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Pneumatic Concept for Tip-Stall Control of Cranked-Arrow Wings

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A novel blowing concept aimed at controlling the tip stall of cranked-arrow wings was experimentally investigated. The concept employs a tangential jet sheet blown spanwise on the tip-panel upper surface, from a chordwise slot located at the leading-edge break. The blown sheet interacts three dimensionally with the external flow, forming a controllable vortex that powerfully influences the tip-panel upper-surface flowfield leading to local lift improvement and stall delay. As a consequence, simultaneous blowing on both the tips alleviates pitch-up, whereas one-side blowing provides roll control; a concurrent overall lift increase occurs in both cases due to vortex augmentation. Low-speed wind-tunnel flow visualizations, pressure measurements, and six-component balance data were acquired on a generic cranked-arrow configuration to verify the concept and obtain preliminary indications of its aerodynamic control potential.

Nomenclature

A_J = jet slot area, in.^{2}
A_{ref} = wing reference area, in.^{2}
C_l = rolling moment coefficient
C_m = pitching moment coefficient
C_N = normal force coefficient
$C_{P,U}$ = upper-surface static pressure coefficient
$C\mu$ = jet momentum coefficient, $(V_J/V_0)^2(A_J/A_{\text{ref}})$
c = local chord, in.
V_J = jet velocity, ft $\times$ s^{-1}
V_0 = freestream velocity, ft $\times$ s^{-1}
x = chordwise coordinate, in.
α = angle of attack, deg

Introduction

CRANKED-ARROW wings, which combine highly swept inboard leading edges for low wave drag with outboard panels of reduced sweep for subsonic span efficiency, are of considerable interest to long-range supersonic cruise aircraft (e.g., the high speed civil transport or HSCT).[1-3] In common with slender wings, however, the cranked-arrow planform has a relatively shallow lift-curve slope that limits its low-speed lift capability, particularly at restricted angles of attack, e.g., during approach and landing. Also, the increase in effective incidence of the tip panels, exacerbated by massive influx of spanwise-driven upper-surface boundary layer, leads to early tip stall with consequent pitch-up instability at relatively low lift coefficients. Flow separation in the tip regions further degrades aileron effectiveness, in turn, limiting the crosswind landing capability. In order to improve the usable lift and pitch/roll control margins for enhancing low-speed landing characteristics, effective flow management for alleviating or delaying tip stall on cranked-arrow planforms will be crucial for the next generation supersonic-cruise aircraft.

Although conventional techniques (e.g., leading-edge flaps or slats, fences, vortex generators, etc.) can provide a degree of tip-stall control, they are either mechanically complex and heavy, or create unacceptable cruise-drag penalty. Flaps and slats based on two-dimensional aerodynamics also may be of questionable effectiveness for controlling the typically three-dimensional-separated and vortex-dominated flowfields, such as those encountered over the tip regions of cranked-arrow wings at above-design lift coefficients. Alternatively, pneumatic techniques such as spanwise blowing that appear to be better adapted for managing three-dimensional separations are worth considering. The different blowing schemes previously investigated on delta wings are shown in Fig. 1. Spanwise sheet ejection from sharp leading edges (Fig. 1a) directly into the vortex layer at its origin was found to reinforce the

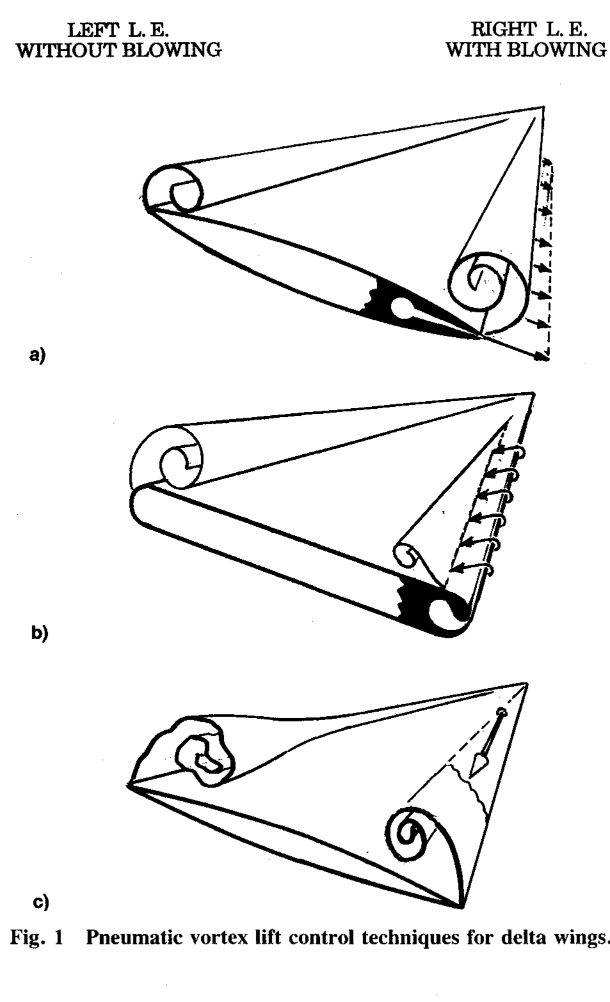

Fig. 1 Pneumatic vortex lift control techniques for delta wings.

