Circulation Control Wing Model Study

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Nomenclature

C_L = wing lift coefficient, $L/q_\infty S$
C_l = lift coefficient of an airfoil, $L'/q_\infty c$
C_M = wing pitching-moment coefficient, leading edge
C_p = pressure coefficient, $(p - p_\infty)/q_\infty$
C_μ = momentum coefficient, $\dot{m}v/q_\infty S$
c = wing chord, ft
L = wing lift, lbf
L' = lift per unit span, lbf/ft
$\dot{m}$ = jet mass flow rate, lbm/s
p = pressure, psia
q_∞ = freestream dynamic pressure, $\rho_\infty V_\infty^2/2$, psi
S = wing planform area, ft^2
V_∞ = freestream velocity, fps
v = jet velocity, fps
α = angle of attack, deg
ρ_∞ = freestream density, lbm/ft^3

Introduction

BLOWING and attachment of a jet of air over the blunt trailing edge of an airfoil or wing increases circulation and, consequently, lift.[1-6] Although some scale model and flight tests have been conducted,[3-5] many of the circulation control studies have been concerned with two-dimensional configurations. The purpose of this study was to sting-mount and test a circulation control wing model of low aspect ratio (large three-dimensional effects) in the Air Force Institute of Technology 5-ft-diam, low-speed wind tunnel. The sting was positioned parallel to the wing chord as shown in Fig. 1. The wing model was attached to the sting through a 0.5-in-diam, six-component strain gauge force balance. Only normal and axial forces were measured.

Wing Model

The wing model had a 20%-thick, 8.5%-cambered, elliptical section (Fig. 1). The wing planform was rectangular with a nominal 10 in. chord and 23 in. span to give an aspect ratio of 2.3. The wingtips were rounded end caps that blended into the upper and lower surfaces and the leading and trailing edges. No fences or end plates were used. The blowing slot was located at approximately 95% chord, and the blunt trailing edge (Coanda surface) was machined to a 0.56 in. radius. The slot height was nominally 0.015 in., and the slot span was nominally 20 in. due to the sting at midspan and slotless end caps. The slot design was not optimized. Adjustment screws were used at six spanwise locations to maintain slot height under pressurized conditions and to improve the uniformity of the slot exit velocity.

Air for slot blowing was introduced into the model plenum from a compressor through a ¾-in.-i.d. air inlet tube aligned along the chord at midspan under the wing. An aerodynamic fairing surrounded the air inlet tube. The air then flowed through a 1-in. section of ¼-in. honeycomb before exiting at the slot.

There were 56 pressure taps around the wing model. 32 were 6 in. from the left wingtip, 12 were 10 in. from the left wingtip, and 12 were 6 in. from the right wingtip. Tubes (⅛ in. diam) were attached to the pressure taps and routed out of the model at the trailing edge at center span along the sting.

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Data Acquisition and Data Reduction

Data acquisition and testing were controlled with a computer and system software, which included routines for all calibrations, measurements, and data reduction. Force and moment data were input from the force balance while wing model surface pressure and plenum pressure measurements were input from two electronically scanned pressure modules with quartz transducers that were connected to the pressure tap tubes.

Forces and pressures were automatically reduced and reported in terms of C_L, C_M, and C_p. C_μ was used to represent the amount of jet blowing. The jet exit velocity was calculated assuming isentropic expansion from plenum pressure to freestream static pressure.

Calibrations and Preliminary Tests

Calibration loads applied to the sting balance were within 2% of the measured forces. Model weight tares obtained with the tunnel off were stored in the computer and used in data reduction. The jet exit spanwise velocity distribution was obtained outside the tunnel with a total pressure probe that was traversed along the slot. An example is shown in Fig. 2. The

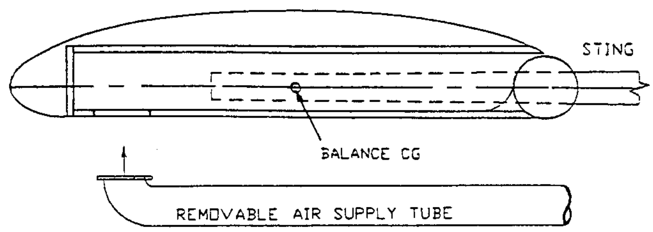

Fig. 1 Wing section and sting orientation.

