



Circulation Control for High Lift and Drag Generation on STOL Aircraft

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The concept of circulation control by tangential upper surface blowing over a circular trailing edge has been investigated for application to fixed wing STOL aircraft. Experimental investigations on both two- and three-dimensional airfoils employing nominal blowing have demonstrated lift gains double to triple that of the conventional flapped airfoil, and associated large increases in drag (which further serve to reduce landing velocities and distances). An additional two-dimensional investigation into the basic fluid mechanics of the concept has shown that jet Mach numbers considerably above choked produced no adverse effects on the mechanism of the trailing edge Coanda flow, but instead yielded additional lift gains. These results appear quite promising where high lift generation is desired for a STOL aircraft having a nominal amount of auxiliary bleed air available, but where substitution of increased pressure ratios can produce added jet velocity to obtain the required momentum (blowing) coefficient.

Nomenclature

c	= airfoil chord, in.
C_D	= aircraft drag coefficient
C_{L, C_L}	= section or aircraft lift coefficient
$C_{M_{25}}^-$	= moment coefficient about $\frac{1}{4}$ MAC
C_μ	= jet momentum coefficient
h	= jet slot height, in.
$\dot{m}$	= jet mass flux, slugs/sec
P_d	= jet (duct) total pressure, psfa
P_∞	= freestream static pressure, psfa
q_∞	= freestream dynamic pressure, psf
R	= trailing edge radius, in.
t/c	= thickness-to-chord ratio
V_j	= jet velocity, fps
α	= incidence, deg
δ/c	= camber ratio
δ_f	= flap deflection angle, deg
θ	= turning angle from slot, deg

Introduction

RECENT research¹ has been conducted at the Naval Ship Research and Development Center (NSRDC—formerly David Taylor Model Basin) into the application of tangential upper surface blowing over the rounded trailing edges of helicopter rotor blades. The results of these investigations, especially the high lift values obtained, have suggested employment of a similar scheme to fixed wing STOL aircraft. Proven benefits of these Circulation Control (CC) airfoils include high lift coefficients at very moderate momentum coefficients and low angles of incidence. Applied to nonrotary wing STOL aircraft, these advantages imply considerable reductions in landing velocities, reduced landing and takeoff distances, and improved pilot approach visibility. The basic problem to be addressed relating to the STOL application of the CC concept (especially to high-speed aircraft) involves the effectiveness of the Circulation Control airfoil as a low aspect ratio thin wing, as opposed to the existing

helicopter application as a high aspect ratio, thick rotor blade.² A closely related and very pertinent problem in the fluid mechanics of the concept is the question of the effectiveness of high jet velocities (sonic or greater, produced by high-pressure engine bleed air) on the somewhat delicate nature of the flowfield over the bluff trailing edge. The present paper will discuss a basic investigation into the trailing edge flow regime produced by high wall jet velocities, and then present the results of a subsonic wind tunnel investigation of a representative three-dimensional aircraft configuration with part-span application of the Circulation Control airfoil. In addition, a preliminary two-dimensional investigation which initially confirmed the high lift effectiveness of circulation control applied to relatively thin conventional airfoils will be described briefly.

The basic Circulation Control concept involves the well-known Coanda principle, where a thin jet of air remains attached to an airfoil's rounded trailing edge due to the balance between centrifugal force and the pressure differential produced by the jet velocity (Fig. 1). The device achieves high lift by control of the airfoil stagnation points and thus the circulation around it. The primary mechanism is the increased streamline deflection produced by the movement of both stagnation points toward the airfoil center-chord; the overall effect is to produce an effective camber considerably greater than the geometric value.

The majority of CC airfoil lift is contributed by the circulation-induced lift coefficient (C_{L_f}) while the vertical thrust component of the jet ($C_\mu \sin \delta_{jet}$) is usually small. As

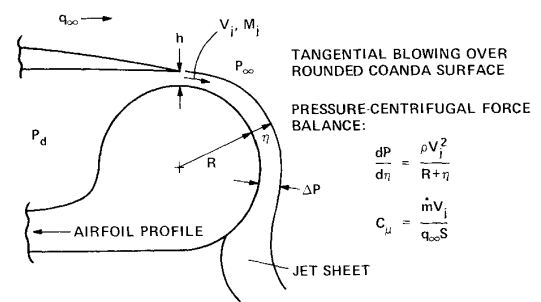


Fig. 1 Basic circulation control aerodynamics.