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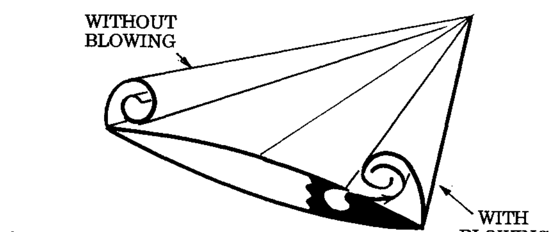
vortex and augment lift.[4] In recent work, this concept was successfully extended to specific aircraft configurations (viz., chine forebodies[5] and leading-edge extensions[6]). Incorporation of pneumatic ducts inside thin wing leading edges, however, is not only structurally difficult, but also penalizes internal volume. Separation control by means of inwards or chordwise tangential injection (Fig. 1b) is effective on well-rounded, blunt leading edges,[7] but incompatible with low wave-drag supersonic wing sections; it also presents structural integration problems as shown in Fig. 1a. Concentrated "spanwise" blowing from wing apex nozzles (Fig. 1c) along the vortex cores delays their breakdown, and consequently improves the stall angle of attack (or $C_{L,\max}$)[8,9]; it is not relevant, however, to low-alpha lift control.

Proposed herein is a novel spanwise, upper-surface tangential blowing technique specifically tailored to vortex lift modulation in the low-alpha range, at the same time being more amenable to airframe integration. This blowing concept, to be elaborated in the next section, was experimentally explored on a delta wing; it was then extended to a generic cranked-arrow wing model, whose longitudinal and lateral control characteristics were evaluated via low-speed wind-tunnel tests.

Blowing Concept

In a distinct departure from previous approaches, the present concept involves a thin jet-sheet blown tangentially outwards, from a swept-back slot flush with the upper surface and located well inboard of wing leading edge. This upper-surface wall-jet interacts three dimensionally with the chordwise outer flow, and rolls up into spiral vortex. Since this vortex—termed "jet vortex"—is primarily driven by the injected momentum, it can be directly controlled in scale and strength independently of angle of attack. The jet vortex may also be made to interact and merge with the adjacent leading-edge separation vortex of like rotational sense, thus modifying the overall vortical flowfield for aerodynamic control.

The proposed concept is illustrated in application to a delta wing in Fig. 2a. The upper-surface blowing slots are located along a pair of rays well inboard of the leading edges. The slots are internally contoured so as to discharge the wall-jet in a spanwise outward direction. This cross-blowing concept is fundamentally different from the traditional coblowing approach (i.e., injecting momentum in the same direction as the external flow) for boundary-layer separation control and vortex reduction.[7] In the present instance, blowing is aimed to forcibly create a jet vortex corotating with the adjacent leading-edge vortex; the consequent merger of these vortices augments nonlinear lift that is under continuous and direct control of the blowing momentum. At low-to-moderate angles of attack, when the flowfields of opposite wing panels remain uncoupled, one-sided blowing will generate roll control. The plenums could further be compartmented longitudinally, and selective blowing applied through the fore or aft slot segments symmetrically on both sides for pitch control. The abovementioned control functions, associated with vortex augmentation due to cross-blowing, will be accompanied by a lift increment.



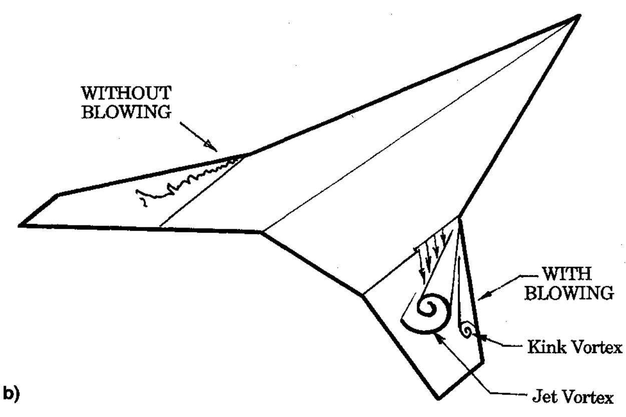


Fig. 2 Proposed blowing technique for low-alpha lift augmentation and control: a) delta wing and b) cranked-arrow wing.

To extend this blowing concept to tip-stall control on cranked-arrow wings (Fig. 2b), the blowing slots were proposed to be located at the leading-edge breaks. This location was selected in order to apply the augmentation effect to a naturally occurring crank vortex, which is known to influence the lift development and breakdown on the outboard wing panel. The slot was oriented chordwise in order to minimize parasite drag. The wall-jet was blown on the upper surface of the tip panels approximately parallel to their leading edges, creating a jet-vortex on the upper surface. The direct suction of the jet vortex, together with an energized leading-edge vortex, was anticipated to add to the lift over a large part of the panel span. Asymmetric (i.e., one-side) blowing will augment roll control. From the airframe integration viewpoint, the proposed pneumatic arrangement has the advantage of avoiding intrusion into the tip structure, the pneumatic ducts and flow controls being located inboard within the thick part of the wing and also considerably closer to the powerplant that is the likely source of compressed air.