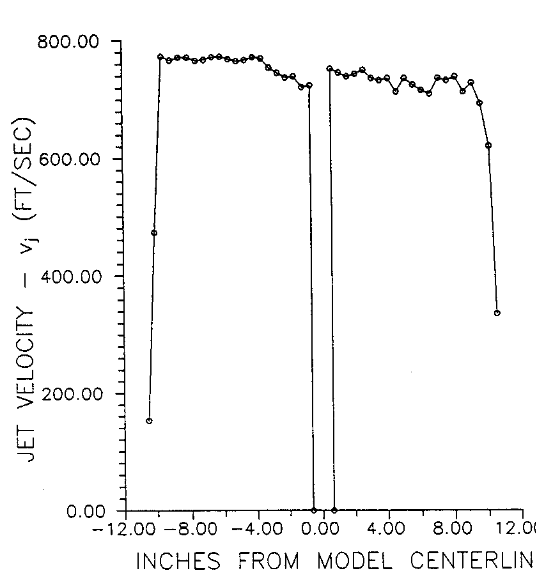

Fig. 2 Slot velocity profile along span.

blowing airjet provides thrust in the axial direction and added lift in the vertical direction. Although the effects were relatively small, the lift results are reported without this lift contribution. Overall corrections for the effects of sting bending, air supply hose, and blowing were less than 10 and 3% to the measured values of C_L and C_M, respectively. Wind-tunnel corrections, although small, were also made for buoyancy, solid blockage, wake blockage, and induced drag.[7]

Results and Discussion

Tests were conducted at a Reynolds number of 9×10^5 and a freestream nominal velocity of 180 ft/s. The angle of attack was varied from −6 to +6 deg in 2 deg increments, and at each angle of attack, slot blowing (C_μ) was varied from zero to maximum.

Tuft studies with the tunnel operating showed no significant spanwise flow in the jet sheet and attachment of the jet up to 90 deg around the blunt trailing edge (measured from the vertical). Pressure data supported the tuft findings of jet attachment and indicated an adverse pressure gradient beyond 90 deg. When the tunnel was not operating the jet remained attached up to at least 135 deg around the trailing edge.

The effects of blowing and angle of attack on C_L are shown in Fig. 3. Generally, C_L increased as C_μ and α were increased. From this data, $\partial C_L/\partial\alpha$ is about 0.05/deg at $C_\mu = 0$, which seems reasonable since the value for elliptical wing planforms with an aspect ratio of 2.3 is typically about 0.059/deg. Improved predictions at this low aspect ratio are 0.048/deg for elliptical planforms,[8] and approximately 0.046/deg for rectangular planforms. Adjusting this last value for 20% thickness increases the predicted slope to approximately 0.055/deg, or slightly higher than the measured slope. Thin airfoil theory predicts a slope of about 0.11/deg, or about 0.13/deg including the effect of thickness.[8] Thus, on the basis of aspect ratio, the measured $\partial C_L/\partial\alpha$ is about $2\frac{1}{2}$ times lower than that of an airfoil.

The rate of change of lift with blowing, $\partial C_L/\partial C_\mu$, at any C_μ did not seem to change much with α, but decreased as C_μ was increased. The trends of the curves are somewhat similar to those found with two-dimensional configurations, but values of the wing C_L are three or more times lower than the values of C_l found in two-dimensional studies[1-3,6] at similar values of α and C_μ.

There are possibly several reasons for this. The wing design with the low aspect ratio and no fences or end plates is a primary factor. Englar[2] has shown that the use of flow fences reduces the tip losses, but this may not always be practical. The nonoptimized slot design probably contributed to reduced jet attachment, and also an additional 2 in. of the 20-in. slot span was not fully effective. The sting also disrupted the Coanda jet flow to some degree. Another factor for reduced C_L was the suction peak on the lower surface near the leading edge as shown in the C_p distributions in Figs. 4 and 5. Redesign of the leading edge to reduce this suction peak on the lower surface would improve the lift performance of the wing. At higher rates ($C_\mu = 0.117$) a suction peak also occurred at the trailing edge as shown in Fig. 5. While the reduced blowing effects are not as fully justified as the reduced $\partial C_L/\partial\alpha$ effects due to aspect ratio, it is clear that the wing and slot design and three-dimensional effects are significant factors.

