Lift Modulation with Lateral Wing-Tip Blowing

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The utilization of a thin jet of air exiting in the spanwise direction from a slot at each of the tips of a straight wing has been investigated as a means of generating weak lift modulation. A theory showing the analytical relationship between blowing intensity and aerodynamic forces was developed and its results were compared against experiments. It was found that the lift gain due to lateral blowing depends on the ⅔ power of the jet blowing intensity.

Nomenclature

A = wing aspect ratio, as a variable
b = wing semispan, as a variable
Δb = semispan perturbation due to lateral blowing
c = wing chord
C_{Di} = induced drag coefficient
ΔC_{Di} = change in induced drag coefficient due to lateral blowing
C_P = pressure coefficient
C_L = lift coefficient
C'_L = lift slope
$\Delta C'_L$ = change in lift slope due to lateral blowing
C_l = local lift distribution
C_μ = jet momentum coefficient
e = wing efficiency factor
$f(A)$ = function in C'_L definition
$F(A)$ = function in relative lift gain expression
k, k_1, k_2 = constants of order one
q_∞ = freestream dynamic pressure
R = jet radius of curvature
U_∞ = freestream velocity
v, w = y,z velocity components
v_j = jet discharge velocity
x,y,z = reference axis coordinates (z is also the jet excursion)
α = angle of attack
γ = local circulation
δ_j = jet slot thickness
ϵ = nondimensional wing semispan perturbation due to lateral blowing
ζ = transformation variable
η = nondimensional integration variable
θ = tip jet local angle with respect to the spanwise direction
θ_0 = ejection angle of the tip jet with respect to the spanwise direction
ρ_j = jet fluid density

Subscript

0 = variables for the no-blowing case

Introduction

JETS in the form of thin sheets exiting in the spanwise direction from the tips of a straight wing, as shown in Fig. 1, can be used to modulate the aerodynamic forces acting on the wing. This modulation originates in aerodynamic interference and exists in addition to any reaction forces attributable to the momentum of the jet. This property of such an arrangement of jets suggests the possibility of using this concept in place of conventional ailerons or flaps to alter the aerodynamic forces acting on an aircraft.

This concept differs from ailerons or flaps in that no deflecting surfaces are involved and in that the additional load arising from the activation of the jets distributes itself differently on the wing.

The application of this type of blowing scheme to lift modulation was first reported by Ayers and Wilde,[1] who performed measurements on a swept wing of aspect ratio 1.39 and 50 deg sweep and observed significant gains in lift as well as a beneficial effect on stall. Carafoli[2] formulated a theory and conducted experiments with a straight wing of aspect ratio 2. He correctly observed that the underlying reason for lift gain is an effective enlargement, brought about by the jet, of the wing span. His theoretical approach was an extension of Prandtl's lifting line theory and succeeded in representing fairly well the experimentally observed trends for moderate blowing intensities, but failed to establish analytical relationships between the wing, jet parameters, and the loads caused by blowing.

Later, Carafoli and Camarasescu[3] reported measurements on small-aspect-ratio wings, observing that lift augmentation is more intense for smaller aspect ratios, further suggesting that the basic mechanism for lift increment is an effective enlargement of the wing span. Further experimental work on lateral blowing was reported by White,[4] who noticed some beneficial effects on drag under certain conditions. Briggs and Schwind[5] considered the lateral blowing concept as a lift augmentation device for STOL aircraft. Their experiments suggest that a new gain in STOL capabilities is possible. Childs[6] conducted a preliminary numerical study of this concept by solving the three-dimensional Navier-Stokes equation by finite differences. Wu et al.[7-9] looked at a tip blowing arrangement with several thin jets exiting from the wing tips from slots whose length was a fraction of the wing chord. Although this arrangement was not meant to extend the effective wing span, it exhibited some similarities to the winglet concept.

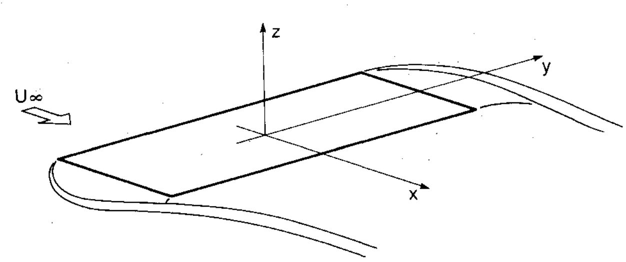

Fig. 1 Lateral wing tip blowing concept.