Results and Discussion

The wind-tunnel investigation was performed in two parts. Initial proof-of-concept studies were conducted on a 60-deg, semispan, sidewall-supported model with pressure instrumentation on the upper surface. Pressure and flow visualization tests were performed at various angles of attack and blowing rates. In the second part, a full-span generic cranked-arrow wing model was employed for flow visualizations, pressure measurements, and force/moment evaluations with both symmetrical and one-side blowing. The tests were conducted in ViGYAN 3- × 4-ft low-speed wind tunnel at freestream velocities ranging from under 1 ft/s (for smoke visualizations) to 65 ft/s (for balance and pressure measurements). Experimental details and main results of the above two studies are summarized in the following:

Delta Wing

The geometry and principal dimensions of the sidewall-supported, semispan model are presented in Fig. 3. The 60-deg swept sharp leading edges were beveled symmetrically on both upper and lower surfaces. The wing construction was mostly hollow to serve as a plenum chamber that exhausted through a slot flush with the flat upper surface. The slot was internally contoured to discharge the blower air (supplied to the wing from an external blower) as a thin, flat wall-jet directed laterally outwards. A spanwise row of upper-surface pressure orifices intersecting the slot was connected to an external Scani-Valve system. Pressures were also measured at several points in the plenum chamber. The averaged plenum pressure, together with the upper-surface static pressure closest to the slot on its outboard side, were used to calculate an average V_j. In lieu of injection momentum, the velocity ratio V_j/V_0 was used to represent the blowing rate.

Smoke flow visualizations were initially conducted in a crossflow plane illuminated by a light sheet aligned with the

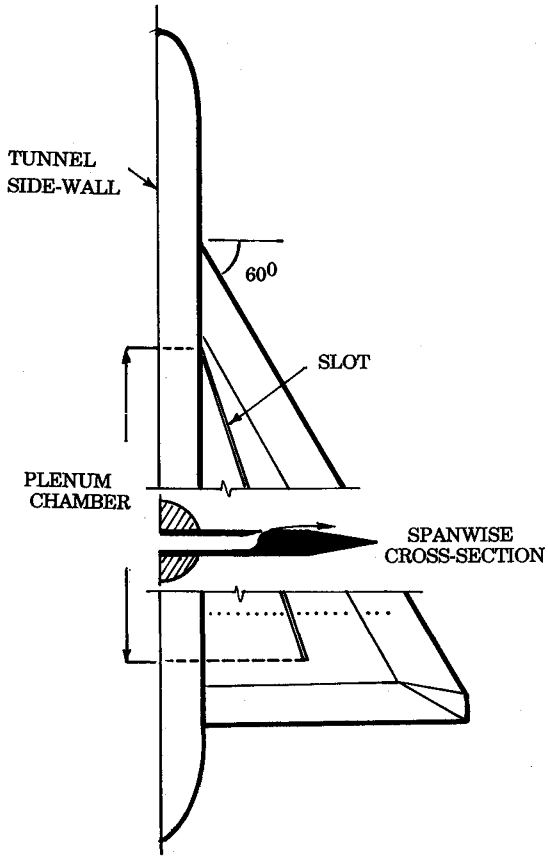


Fig. 3 Geometry of 60-deg semispan delta wing model.

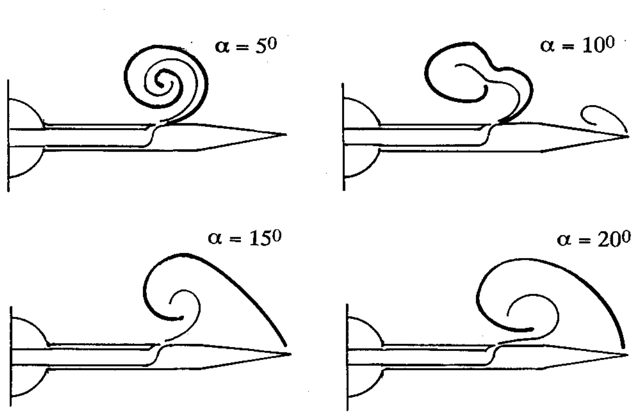


Fig. 4 Delta wing flow patterns with blowing at increasing angle of attack.

