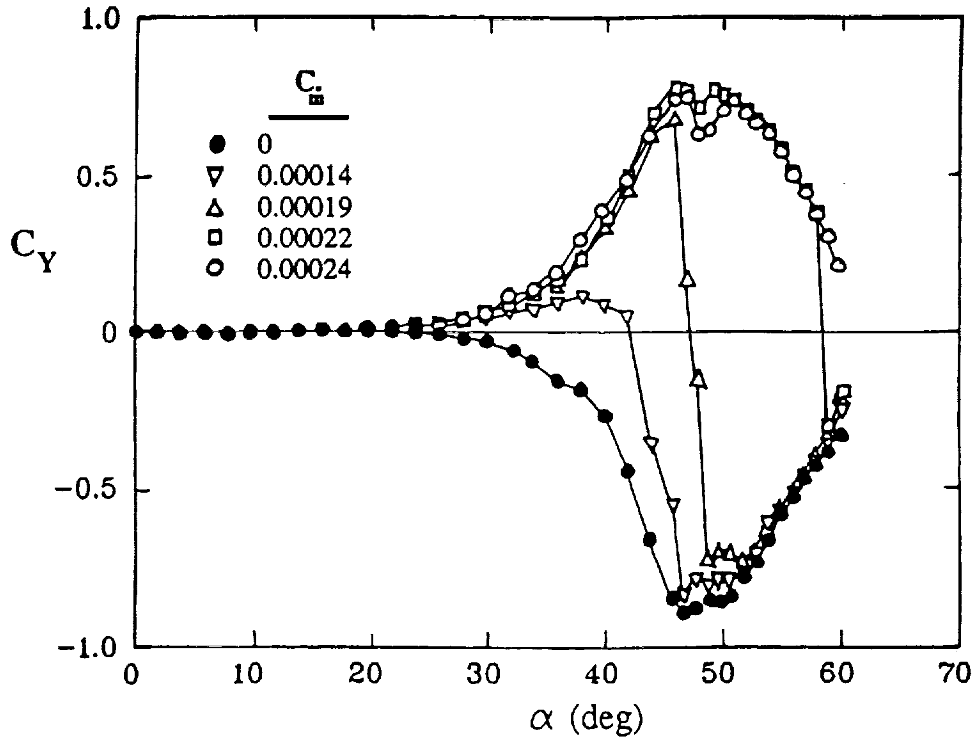


Forward-Blowing Effectiveness for Pointed Tangent Ogive (Laminar Separation)

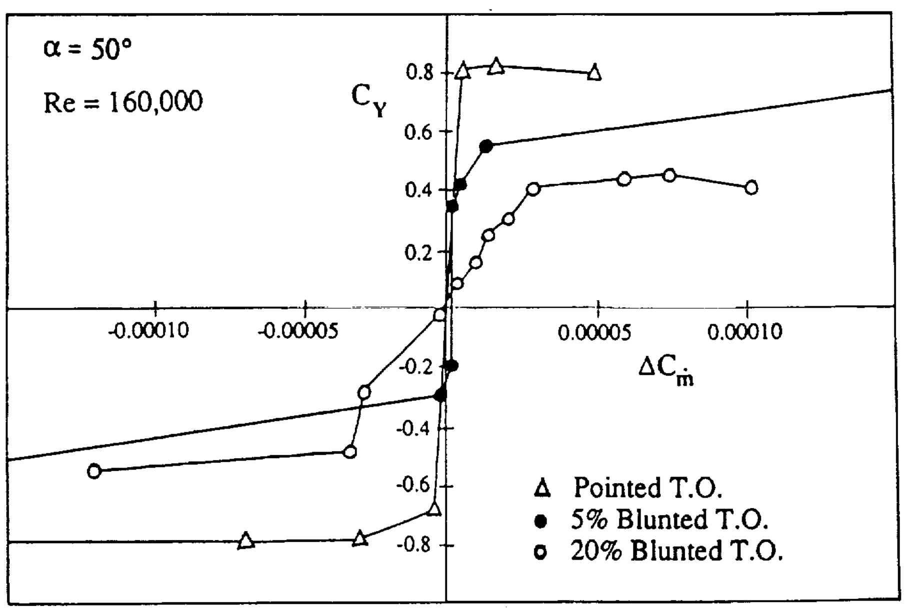
Side-force (C_Y vs. α) results for the pointed forebody (with laminar separation), shown in the figure, are similar to those from the blunted forebody except that the pointed body develops asymmetric flow naturally when $C_{\dot{m}} = 0$.



Forward-Blowing Effectiveness on Blunted and Pointed Forebodies (Laminar Separation)

This comparison of blowing-effectiveness curves for the pointed and blunted tangent ogives at $\alpha = 50°$ shows that the pointed forebody with forward–blowing control jets develops side-force-control characteristics comparable to the blunted forebody, continuing the trend indicated earlier of greater extremes of C_Y and greater sensitivity to blowing rate with reduced nose bluntness.