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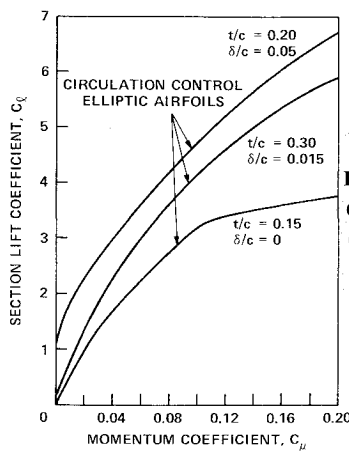


Fig. 2 Lift characteristics of 2-D Circulation Control airfoils, $\alpha = 0^\circ$.

Fig. 2 shows, the lift generated by a typical 15% thick elliptic CC airfoil at zero incidence and moderate momentum coefficients can be significant. Increase in camber, thickness ratio, trailing edge radius, and aft slot location³⁻⁵ can double the 15% thick CC section's performance. It should be mentioned that the CC ellipses shown in Fig. 2 do not possess the same trailing edge geometries, and thus lift does not increase progressively with thickness ratio for these cases.

An additional advantage of the CC airfoil is the production of high profile drag with increased blowing. This is due to the turning of the jet into the oncoming lower surface freestream and the resulting increased wake caused by viscous mixing of the jet and freestream. Thus avoided is a problem common to both blown flap and jet flap airfoils, that of converting the wing jet momentum into jet thrust, and accompanying difficulties in slowing the aircraft down on approach.

Based on a considerable amount of two-dimensional data on elliptic CC airfoil sections, the high lift potential of the concept was confirmed¹: lift coefficients greater than 6.5 for momentum coefficients less than 0.20, lift augmentation ratios ($\Delta C_L / C_{L0}$) of over 70, and lift generation essentially independent of incidence. It remained to be shown that similar performance could be achieved from a non-elliptic thin airfoil section characteristic of modern aircraft, especially if applied to a low aspect ratio wing.

Preliminary Two-Dimensional Investigations

A representative 10% thick NACA airfoil profile (66-210) was chosen as the basic model for a small-chord investigation in the NSRDC 15x20 in. Subsonic Tunnel. As the bluff Coanda trailing edge configuration was not suitable for high speed flight, a method for conversion from the sharp cruise airfoil to the rounded high lift configuration had to be chosen. Figure 3 shows a hinged short chord flap rotating through 180° to expose a cylindrical surface which becomes the Coanda trailing edge. This concept has the additional advantage that in an intermediate position it may be operated as a blown flap during aircraft takeoff, thus generating moderate-to-high lift coefficients at greatly reduced drag. Furthermore, in the cruise configuration, the upper surface slot is available for blowing over the undeflected flap to assist in high speed maneuverability. The geometry of the slot and rounded trailing edge was based on criteria⁶ from the previously mentioned elliptic airfoil investigations; their adaptation to the thin NACA 66-210 profile produced a short flap chord length of 15% of the airfoil chord (an advantage, considering the hinge loads during flap rotation).

The two-dimensional investigation was conducted using surface static pressure taps and a total-head wake rake to record lift, pitching moment, and drag coefficients over a wide range of incidence and momentum coefficient. As the flap was not rotatable in the small chord model, only the Coanda trailing edge configuration was investigated. Leading

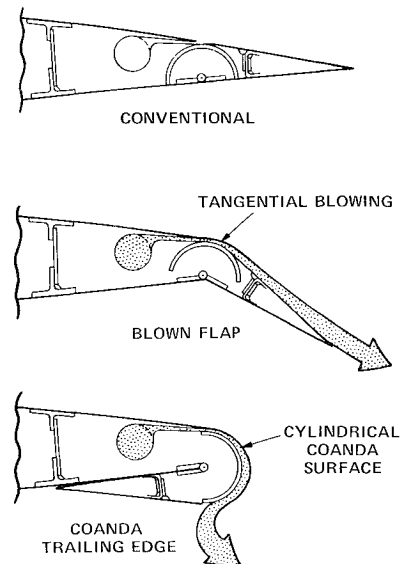


Fig. 3 Circulation control wing modes of operation.

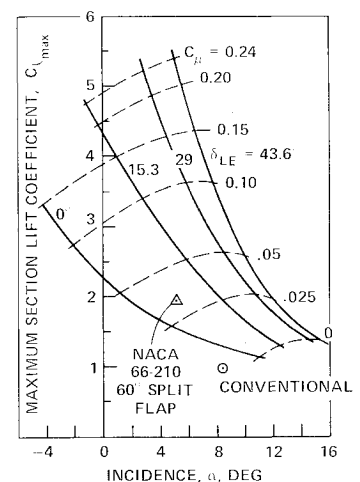


Fig. 4 Maximum 2-D lift coefficients of a NACA 66-210 CC wing.

edge droop was incorporated in order to prevent the severe leading edge separations produced by high suction peaks on the small nose radius. Figure 4 is a map of the maximum lift coefficients obtained at various combinations of blowing and leading edge droop (where all coefficients are referenced to undeflected chord). Results show an improvement of 250% over the conventional airfoil with a 20% chord split flap deflected 60° and tested at five times the Reynolds number.