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A study of the vortex structure of the flowfield associated with the type of tip blowing considered here has been reported by Lee et al.[10] These studies indicated that, for a tip jet whose chord is comparable to the wing chord, the wing tip vortex will usually engulf the vortices produced by the jet in crossflow, with the result that in most cases only one vortex is found downstream of the wing tip. In contrast, in the case of tip blowing with discrete jets, the work of Wu et al. suggests that the complex vortex structure of a nonsymmetric jet in crossflow[11] is preserved.

In this work, the derivation of analytical relationships relating aerodynamic forces to jet and wing parameters for low-to-moderate blowing intensity was emphasized. The study was done both theoretically and experimentally. On the theoretical side, the analysis exploited the low blowing intensity in a perturbation sense, allowing for the derivation of scaling laws. The experimental study was done on a rectangular wing whose aspect ratio could be varied between 3.14 and 0.4, obtaining aerodynamic loads over a wide range of wing and jet parameters. A comparison was then made between theoretical and experimental results. Further details of the experimental study have been reported elsewhere.[12,13]

As originally pointed out by Carafoli,[2] in the case of a tip jet whose chord is comparable to the wing chord, the effect of lateral blowing on a straight wing can be visualized by thinking of the lateral jet as a fluid extension of the wing itself. Although the precise way in which this fluid extension affects the aerodynamics of the wing is one of great complexity, the phenomenon can be characterized by three main facts: the outward displacement of the tip vortices by the jet, the rolling up of the jet sheet, and the turbulent entrainment into the jet. The outward displacement of the tip vortices taken in isolation would cause the wing to react as if it had undergone an increment of its span. The jet roll-up is caused by the pressure difference between the upper and lower surfaces of the jet. The rolled-up jet eventually coalesces with the tip vortex. Viscous entrainment into the jet affects the pressure distribution on the wing surface and contributes to the complexity of the roll-up process. In the theoretical part of this work, symmetrical blowing from both wing tips was considered, which could be experimentally simulated using a half-span wing model. Differential blowing would produce rolling moments.[14]

Theoretical Approach

The theoretical analysis is based on three main assumptions:

1) The most important effect of weak lateral blowing is to produce an outward displacement of the tip vortices, the equivalent to an effective enlargement of the wing aspect ratio.

2) The change in aspect ratio is regarded as an inviscid phenomenon. In other words, the effect of entrainment on the penetration of the jet into the freestream is neglected.

3) The jet penetration is dominated by its momentum flux. This assumption allows for the idealization of the jet as an infinitely thin sheet, with no mass of its own, but with finite momentum.

Under these assumptions, a closed-form analysis is possible, the validity of which is corroborated by experiments.

Span Perturbation Concept

The effect of blowing in altering the wing span is computed by perturbing the wing span by a small amount, dependent on jet parameters and angle of attack. It is assumed that the wing is rectangular, that the tip slot extends over the entire chord, and that it is aligned with the zero-lift direction of the wing chord. The load of the wing is assumed to be locally elliptical near the tip, both before and faster blowing. The lift produced by the wing with perturbed span is

$$C_L = (C'_{L0} + \Delta C'_L)\alpha \tag{1}$$

The lift slope is expressed as

$$C'_L = 2\pi f(A) \tag{2}$$

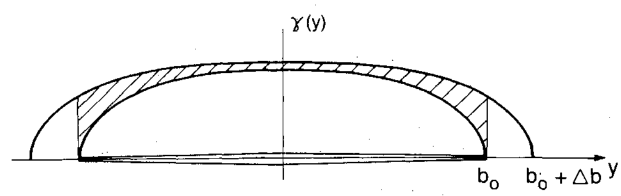

Fig. 2 Span perturbation.