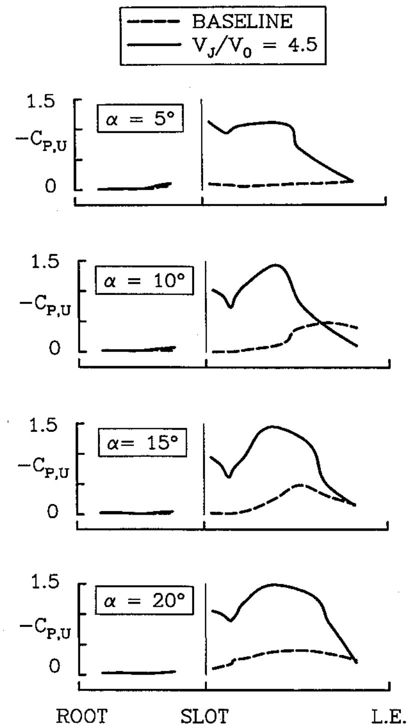


Fig. 5 Delta wing upper-surface pressure distributions with and without blowing at increasing angle of attack.

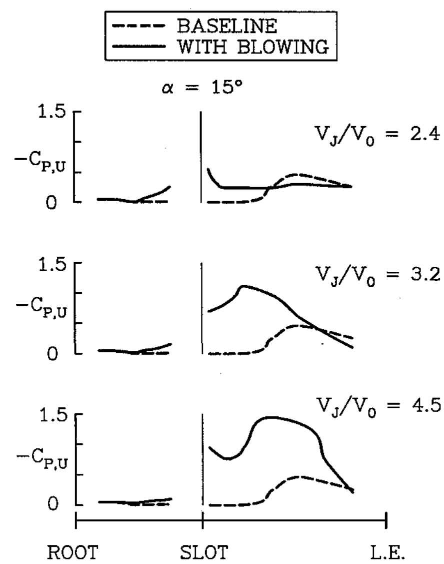


Fig. 6 Delta wing upper-surface pressure distributions at $\alpha = 15$ deg, and with increasing V_J/V_0.

pressure ports. Smoke was introduced into the wing along with the blower input to mark the slot-jet. A series of flow patterns (traced from photographs) at increasing angle of attack are presented in Fig. 4, showing the jet roll-up and its interaction with the upper-surface flow. At $\alpha = 5$ and 10 deg, when the wing upper-surface flow remained attached (or was reattached inboard of a leading-edge separation bubble), the jet is observed to roll up into a discrete vortex of a scale comparable with the wing quarterspan. At $\alpha = 15$ deg, a leading-edge vortex appears to be in the process of coalescence with the jet vortex, the center of merged vorticity consequently shifting outwards. At $\alpha = 20$ deg, the vortex merger appears complete, and a magnified vortical flow envelopes most of the wing surface between slot and leading edge. At angles of attack above 20 deg (not shown), blowing was observed to re-energize a burst-vortex type pattern that existed on the unblown wing.

Upper-surface pressure measurements at the same angles of attack and a constant $V_J/V_0 = 4.5$ are shown in Fig. 5. In each case a region of heightened suction appears outboard of the slot location, expanding with increasing alpha and representing the growth of merged vortex already seen in flow visualizations. Additional pressure measurements with increasing V_J/V_0 at a constant $\alpha = 15$ deg, shown in Fig. 6, suggest that the jet vortex becomes fully developed at $V_J/V_0 = 3.5$. Although limited in scope, the present results indicate the cross-blowing technique to have significant lift-improvement and aerodynamic-control potential on delta wing aircraft, particularly when operating at restricted angles of attack.

Cranked-Arrow Wing

The geometry and principal dimensions of the generic wing model, as well as the implementation of the blowing concept,

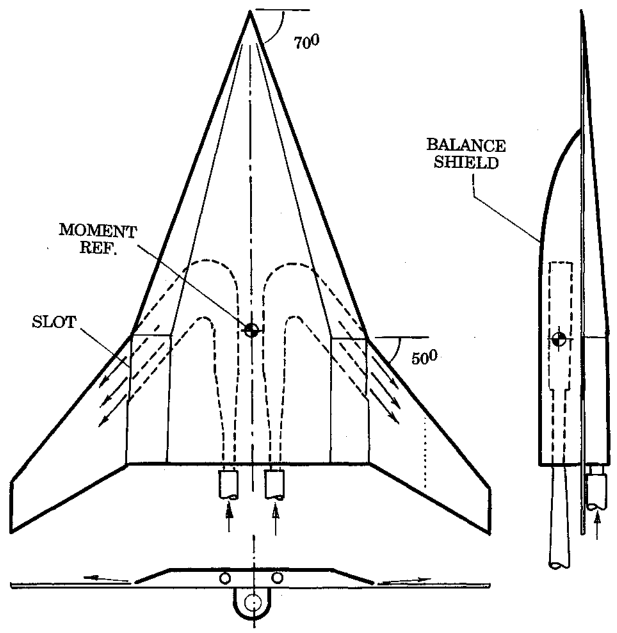


Fig. 7 Geometry of 70-deg/50-deg cranked-arrow wing model.