High Jet Velocity Investigation

Jet Detachment Criteria

The higher C_{μ} values of Fig. 4 represent jet velocities (V_j) that are sonic or slightly above, and as the lift augmentation for these points was considerably reduced relative to lower blowing values, it appeared that the use of higher velocity wall jets might prove somewhat undesirable. The problem of how large a jet velocity could be employed without producing detrimental effects on the Coanda flow mechanism thus arose. Indeed, a number of investigators⁷ have identified a velocity-dependent (i.e., pressure ratio-dependent) jet-detachment limit, above which complete detachment of the jet from the Coanda surface would occur with resultant loss in lift.

Reference 7 discusses the details of the various jet detachment limits, where all results indicate that detachment is brought on by high pressure ratios across the nozzle, large slot heights, and small radii on the Coanda surface. Rather poor agreement exists between the various detachment criteria,

especially between those run statically without a freestream and those run with a freestream. (The presence of an external flow clearly produced greatly reduced local static pressures on the trailing edge, and thus increased effective pressure ratios across the slot.) Based on this disagreement, it was felt necessary to conduct an additional investigation on a circulation control airfoil under high lift conditions to identify or confirm pertinent detachment limits, and to determine if those slot heights and pressure ratios likely to be encountered on a full scale flight vehicle would be within these limits.

2-D High V_j Investigation

To maintain generality of results so that application could be made to both wing and rotor blade sections, it was desired to test a “neutral” section, i.e., to eliminate such parameters as camber and thickness distribution from the range of variables. Figure 5 shows the resulting 2-D airfoil. The leading edge was a 20% uncambered ellipse from nose to the midchord; from there aft to the slot the airfoil profile was of constant thickness. This flat aft surface maintained the “neutrality” of the model by eliminating different aft surface contours and resulting dependent boundary layer developments in regions of likely separation. Since a variable of prime importance was the slot-height-to-radius ratio, the slot height was variable from 0 to 0.100 in. by use of adjustment screws.

The model was pressure tapped as shown in the figure, and two-dimensionality was assured by tangential blowing from the tunnel sidewalls.⁸ Two additional features of the model were distinct from those CC airfoils previously tested at NSRDC. A 1/8-in. thick wedge-shaped plate was attached to the cylinder, and a row of nine 0.0156-in. diameter static pressure taps was embedded in the plate normal to the cylinder surface. This device was designed to measure the static pressure variation across the jet to determine the relationship between pressure differential and jet detachment, if any. Also, a flush mounted hot film shear stress probe was embedded in the surface of the cylinder to accurately measure jet shear stress without producing any disturbing effect on the jet. This instrumentation could also be used to locate the point on the Coanda surface where the jet eventually separated. The trailing edge cylinder could be rotated and repositioned, and thus measurements of shear stress, static pressure across the jet, and surface static pressure could be made at streamwise locations (θ) on the Coanda surface from 0° to 180° from the slot.

Using the above apparatus, a test program was undertaken, primarily to investigate the following: effect of varying h/R and P_d/P_∞ on airfoil performance; jet detachment criteria, including the effects of an external flow and shock-induced recompression in the jet; jet separation criteria for choked and unchoked flow, plus dependence on h/R , P_d/P_∞ , and static pressure gradient across the jet. Details of the program, model, and calibration procedure for the hot film probe are discussed in Ref. 7.

A number of important conclusions were drawn from the results of the investigation. Static pressure variation across the jet was clearly not constant, thus prohibiting the use of

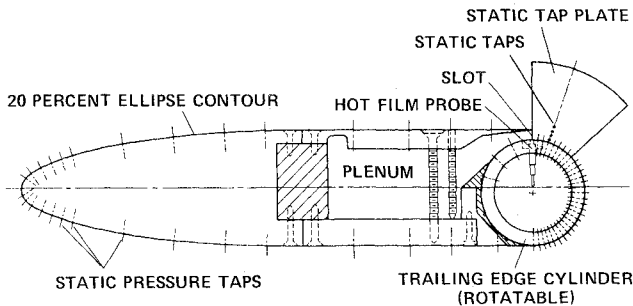


Fig. 5 Two-dimensional model geometry.