The increment of lift slope must be referred to the aspect ratio of the unperturbed wing. Defining the relative semispan change as

$$\epsilon = \Delta b / b_0 \tag{3}$$

it results

$$\Delta C'_L = 2\pi\{f[A_0(1+\epsilon)](1+\epsilon) - f(A_0)\} \tag{4}$$

Expanding in series

$$\frac{\Delta C'_L}{C'_{L0}} = \left[1 + A_0\frac{\dot{f}(A_0)}{f(A_0)}\right]\epsilon + \mathcal{O}(\epsilon^2) \tag{5}$$

where $\dot{f}(A_0)$ represents $\mathrm{d}f/\mathrm{d}A$ evaluated at A_0. Equation (5) also includes the lift acting on the fluid extension of the wing. That part of the lift does not contribute to lift augmentation, since it is supported by the jet itself. However, to first order in ϵ, the lift given by Eq. (5) is the same as the lift acting on the solid part of the wing. To prove this, compare two wings of equal chord, set to the same angle of attack, with self-similar loading, with spans b_0 and $b_0 + \Delta b$, and circulation $\gamma(\eta)$ and $(1 + a\epsilon)\gamma(\eta)$ each, as shown in Fig. 2. The lift increment represented by the shaded region is

$$\Delta C_L \propto \int_{-b_0}^{b_0} \left\{(1+a\epsilon)\gamma\left[\frac{y}{b_0(1+\epsilon)}\right] - \gamma\left(\frac{y}{b_0}\right)\right\}\frac{\mathrm{d}y}{b_0} \tag{6}$$

Expanding the argument of the first term in the integrand in series,

$$\Delta C_L \propto -\epsilon\int_{-1}^{1} \dot{\gamma}(\eta)\eta\,\mathrm{d}\eta + a\epsilon\int_{-1}^{1}\gamma(\eta)\,\mathrm{d}\eta + \mathcal{O}(\epsilon^2) \tag{7}$$

Integrating the first term by parts

$$\frac{\Delta C_L}{C_{L0}} = (1+a)\epsilon + \mathcal{O}(\epsilon^2) \tag{8}$$

Setting $a = A_0\dot{f}(A_0)/f(A_0)$, Eq. (8) indicates that the lift supported by the fluid extension of the wing is of order ϵ^2.

The effect of blowing on induced drag can be estimated in the same manner. Calling e the wing efficiency factor, the induced drag is given by

$$C_{Di} = C_L^2/\pi e A \tag{9}$$

A change in induced drag has then the form

$$\Delta C_{Di} = \frac{\{C_L[A_0(1+\epsilon)]\}^2}{\pi e A_0(1+\epsilon)}(1+\epsilon) - \frac{C_L^2(A_0)}{\pi e A_0} \tag{10}$$

In Eq. (10), the lift coefficient is expressed as a function of aspect ratio. Expanding for small ϵ,

$$\frac{\Delta C_{Di}}{C_{Di0}} = 2A_0\frac{\dot{f}(A_0)}{f(A_0)}\epsilon + \mathcal{O}(\epsilon^2) \tag{11}$$

As was the case with the lift, this expression contains the induced drag acting on the fluid extension of the wing. In a

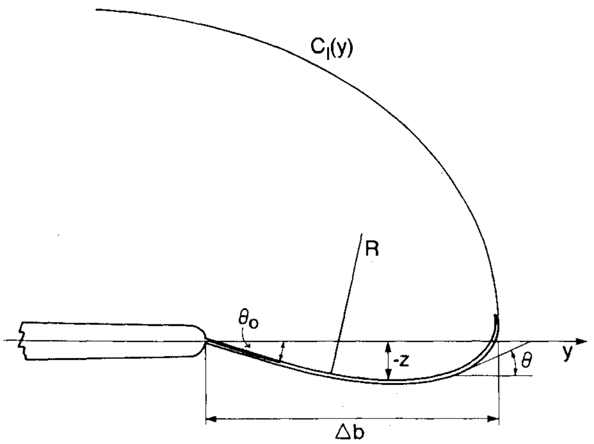

Fig. 3 Tip jet parameters.

similar manner, it is possible to prove that the drag acting on the fluid extension is of order ϵ^2. With the circulation distributions shown in Fig. 2, the induced drag increment is

$$\Delta C_{Di} \propto \int_{-b_0}^{b_0} \left\{ (1+a\epsilon)^2 \gamma \left[\frac{y}{b_0(1+\epsilon)} \right] \frac{\gamma(0)}{A_0(1+\epsilon)} - \gamma\left(\frac{y}{b_0}\right) \frac{\gamma(0)}{A_0} \right\} \frac{dy}{b_0} \tag{12}$$

Expanding the circulation for the perturbed span case and integrating by parts as before

$$\frac{\Delta C_{Di}}{C_{Di0}} = 2a\epsilon + \mathcal{O}(\epsilon^2) \tag{13}$$

This equation indicates that the contribution to induced drag by the fluid portion of the wing is of order ϵ^2.