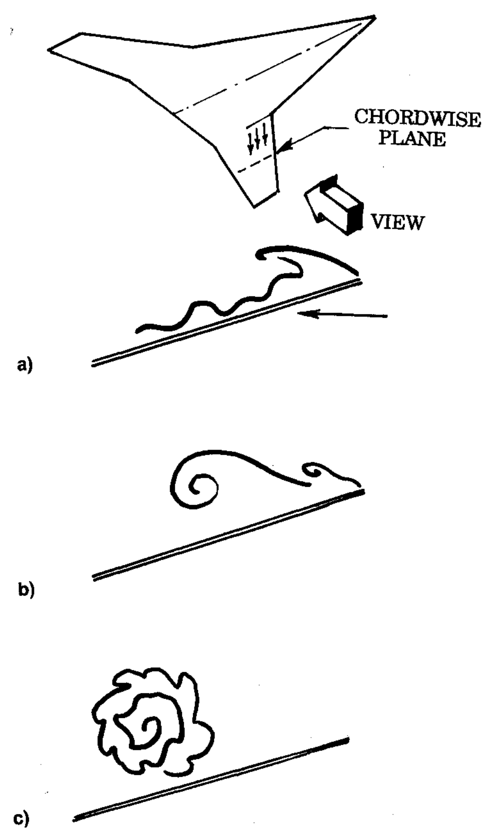


Fig. 8 Flow patterns in chordwise plane at α = 20 deg, increasing jet momentum: a) blowing off, b) medium blowing, and c) strong blowing.

are shown in Fig. 7. The sharply beveled inboard leading edges and the flat-plate tip panels were swept at 70 and 50 deg, respectively. The hollow inner part of the wing contained divided plenum chambers, each exhausting through a chordwise slot located at the leading-edge break. These upper-surface slots extended over the first 50% of local chord, and were shaped internally to produce a flat tangential jet directed parallel to the tip-panel leading edge. An external blower provided the jet flow whose rate was controlled and metered independently on either tip. The jet velocity was computed

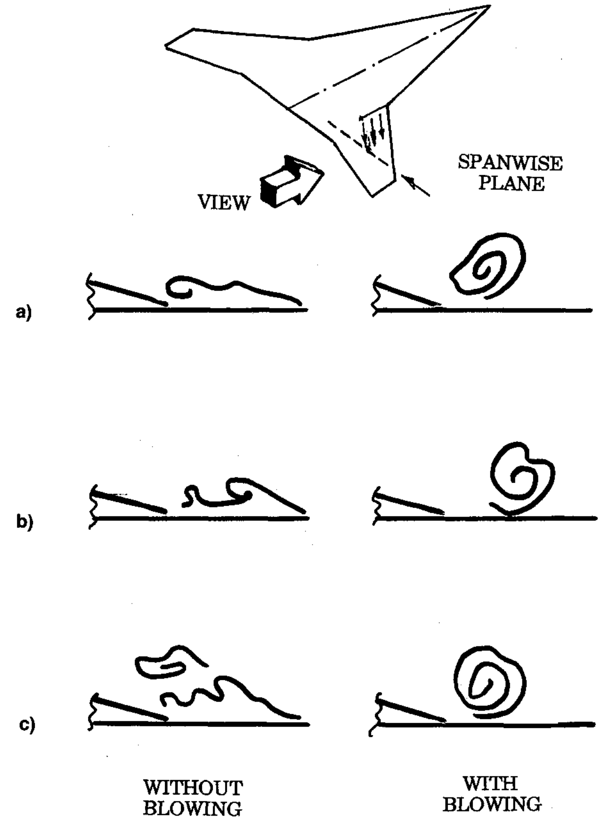


Fig. 9 Flow patterns in spanwise plane at increasing alpha, with and without blowing: α = a) 15, b) 17.5, and c) 20 deg.

from averaged plenum and freestream static pressure measurements. The model was mounted on an internal six-component balance. A chordwise row of static pressure taps was provided on the upper surface only of the right tip panel.

Preliminary smoke visualizations were performed on this model to qualitatively ascertain the blowing effects on tip-panel flowfield. The visualizations were obtained in a light sheet successively positioned chordwise or spanwise on the right tip panel, with smoke mixed in the blown air. The effect of increasing jet velocity at a fixed α = 20 deg, as observed in a chordwise plane, are depicted in Fig. 8. The "blowing off" case (Fig. 8a) showed leading-edge stall followed by flow unsteadiness over the whole tip panel. "Medium blowing" (Fig. 8b) produced an appreciably steadier separated flowfield, with a distinct double-vortex pattern emerging. With harder blowing (Fig. 8c), a large stationary vortical flow dominated the tip upper surface, displaying a coherent vortex structure, in spite of increased background turbulence. (These flow pattern sketches are based on smoke photographs, which unfortunately, are of inadequate quality for clear reproduction). A second set of patterns observed in a crossflow (spanwise) plane is presented in Fig. 9, comparing blowing off and medium blowing cases at three increasing angles of attack. These spanwise views are consistent with the chordwise sectional flow visualizations in showing that blowing produced a dominant jet vortex fully replacing the originally stalled flow throughout the tip span.