Pitching moment results (about the leading edge) are shown in Fig. 6. As expected, C_M becomes more negative as blowing and angle of attack are increased. These negative pitching

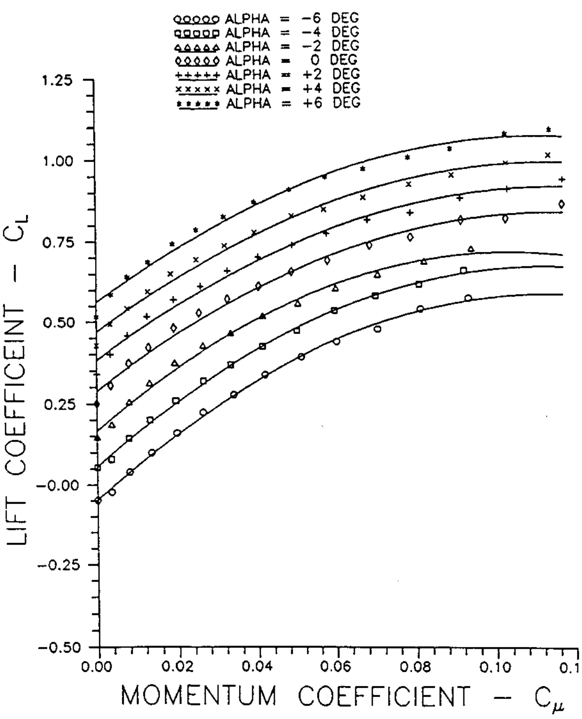

Fig. 3 Effect of blowing and angle of attack on lift coefficient.

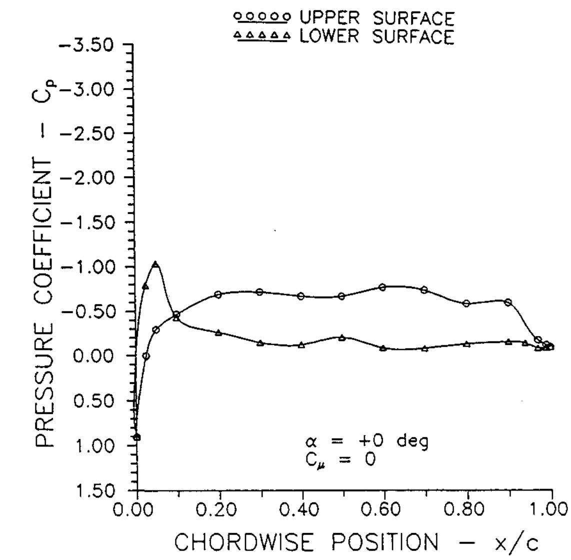

Fig. 4 Pressure distribution along chord, $C_\mu = 0$, $\alpha = 0$ deg.

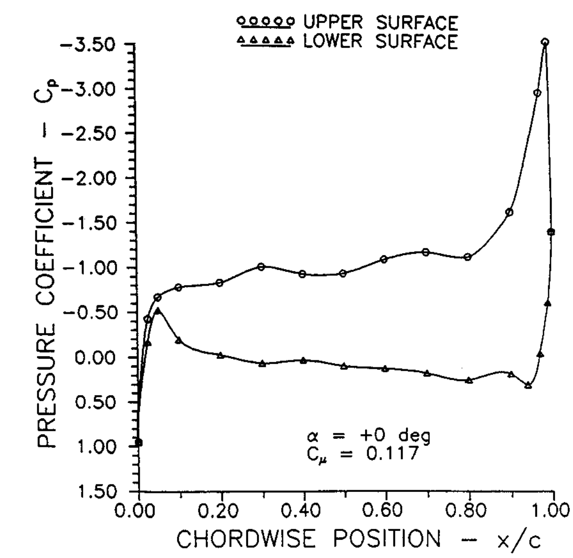

Fig. 5 Pressure distribution along chord, $C_\mu = 0.117$, $\alpha = 0$ deg.