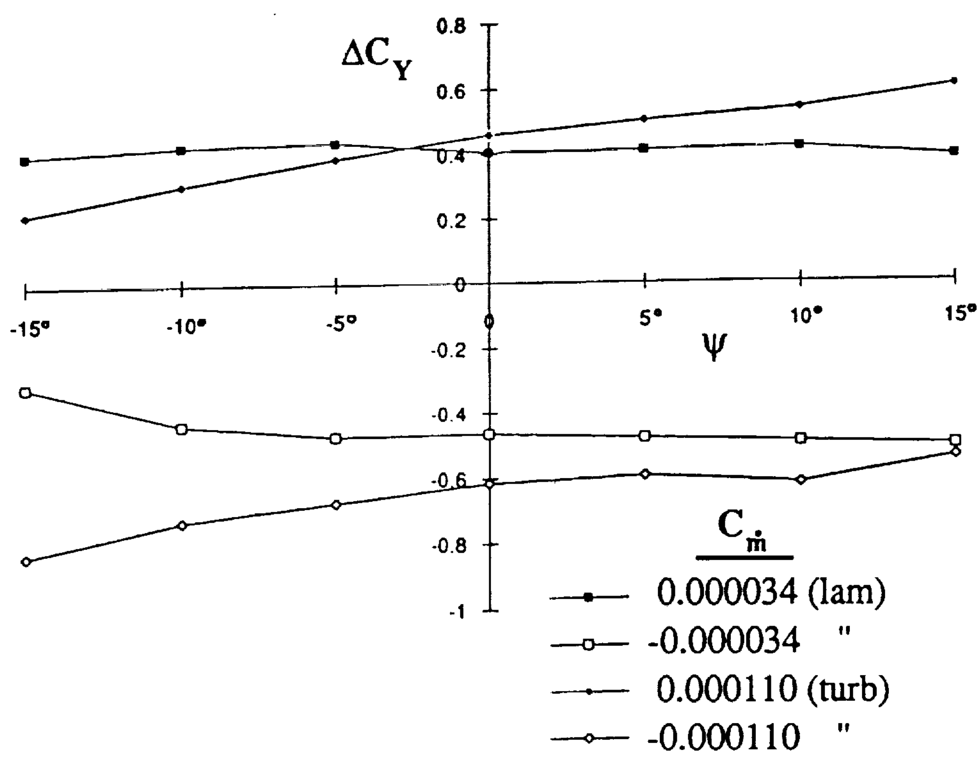
Note that minimal mass flowrates produce the pneumatic vortex control described here: a quick calculation based on data from this study shows that just 0.04 lbm/s is needed to achieve maximum C_Y for an F/A-18 class vehicle at sea level, M = 0.5.



Yaw Influence on Pneumatic Side-Force-Control Effectiveness

(Laminar and Turbulent Separation)

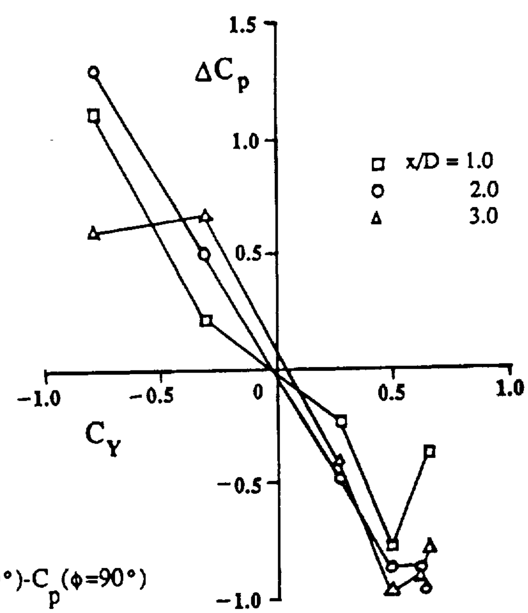
Using the configuration with jets normal to the surface on the 20%-blunted tangent ogive forebody, sensitivity of pneumatic-side-force-control effectiveness to yaw was evaluated over the yaw-angle range $-15° \leq \psi \leq 15°$ with both laminar and turbulent separation. Results for $\alpha = 50°$ are shown in the figure, where it is evident that, regardless of the nature of the flow separation, the pneumatic control capability is retained throughout the indicated yaw range.



Lateral Pressure Difference Associated with Forebody Flow Asymmetry

Pressure data from experiments on high-α forebody flow fields (Roos, F.W. and Kegelman, J.T., "Aerodynamic Characteristics of Three Generic Forebodies at High Angles of Attack," AIAA Paper No. 91-0275, January 1991) suggests that a simple two-point C_p-difference measurement might suffice to serve as input for a side-force control system. The figure shows a nearly linear relationship between ΔC_p, the side-to-side C_p difference at a given axial station along the forebody, and C_Y, the side-force coefficient. This relationship suggests that the measured level of ΔC_p might be used to set $C_{\dot{m}}$, thereby controlling C_Y.

3.5D Tangent Ogive, $\alpha = 45°$



$\Delta C_p = C_p(\phi=270°)-C_p(\phi=90°)$

Conclusions

- A 20%-blunted, 3.5-caliber tangent ogive forebody develops no side force throughout the range $0 \leq \alpha \leq 60°$, for both laminar and turbulent separation.

- Slight blowing through either of two symmetrically positioned orifices at the blunt nose of the forebody produces flow asymmetry (and corresponding side force) that is proportional to jet mass flowrate within maximum and minimum limits that vary with α, the degree of nose bluntness, the specific jet configuration, and laminar vs. turbulent boundary-layer separation.

- Forward-blowing jets are generally more effective than jets normal to the forebody surface.

- Reducing the relative bluntness increases the magnitude of side force developable by blowing, and also increases sensitivity to blowing rate, at least for the laminar-separation cases studied.

- A simple, two-point pressure-difference measurement shows promise of serving as input for a pneumatic-side-force-control system.

In summary, a promising, very-low-energy concept for pneumatic forebody vortex-asymmetry control has been demonstrated, and a simple control input for the forebody blowing has been identified.