For a corroboration of the low-velocity smoke visualizations, oil flow tests were conducted at a freestream speed of 65 ft/s (i.e., as used for pressure and balance measurements). The Reynolds number of these tests was 0.8×10^6, based on mean aerodynamic chord. Upper-surface chordwise pressures were measured mainly as a backup for the oil flow interpretations. The oil flow patterns on the left tip panel shown in Fig. 10, typically developed over a two-minute run time, which attests to the temporal stability of the associated flowfields. At α = 4 deg, the unblown tip shows the footprint of the

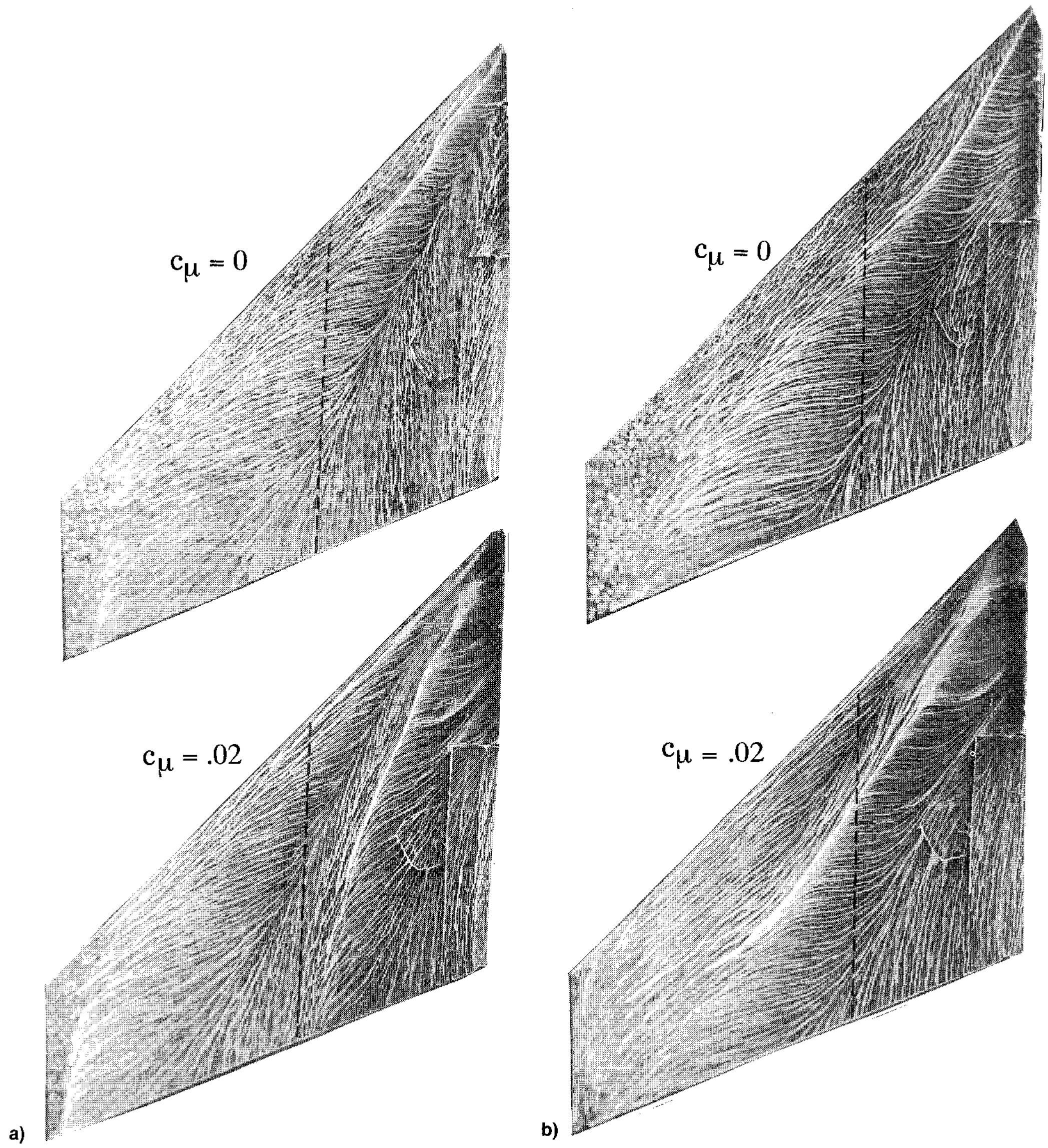


Fig. 10 Oil flow patterns on left wing tip panel with and without blowing. α = a) 5 and b) 10 deg.

"kink" vortex (so-termed because of its origination from the leading-edge kink), produced by the roll up of tip panel leading-edge separation. Blowing moves the kink vortex closer to the tip leading edge; simultaneously, a second and more prominant vortex track appears inboard, clearly emanating from the slot and accordingly recognized as the jet vortex. At α = 10 deg, the jet-vortex track covers more of the tip-panel span, and an energized leading-edge kink vortex is also evident.