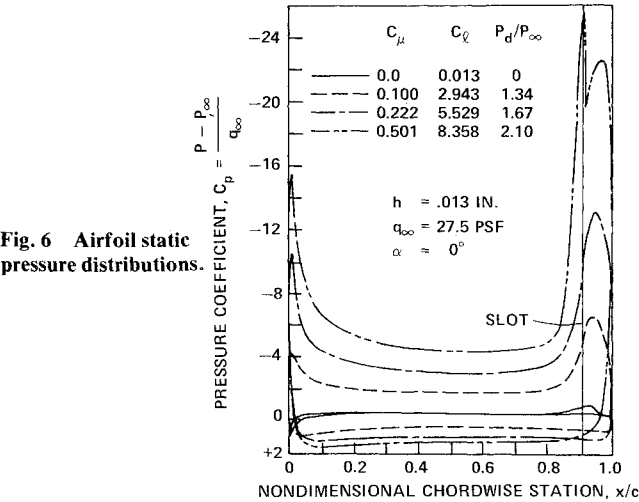


Fig. 6 Airfoil static pressure distributions.

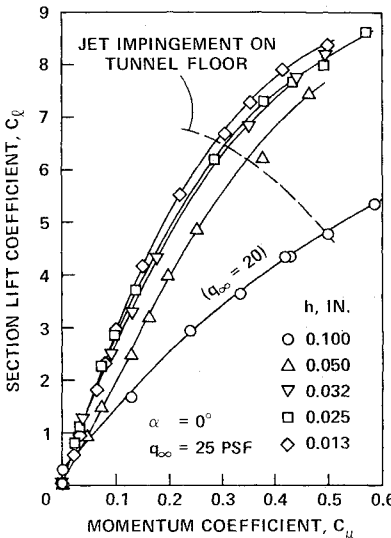


Fig. 7 Airfoil lift as a function of blowing and slot height.

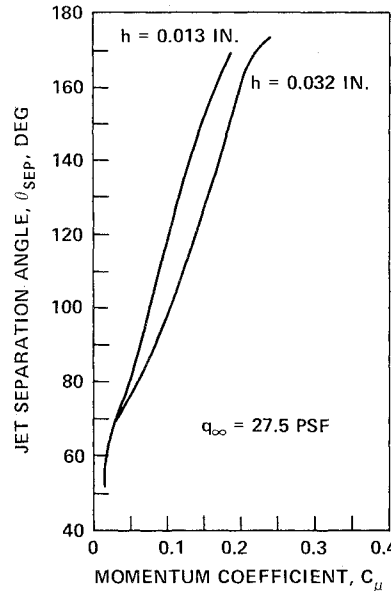


Fig. 8 Location of jet separation point.

that boundary-layer assumption in any theoretical analysis of the flow. Data taken with an external freestream differed considerably from static data; it thus appears that any attempt to predict jet-related properties of a CC airfoil from static rather than dynamic data can be very misleading. The jet detach-

ment limits predicted by static data in Ref. 7 may thus be open to question.

Figure 6 shows measured pressure distributions for $h=0.013$ -in., which gives some insight into the airfoil loading produced by blowing. This "saddle-back" shape is fairly typical of CC airfoils; at positive incidence the leading edge peak is more pronounced, while at negative incidence, the rear adverse pressure gradient is further aft and greater. Once the sonic (choked, $P_d/P_\infty = 1.89$) pressure ratio is reached, a noticeable pressure rise occurs immediately downstream of the slot, but in spite of this, jet detachment was never experienced under the conditions investigated.

Figure 7 depicts airfoil lift coefficient as a function of blowing at various slot heights. For a constant momentum coefficient, reduced h denotes reduced mass flow but increased jet velocity and kinetic energy. The result is increased circulation produced by improved jet turning and stagnation point movement. This is confirmed by Fig. 8, where the separation point of the jet on the trailing edge lower surface is located by use of the hot film probe for two different slot heights. ("Separation" denotes the point where the pressure rise in the jet eventually causes it to leave the Coanda surface some distance from the slot, whereas "detachment" is immediate separation at the slot followed by no turning). It is very interesting to note that the jet manages to turn through more than 170° from the slot, even in the face of the oncoming freestream. This location of the aft stagnation point as a function of blowing provides a very valuable input to the analytical solution of the CC airfoil in a freestream, a formidable problem due to the viscous wall jet calculation which must be tied together with a lifting airfoil solution. Knowledge of the stagnation point location allows at least a first-cut prediction of the airfoil pressure distribution by existing techniques and thus a theoretical correlation between lift and momentum coefficients.

Several of the above conclusions, especially those dealing with the jet separation point locations, are felt to be previously undemonstrated experimentally and thus represent a new and valuable contribution to the state-of-the-art. Relative to application to a STOL aircraft, the investigations showed no apparent drawbacks of high-velocity, high-pressure-ratio Coanda wall jets applied to trailing edge geometries similar to those proposed for use on a flight-worthy aircraft. With this assurance, a three-dimensional investigation was undertaken.