Scaling Laws

To compute the relative change of span due to blowing the jet is idealized as an infinitely thin sheet containing finite momentum, subjected to the load represented by the unshaded area in Fig. 2. Under the effect of this load the jet sheet curls upward. This load is a function of the chordwise coordinate, causing the jet to curl up sooner near the leading edge of the wing. Δb is identified with the characteristic length that the jet penetrates into the freesteam. The jet is supposed to curl up under the effect of a chordwise average of the local lift load.

Under these assumptions, the balance of pressure and centrifugal force on a thin inviscid jet sheet, as illustrated in Fig. 3, is expressed by

$$\frac{1}{R(y)} = \frac{C_l(y)}{C_\mu} A_0 \tag{14}$$

where R is the local radius of curvature and C_l the local lift coefficient. The jet momentum coefficient is defined as

$$C_\mu = \frac{\rho_j v_j^2 \delta_j}{q_\infty c} \tag{15}$$

In differential form, Eq. (14) is

$$\frac{d^2 z}{dy^2} = \left[1 + \left(\frac{dz}{dy} \right)^2 \right]^{3/2} \frac{C_l(y)}{C_\mu} A_0 \tag{16}$$

With the transformation $\sinh\zeta = dz/dy$, this equation becomes

$$\frac{d\zeta}{dy} = \cosh^2\zeta \frac{C_l}{C_\mu} A_0 \tag{17}$$

which can be integrated to give

$$\frac{\dot{z}}{\sqrt{1+\dot{z}^2}} = A_0 \int_{b_0}^{y} \frac{C_l(\eta)}{C_\mu} d\eta + \left. \frac{\dot{z}}{\sqrt{1+\dot{z}^2}} \right|_{y=b_0} \tag{18}$$

where $\dot{z} = dz/dy$. Introducing the jet slope $\tan\theta = dz/dy$, Eq. (18) becomes

$$\sin\theta = A_0 \int_{b_0}^{y} \frac{C_l(\eta)}{C_\mu} d\eta + \sin\theta_0 \tag{19}$$

A characteristic length ratio for the jet curl-up position is obtained by setting $\theta = \pi/2$, corresponding to a jet orientation perpendicular to the wing plane. This leads to the following integral expression for ϵ:

$$\int_1^{1+\epsilon} C_l(\eta) d\eta = \frac{C_\mu}{A_0 b_0} (1 - \sin\theta_0) \tag{20}$$

where θ_0 is the angle of the jet with the spanwise direction at exit. To solve this equation, it is assumed that the lift distribution near the wing tip has the form

$$\frac{C_l^2}{C_{l0}^2} + \frac{y^2}{b_0^2(1+\epsilon)^2} = 1 \tag{21}$$

which can be expanded as

$$C_l(y) = \sqrt{2} C_{l0} \sqrt{1 + \epsilon - \frac{y}{b_0}} + \mathcal{O}(\epsilon^2) \tag{22}$$

Substituting this expression in Eq. (20) and multiplying the result by a constant k_1 of order one to account for the approximate nature of the analysis, the effective relative enlargement of the span is

$$\epsilon = k_1 \frac{3^{2/3}}{2} \left[\frac{C_\mu [1 - \sin(\theta_0)]}{C_{l_0} b_0 A_0} \right]^{2/3} \tag{23}$$

Introducing the following relationship, valid in the linear range, with k_2 a constant of order one,

$$C_{l0} = k_2 2\pi \frac{f(A_0)\alpha}{b_0} + \mathcal{O}(\epsilon) \tag{24}$$

the following expression, valid for $\epsilon \to 0$, is obtained:

$$\epsilon = k \left[\frac{C_\mu [1 - \sin(\theta_0)]}{2\pi f(A_0) A_0 \alpha} \right]^{2/3} \tag{25}$$

where k is a constant of order one. Only the case of blowing tangentially to the span, where $\theta_0 = 0$, will be considered. In this case, Eq. (5) gives

$$\frac{\Delta C_L}{C_{L0}} = k F(A_0) \left[\frac{C\mu}{\alpha} \right]^{2/3} \tag{26}$$

here $F(A_0)$ is a universal function of aspect ratio given by

$$F(A) = \left[1 + A \frac{\dot{f}(A)}{f(A)} \right] \left[\frac{1}{2\pi f(A) A} \right]^{2/3} \tag{27}$$

Equation (26) establishes the scaling law relating lift increment to blowing intensity and angle of attack. It also becomes clear that it is impossible to linearize the lift gain about weak blowing or small angle of attack.