Chordwise upper-surface pressure distributions at the mid-span of the tip-panel at increasing angles of attack are presented in Fig. 11. At α = 6 and 8-deg, blowing generates more concave-shaped distributions, indicating pressure recovery associated with reattaching flow, unlike the nonblown case where a relatively flat distribution is evidence of stalled flow. At these lower angles of attack when the jet vortex remains fully inboard of the instrumented chord (see visualization in Fig. 10, A), the pressure signatures essentially reflect an energized kink vortex. A distinct change, however, occurs when going to α = 10 deg, as shown by the emergence of a "suction bulge" over the rear-half of the tip chord. Supported by the evidence of oil pattern of Fig. 10b, this suction can be recognized as the footprint of jet vortex that now intersects the instrumented chord. Returning to Fig. 11, the influence of jet-vortex suction in the pressure distributions can be seen to persist to α = 16 deg.

The above qualitative indications of tip-panel flow improvement due to blowing were assessed via balance measurements. The test configuration being essentially planar with separations fixed at leading edges, the normal force and pitching moment data provide a basic aerodynamic characterization of the blowing effect. These data are plotted in Fig. 12 vs angle of attack, comparing the unblown (baseline) case with a typical symmetrical-blowing test at $C\mu$ = 0.0186 per side. An increase in normal force starting at α = 5 deg, together with a delay in pitch-up from α = 6–12 deg, are positive indications of tip-panel lift improvement. The variations of normal force and pitching moment coefficients with increasing blowing momentum at a constant α = 10 deg are shown in Fig. 13. These results (representative of the 5–20-deg angles-of-attack range) indicate that the tip blowing effects are smoothly controllable with $C\mu$ up to 0.015, a range that is comparable with blowing momentum levels for effective vortex control determined in the previous pneumatic techniques.[4–6] With future refinements in the blowing slot geometry (such as reduction of length and with sweepback angles less than 90 deg), additional improvements in the pneumatic efficiency are conceivable for tip flow control.

The effect of blowing on tip-panel lift improvement can be assessed independently in terms of a rolling moment resulting from one-sided blowing. Rolling moment coefficient vs angle of attack with left- or right-side blowing at $C\mu$ = 0.02 are presented in Fig. 14. The rolling-moment due to one-side blowing in combination with ailerons shown in Fig. 15 indicates what might be expected in practical application. Whereas

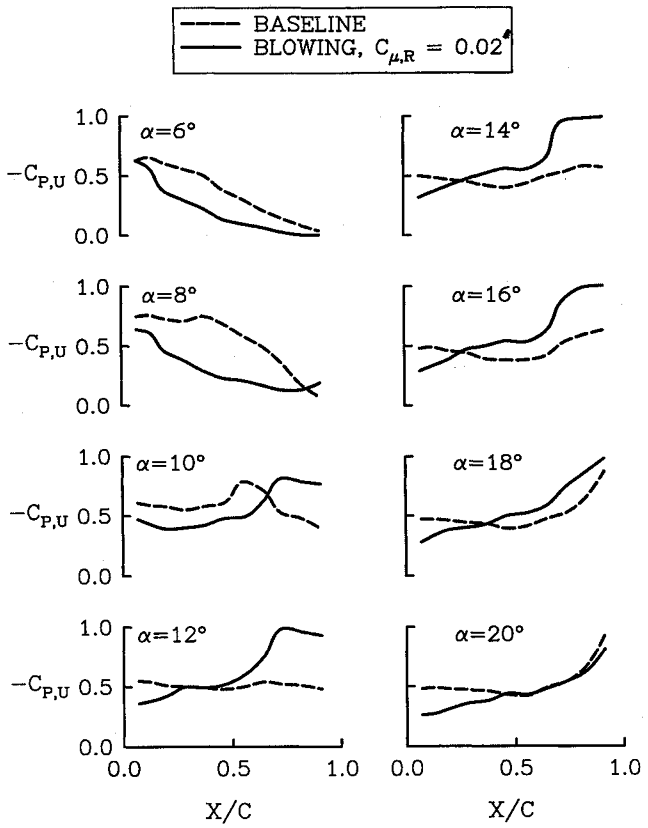


Fig. 11 Upper-surface chordwise pressure distributions on right tip panel with and without blowing, increasing angle of attack.