3-D Circulation Control Wing Investigation

Model

A 1/5-scale model of a Navy T-2C aircraft was modified so that its original 37-percent-chord single slotted flap was replaced with a Coanda trailing edge very similar to that shown in Fig. 3. The trailing edge parameters (h/R , R/c , and slot location) used in converting the NACA 64A-212 airfoil into the CC Wing configuration were identical to the previously mentioned 2-D model. In order to compare resulting blown data with the original T-2C performance and to investigate the effects of a low effective aspect ratio lifting surface, the blown flap span remained consistent with that of the original flap, 49.5% of the wing semi-span (see Fig. 9). Full rotation of the 15% chord blown flap (for which 0° , 45° , 90° , 135° , and 180° flap angle positions were available) caused a reduction in mean chord of 11.4%, or a 6% reduction in total wing area. (All coefficients will be referenced to the undeflected total model wing area of 10.2 ft.²). The wing leading edge corresponding to the flapped area was dropped 30° for control of leading edge separation. Engine inlets were faired in with smooth contours to avoid the complexity of flow-through model scaling and construction.

Tunnel Investigation and Results

The modified model was installed on the centerline of the NSRDC 8- $\times$ 10-ft North Subsonic Tunnel. Cotton tufts were

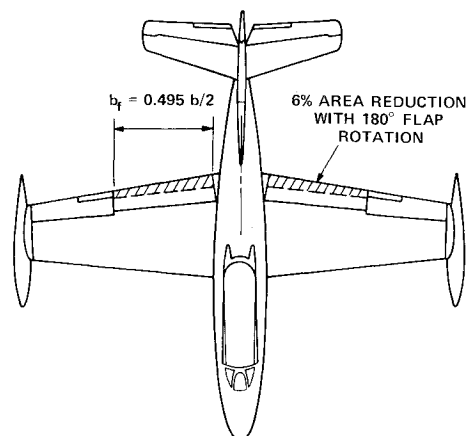


Fig. 9 Planform of the T-2C aircraft.

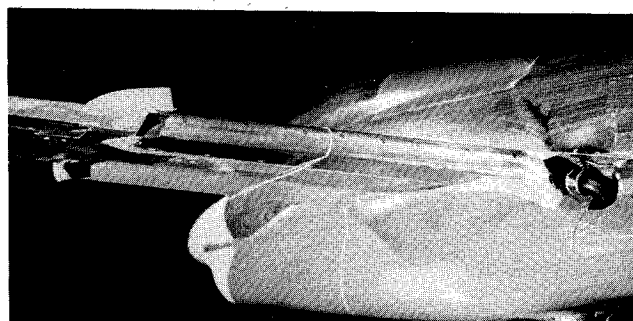


Fig. 10 Coanda jet static turning.