The dependence on aspect ratio is much more complex and can be known only approximately for an arbitrary aspect ratio. However, for very small and very large aspect ratios, simplifications leading to power laws are possible.

In the limit of infinitely small aspect ratio,

$$\lim_{A\to 0} f(A) = \frac{A}{4} \tag{28}$$

leads to

$$\lim_{A\to 0} \Delta C_L \propto C_\mu^{2/3}\left(\frac{\alpha}{A}\right)^{1/3} \tag{29}$$

For the case of very large aspect ratio,

$$\lim_{A\to\infty} f(A) = 1 - \frac{2}{A} \tag{30}$$

gives

$$\lim_{A\to\infty} \Delta C_L \propto \left(\frac{C_\mu}{A}\right)^{2/3}\alpha^{1/3} \tag{31}$$

To find an expression for $F(A)$ for an arbitrary aspect ratio, a formula for the lift slope valid for any aspect ratio is required. Such a formula has been obtained by Germain[15]

$$f(A) = \left[1 + \frac{2}{A} + \frac{16}{(\pi A)^2}\log(1 + \pi e^{-9/8}A)\right]^{-1} \tag{32}$$

Experimental Investigation

Apparatus and Techniques

The low-speed wind tunnel, with a 45.7×45.7 cm test section, is a continuous operation, closed-loop facility driven by a varible-pitch fan. Pitch control is achieved by remote adjustment of the blade pitch. A maximum centerline freestream speed of 57 m/s is obtainable. Calibration and setting of the tunnel was done by observation of a reference pressure difference across the constraction, the two reference locations being sufficiently removed from the test section to avoid model interference.

The requirements for the model were symmetry about the chordline, simplicity of construction, modest aspect ratio, and minimum jet interference with the wind-tunnel walls. An NACA 0018 airfoil section with a chord of 15 cm and a span, not including the tip piece, of 22.6 cm was selected. The basic aspect ratio of the wing model was 3.14. This thick section was chosen to facilitate the incorporation of both a plenum duct and a large number of pressure tappings. Initial scalings of the mass flow requirements and expected translations of the tip vortex suggested that a slot height of 0.16 cm would be suitable. The slot was positioned in the plane of symmetry, extended over 73.3% of the chord and oriented such that the jet exited in the spanwise direction. The tip shape was given by a diameter distribution equal to the wing thickness distribution. The resulting planform and overall dimensions are shown in Fig. 4. The model was mounted on a 20.3 cm diam disk flush inserted into the tunnel floor that could be rotated to provide incidence adjustment. A circular splitter plate that could slide along the span of the model enabled simulation of various aspect ratios.

A total of 192 surface pressure tappings, divided equally between 8 spanwise stations, were installed in the model. At each station, the pressure tappings were divided equally between the upper and lower surfaces. An additional tapping was provided in the plenum to assess blowing pressure.

A high pressure air supply capable of providing a maximum 0.25 kg/s of mass flow was used for the tip jet blowing. The mass flow was measured using a Venturi-type mass flow meter and correlated with estimates from measurements of the internal duct pressure.

Data Acquisition

The 192 pressure tappings in the wing were connected to a 4 barrel "J" series Scanivalve module with 48 ports per barrel. The Scanivalve was automatically stepped and the data acquired by a PDP 11/23 minicomputer, enabling a full spanwise load distribution to be recorded by a single pass of the Scanivalve. Each individual Scanivalve pressure was obtained as the average of 30 samples at a frequency of approximately 1 kHz. The data were reduced to pressure coefficients, sectional lift coefficients, and overall load coefficients. An experimental accuracy of ±4% is suggested for the force coefficients. This tolerance accounts for inaccuracies in the transducer calibration, the setting of the freestream dynamic pressure, and the accuracy of the digital data aquisition system.