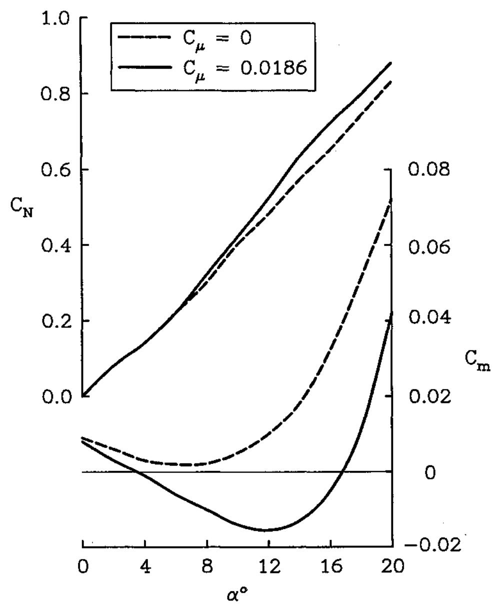


Fig. 12 Cranked-arrow wing normal force and pitching moment vs alpha, with and without blowing.

tip-stall onset on the baseline configuration degrades the ailerons rapidly above α = 10, blowing (viz., at $C\mu$ = 0.01) fully compensates for the loss of lateral control up to α = 18 deg, and provides additional roll effectiveness with $C\mu$ = 0.02. These results suggest that the proposed blowing technique might be adaptable for amplifying the control power of mechanically actuated surfaces (viz., ailerons, elevators, rudders, canards, etc.), thus allowing significant reductions in their size, for the benefit of cruise drag and actuation-power requirements.

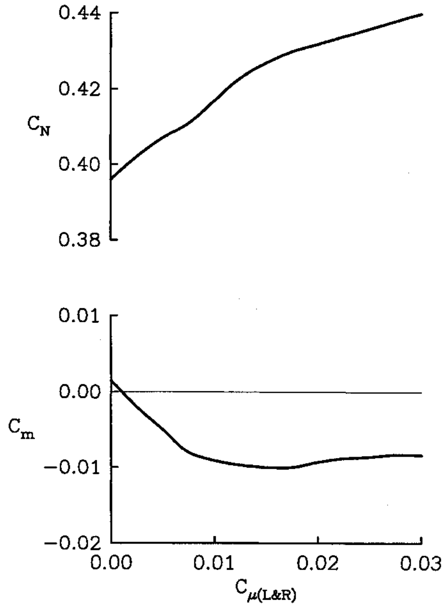


Fig. 13 Normal force and pitching moment coefficients vs blowing momentum coefficient, α = 10 deg.

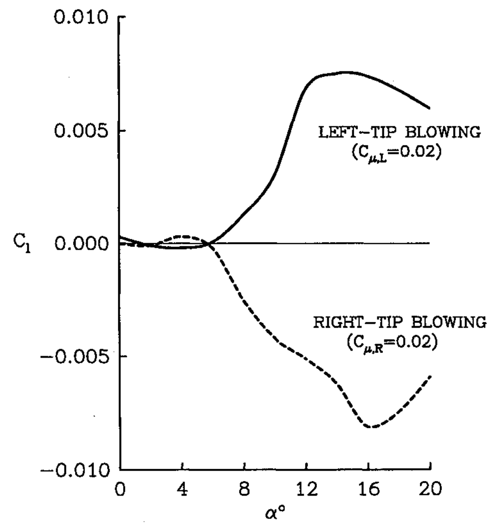


Fig. 14 Rolling moment coefficient vs alpha with one-side tip blowing.

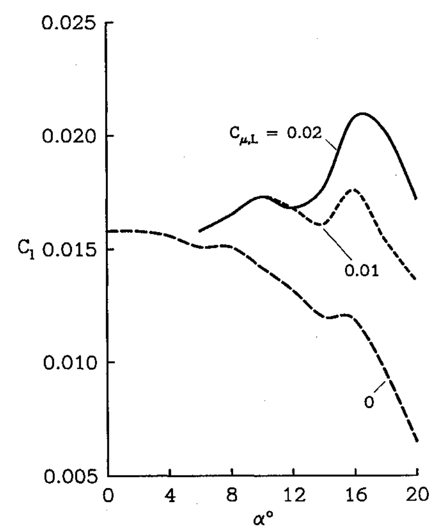


Fig. 15 Rolling moment vs alpha with combined ailerons and blowing.

Summary and Conclusions

A novel blowing concept was proposed and exploratory low-speed tunnel evaluation conducted with the objective of alleviating tip-stall of a cranked-arrow wing planform. The technique comprises an upper-surface wall-jet, blown over the tip panel from a chordwise slot located at the leading-edge break, which in three-dimensional interaction with the external flow rolls up into a jet vortex. The jet vortex exerts a powerful stabilizing influence on the tip-panel upper surface flowfield and delays its stall, thus raising the pitch-up angle of attack. One-side blowing is thus usable for lateral control improvements when aileron effectiveness begins to degrade. The longitudinal and lateral aerodynamic benefits are fully controllable in a range of jet momentum coefficients that favorably compare with those employed in previous blowing techniques for vortex control. The postulated flow mechanism was verified through flow visualizations and pressure measurements; six-component balance data provided preliminary indications of the pitch and roll control potential of the concept. Results of the present exploratory tests, performed on a generic flat-plate wing at modest Reynolds numbers, provide encouragement for follow-up investigations in order to develop the full potential of proposed tip-stall control technique, as a means to enhance the low-speed flight and landing characteristics of future civil and military supersonic-cruise aircraft.

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