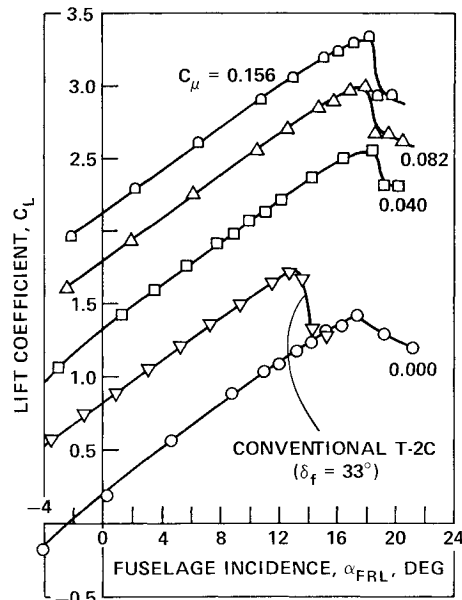
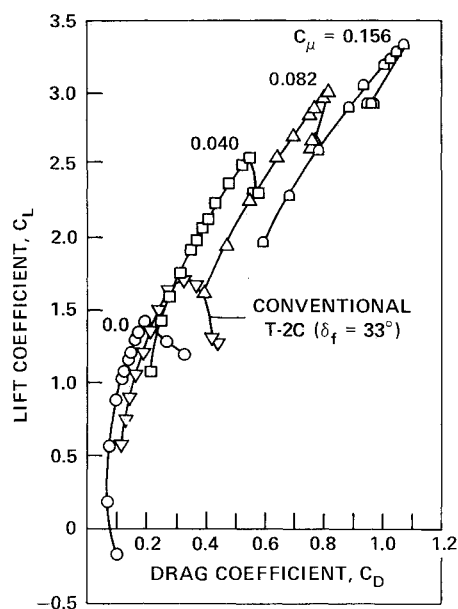
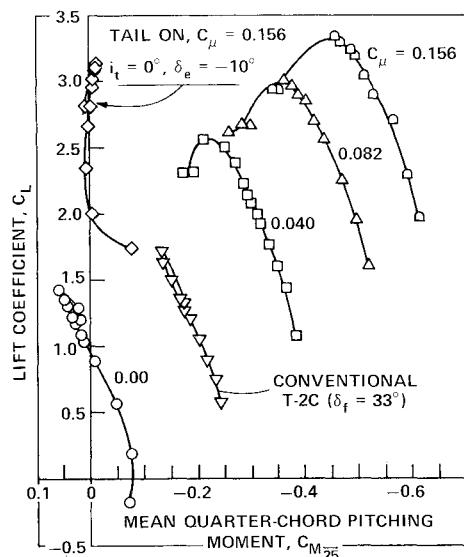
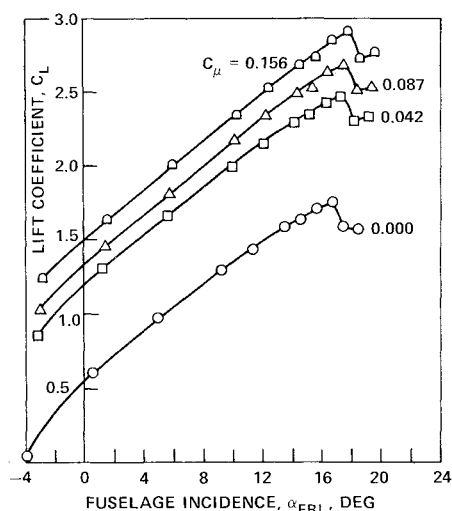
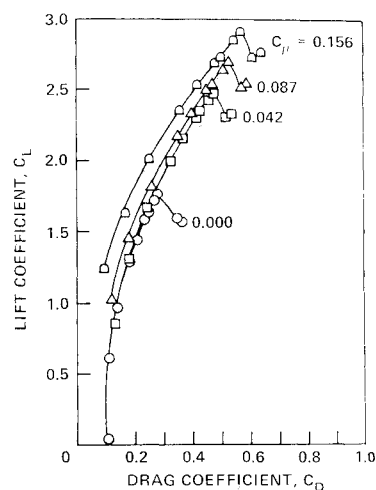
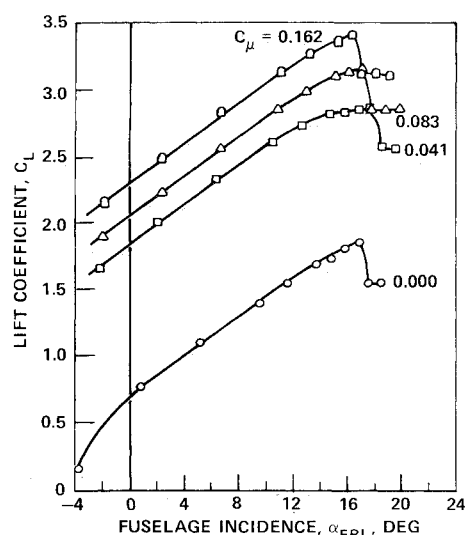


Fig. 11 Tail-off lift characteristics for the T-2C CC wing, $\delta_f = 180^\circ$.

added to the tunnel floor to denote any jet impingement; these were never seen to be disturbed by the downward jet deflection. Full 180° Coanda turning was exhibited by a tuft attached to the trailing edge (Fig. 10) in the absence of a freestream.

Preliminary runs⁹ made with the above configuration at 180° flap angle indicated that very premature stall was occurring even with minimal blowing. A series of flow visualization runs was conducted using heavily tufted areas on the wings and a neutrally buoyant helium bubble generator to identify the cause of the problem: the severe lift discontinuity between blown and unblown wing panels caused a very strong

Fig. 12 Tail-off drag polars, $\delta_f = 180^\circ$.Fig. 13 Tail-off pitching moment, $\delta_f = 180^\circ$.Fig. 14 Tail-off lift characteristics, $\delta_f = 45^\circ$.Fig. 15 Tail-off drag polars, $\delta_f = 45^\circ$.Fig. 16 Tail-off lift characteristics, $\delta_f = 90^\circ$.

vortex to be produced at that junction. This vortex, rotating in the same direction as the tip vortex but apparently much stronger, was found to be producing severe upwash angles over the outboard panel. This caused the entire outboard section to stall at a low geometric incidence; furthermore the stall propagated inboard to the blown section and severely degraded the jet-induced circulation. A temporary cure for the problem was made by adding 10° of droop to the outboard leading edge to alleviate the stall problem, and by locating flow fences (see Fig. 10) between the flapped and outboard sections to prevent the inboard spread of the stall should it occur. The immediate doubling of the stall angle and addition of 0.65 to $C_{L_{max}}$ at $C_\mu = 0.156$ showed the importance of controlling the detrimental vorticity.