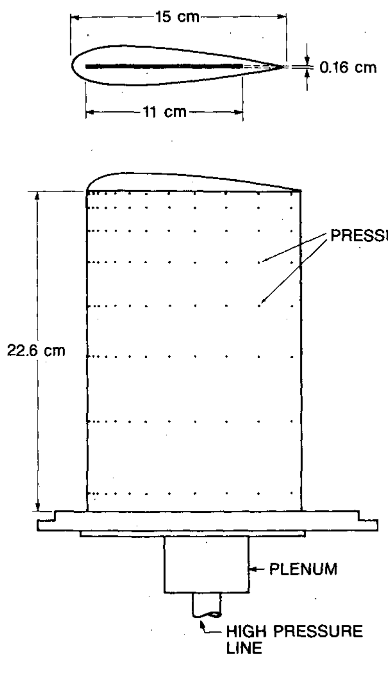

Fig. 4 Wind-tunnel model.

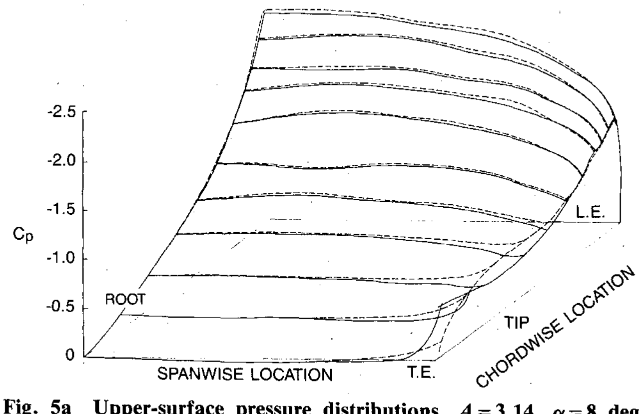

Fig. 5a Upper-surface pressure distributions, $A = 3.14$, $\alpha = 8$ deg (—$C_\mu = 0.0$, ----$C_\mu = 0.1$).

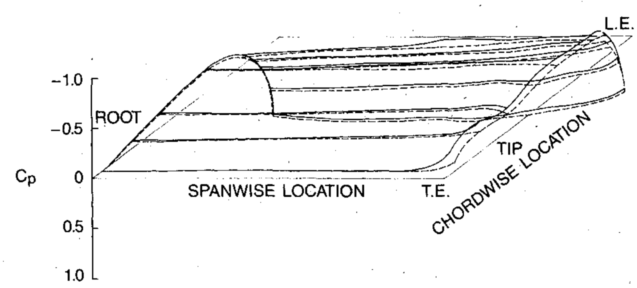

Fig. 5b Lower-surface pressure distributions, $A = 3.14$, $\alpha = 8$ deg (—$C_\mu = 0.0$, ----$C_\mu = 0.1$).

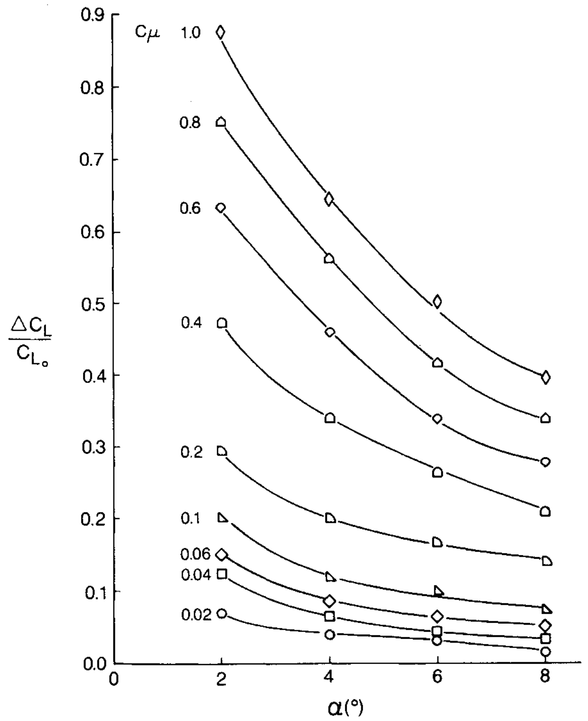

Fig. 6 Relative lift increment, $A = 3.14$.

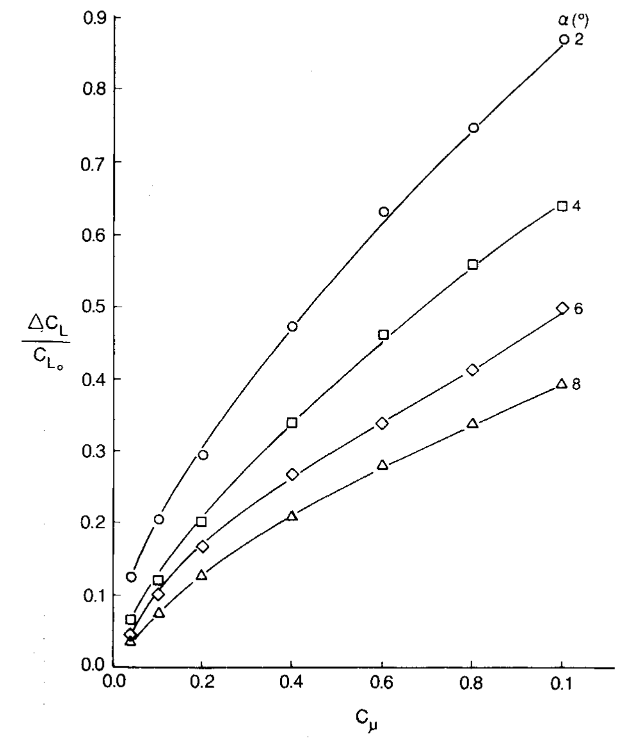

Fig. 7 Relative lift increment, $A = 3.14$.

Results and Discussion

The mechanism that brings about the lift augmentation is visualized in Fig. 5, showing pressure distributions on the upper and lower surfaces of the wing. The effect of blowing is reflected in a displacement of the surface representing the pressure distributions. Near the wing tip, there is a more pronounced distortion of the pressure pattern, indicating a more intense and localized change of load. The global displacement of the pressure plot is consistent with an effective enlargement of the span, the main assumption of the theoretical development. Such enlargement causes the tip vortices to move outward, decreasing the induced angle of attack and consequently

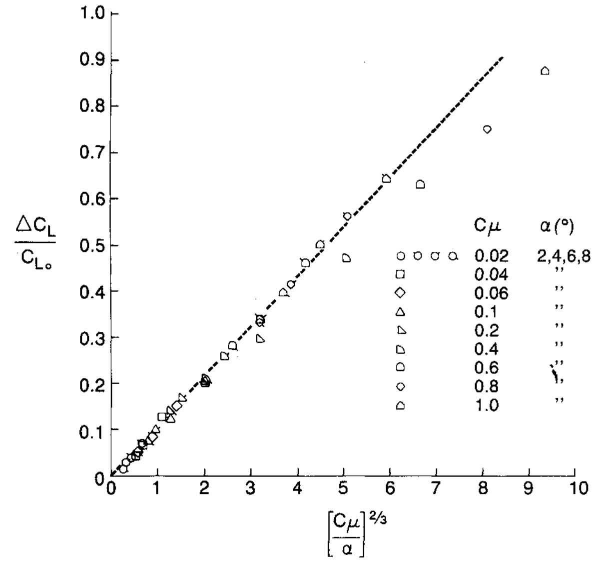

Fig. 8 Collapse of measured data points, $A = 3.14$.

increasing the load along the span. Near the tip, three regions can be distinguished. Close to the leading edge, suction is slightly decreased. This is probably due to the effective contouring imposed by the jet on the wing planform. A larger portion of the region near the tip is subjected to a significant increase in suction. This added suction denotes an acceleration of the fluid due to viscous entrainment into the jet and to the velocity induced by the rolled-up vortices, indicating the presence of both viscous and inviscid mechanisms. The decreased suction in the small region near the trailing edge is probably due to the removal, by blowing, of the tip vortex that had established itself above that area before blowing was applied.

Examination of the load distribution on the lower surface shows that there is a more pronounced increase in pressure near the tip. Since viscous entrainment into the jet is also expected to be present on its lower surface and would tend to accelerate the flow, the observed deceleration suggests that the inviscid effect of span increase is more important than the effect of viscous entrainment for a symmetrical slot arrangement. The main source of lift is the redistribution of downwash along the span, causing a change in the induced angle of attack. With regard to the effect of aerodynamic twist imparted to the wing by the curled-up jet, it appears to be localized near the tip and of minor importance relative to the total lift coefficient.