Figure 11 shows the resulting lift at four blowing rates, and a comparison to the conventional T-2C (33° flap angle and no leading edge droop). The 96% increase in $C_{L_{max}}$ at $C_\mu = 0.156$ represents a reduction in stall speed from 94 to 68 knots for the 13,000 lb gross weight aircraft. Furthermore, the unblown bluff CC airfoil shows only a 20% loss in C_L relative to the conventional flapped T-2C, thus suggesting non-critical consequences in event of a complete blowing failure while in the Coanda configuration.

Drag polars in Fig. 12 show at the higher blowing rate a drag increase of 240% at $C_{L_{max}}$ over the slotted flap configuration. Although a significant portion of this is the induced drag component resulting from the higher lift, it is im-

portant to note that no thrust (negative C_D) component is being produced by the momentum efflux. The tail-off mean quarter-chord pitching moment (Fig. 13) displays rather large nose-down values at higher C_μ . These are caused by the very high trailing edge suction peaks produced by the high jet velocities (see Fig. 6). However, as the one tail-on curve shows, the aircraft can be trimmed at the highest blowing rate tested with only a 5% lift loss due to the required down-load on the tail. A series of elevator deflection runs indicated that trim could be achieved over the entire blowing range for values of δ_e between -11° and $+2^\circ$. With respect to longitudinal stability, test data shows that increased blowing tends to be stabilizing for the tail-off cases; for tail on, all C_μ values tested showed a stable configuration, although somewhat less stable for higher blowing.

Figures 14 and 15 depict lift and drag as a function of incidence at constant blowing for 45° of flap deflection, the proposed takeoff configuration. Although lift increase with blowing is less than the landing configuration, drag is seen to be reduced with C_μ , which is attributable to jet thrust from the slot. Tail off pitching moments are less negative than for the 180° flap, thus indicating no problems in trimming the aircraft on takeoff.

For comparison to the 45° and 180° cases, Fig. 16 presents lift data for the intermediate 90° flap. (The 45° and 90° cases are characteristic of the conventional blown flap or jet flap). It is seen that this data is quite similar to that of the 180° flap deflection at higher C_μ , and exceeds it at lower blowing. This is because of the increased camber due to the actual physical flap deflection without the loss of effective chord. Figure 17 compares the above lift data for all five flap angles tested, while Fig. 18 compares incremental $C_{L\max}$ due to blowing. It is seen that better lift augmentation ($\Delta C_L / C_\mu$) at a given momentum coefficient is provided by the rounded Coanda trailing edge, but that slightly greater total lift is generated by the high camber and additional effective chord of the 90° flap. In general, the lifting effectiveness of the two concepts as presented is similar, but the CC wing has the potential for increased drag due to the forward turning of the jet. It should be mentioned however, that the 90° flap produced between 14.3 and 43.3 percent increase in nose-down quarter-chord pitching moment for the same C_L and C_μ conditions as the 180° flap, this could produce a serious trim problem, depending on tail effectiveness.

It was suspected that the 135° and 180° cases were performing at somewhat less than maximum turning. This was confirmed by cotton tufts positioned at spanwise stations along the trailing edge which showed that the jet was

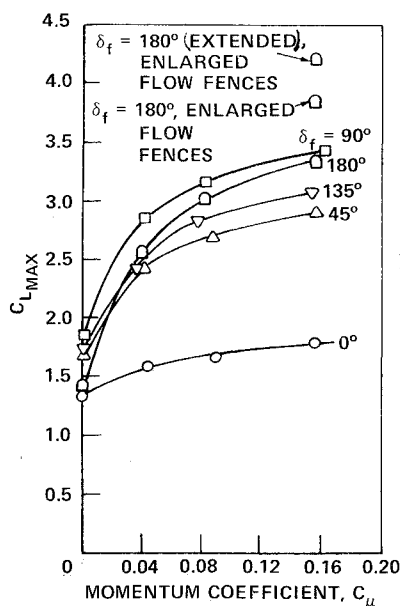


Fig. 17 Maximum lift due to blowing.