The relative lift increment is shown in Figs. 6 and 7. Figure 6 shows that the efficiency of this concept is greater for smaller angles of attack, as indicated by Eq. (26), while Fig. 7 clearly shows the nonlinear character of the lift increment as a function of the blowing intensity. Figure 8 shows the expected collapse of the experimental data points when plotted against $(C_\mu/\alpha)^{2/3}$, as suggested by Eq. (26). The only data points that fail to collapse are the ones for $\alpha = 2$ deg. In these cases, the wing tip vortex is unable to engulf completely the crossflow-type vortices that the jet produces, with more than one vortex being observed downstream of the wing tip.[10] The experimental points in Fig. 9 were obtained from the interpolated curves presented in Ref. 3.

Measurements for different aspect ratios are presented in Fig. 10. The collapse occurs below the theoretical curve, probably due to inaccuracies in aspect ratio setting and lift evaluation. In addition, the assumption of the theoretical analysis that the effective perturbation of the span should be small is more easily violated at small aspect ratios. Nevertheless, the experimental results confirm the increased efficiency for small aspect ratio, as indicated by Eq. (29).

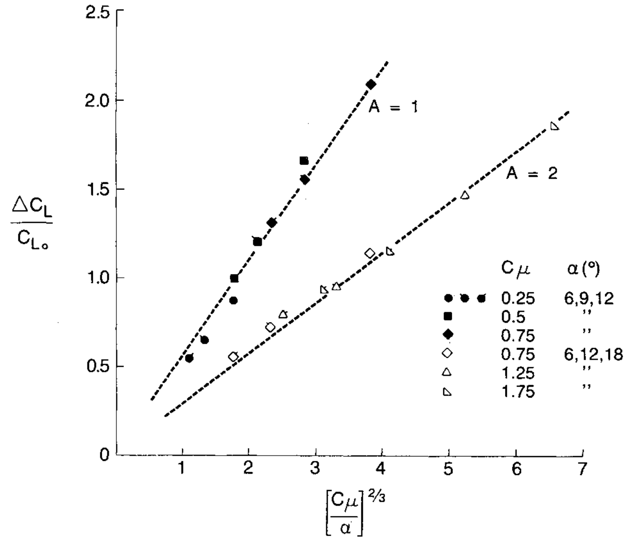

Fig. 9 Collapse of measured data from Ref. 3.

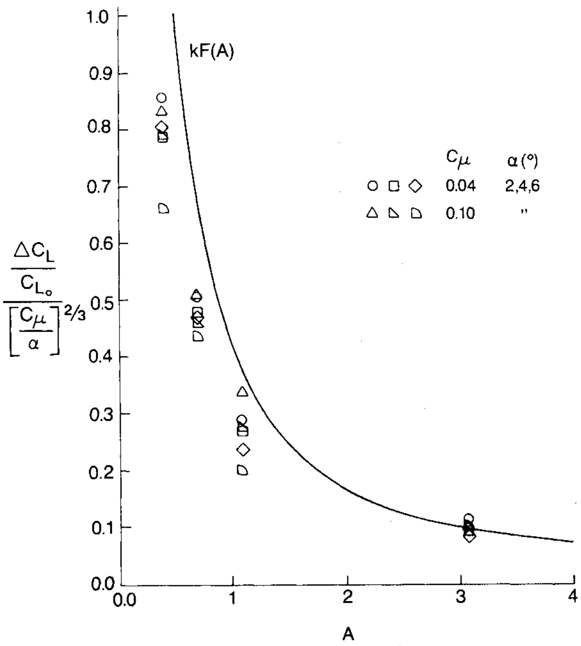

Fig. 10 Effect of aspect ratio, comparison between theory [Eq. (29) with $k = 0.3$] and experiment.

Conclusions

The problem of lateral tip blowing from a slot extending all along the chord of a rectangular wing has been studied theoretically and experimentally. A theory was developed that provides scaling laws relating wing and jet parameters. The basis for the theory is the assumption that lateral blowing displaces the tip vortices outward, thereby bringing about an enlargement of the wing aspect ratio and a decrement of downwash along the span. Measurements for a symmetrically located slot confirm the findings of the theory.

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