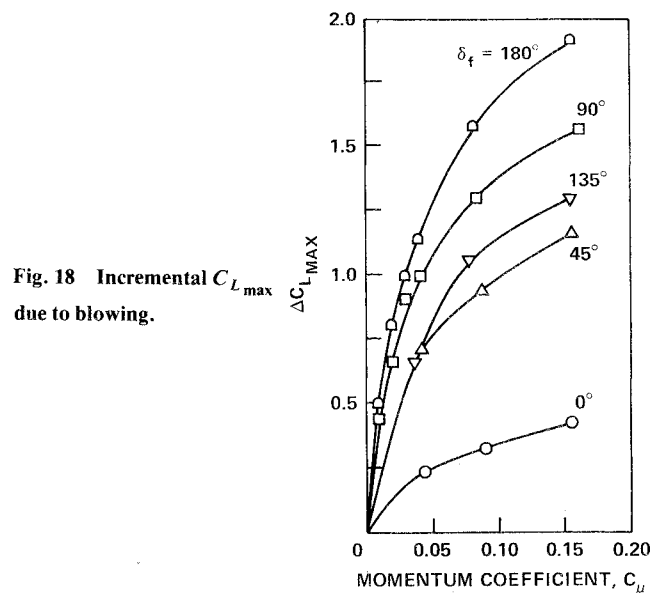


Fig. 18 Incremental $C_{L\max}$ due to blowing.

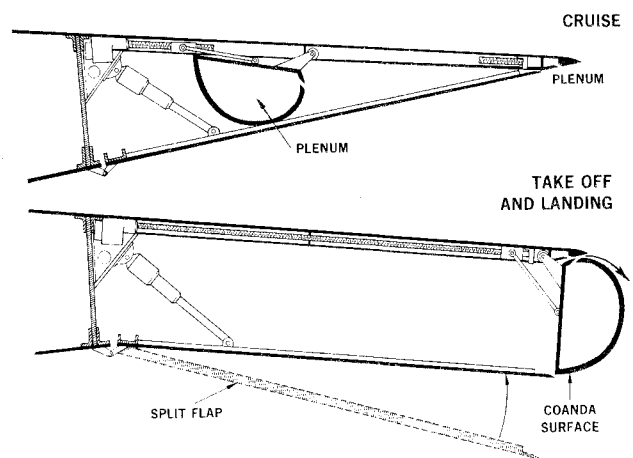


Fig. 19 Extended chord Coanda trailing edge.

separating prematurely near the inboard and outboard ends of the blown surface.

Two additional investigations showed that distinct improvements could be made in the Coanda configurations. Large flow fences placed primarily along with airfoil lower aft surface at both ends of the blown trailing edge restored Coanda turning there and resulted in an increase of 0.5 in $C_{L\max}$ at $C_\mu = 0.156$, thus altering the Fig. 17 results as shown. The problem of loss in chord due to 180° flap rotation can be solved by an extended configuration as shown in Fig. 19. Here, the Coanda surface is stored within the trailing edge and rotates aft to deploy, thus producing a slightly increased chord. For takeoff, the lower surface deflects as a split flap without blowing, or alternately, blowing may be initiated from the trailing edge as a jet flap with no mechanical deflection of any parts. Two-dimensional tests of this configuration with Coanda blowing have shown 20 to 25 percent increases in C_L over the 180° rotated flap configuration at the same incidence and C_μ . This represents roughly a 10 to 12% increase in the T-2C data, as shown in Fig. 17.

Conclusions

The results of the above two- and three-dimensional investigations have confirmed that the Circulation Control concept is indeed applicable to fixed wing aircraft of lower aspect ratio to give them appreciable STOL capability. The concept is particularly promising when the quantity of available air

for high lift application is limited. A first-cut application of the concept applied to a 1/5-scale T-2C model has shown a doubling of the aircraft's lifting capability and a 2.4 fold increase in drag with momentum coefficient of less than 0.16, and trimmed flight throughout the test range using the existing aircraft control surface deflections without modification. Furthermore, an investigation into the nature of high Coanda jet velocities at pressure ratios above choked has shown no detrimental effect on the trailing edge flowfield or the lift-producing abilities of the Circulation Control airfoil. This is of value to those aircraft of very limited auxiliary mass flows, in that the required jet momentum could be generated by increased jet velocities at the slot produced by higher pressure ratio air bleed. The kinetic energy produced by these pressure ratios apparently is favorable in increasing jet turning, but caution must be exhibited in that the limits beyond which high pressure can produce jet detachment have not been accurately defined.

The above studies did indicate that certain improvements to the concept could be made and should be further investigated. Partial span blowing was found to produce strong detrimental vorticity at the lift discontinuity, which should be reduced or eliminated by an increased blown span or properly located fences. Consideration should be given to full span blowing, with differential blowing between left and right wings to replace the mechanical ailerons and provide roll control. An extended flap configuration demonstrated significant lift gains, and warrants additional consideration and testing. Lateral characteristics need be investigated at high lift conditions to examine limits of control surface effectiveness at low dynamic pressures. And finally, if application to modern high speed aircraft is to be realized, the effects of sweep, very thin wing sections and very low aspect ratios need be considered.

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