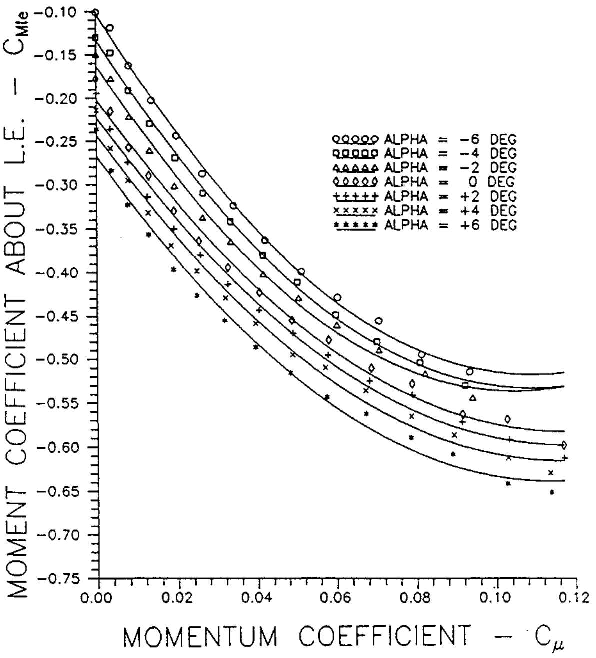

Fig. 6 Effect of blowing and angle of attack on pitching-moment coefficient.

moments are characteristic of circulation control wings and increase the trim requirements.

While this study was undertaken to show the effects of aspect ratio, the wing would require significant redesign for use in most applications. Englar[2-4] has provided design details and test results for a number of proposed applications.

Conclusions

Tests of a sting-mounted circulation control wing of aspect ratio 2.3 showed that the values of the wing lift coefficient were at least three times lower than those reported for similar two-dimensional configurations and blowing conditions. The lower values of wing lift coefficient obtained are reconciled on the basis of low aspect ratio, nonoptimized wing and slot design, partial span blowing, and sting mounting. Three-dimensional effects on circulation control wings of low aspect ratio can significantly reduce the benefits of circulation control, and practical methods to reduce these effects are needed.

References

[1]Wood, N. J., and Nielsen, J. N., "Circulation Control Airfoils Past, Present, Future," AIAA Paper 85-0204, Jan. 1985.

[2]Englar, R. J., "Circulation Control for High Lift and Drag Generation on STOL Aircraft," *Journal of Aircraft*, Vol. 12, No. 5, 1975, pp. 457–463.

[3]Englar, R. J., Trobaugh, L. A., and Hemmerly, R. A., "STOL Potential of the Circulation Control Wing for High Performance Aircraft," *Journal of Aircraft*, Vol. 15, No. 3, 1978, pp. 175–181.

[4]Englar, R. J., "Development of the A-6/Circulation Control Wing Flight Demonstrator Configuration," David Taylor Naval Ship Research and Development Center, DTNSRDC Rept., ASED 79/01, Bethesda, MD, Jan. 1979.

[5]Loth, J. L., Fanucci, J. B., and Roberts, S. C., "Flight Performance of a Circulation Controlled STOL Aircraft," *Journal of Aircraft*, Vol. 13, No. 3, 1976, pp. 169–173.

[6]Harvell, J. K., and Franke, M. E., "Aerodynamic Characteristics of a Circulation Control Elliptical Airfoil with Two Blown Jets," *Journal of Aircraft*, Vol. 22, No. 9, 1985, pp. 737–742.

[7]Rae, W. H., and Pope, A., *Low-Speed Wind Tunnel Testing*, 2nd ed., Wiley, New York, 1984.

[8]McCormick, B. W., Jr., *Aerodynamics of V/STOL Flight*, Academic Press, New York, 1967.

Simplified Tunnel Correction Method

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Introduction

IN wind-tunnel testings, large models relative to the test section size present challenging problems, known as wall effects. In this study, the classical method[1] was used to correct wind-tunnel data for downwash due to the walls, in conjunction with the classical method[1] of blockage correction to account for the increased velocity due to the presence of the model and wake in the test section. The classical method of blockage correction requires the obtaining of factors or constants from published documents that may or may not be available to users of this method. In some cases, this correction method cannot be applied on-line, depending on the test program.

This Note presents a simple and effective method of applying blockage corrections to the aerodynamic characteristics of airplane models tested in low-speed wind tunnels with closed test section. The method does not require reference to other documents, and the applicability of the method was experimentally investigated, using two complete airplane models; one with a rectangular wing and the other with a delta wing. The method is suitable for on-line processing. The validity of the correction methods used was examined by comparing the corrected data obtained in a typically large model-to-tunnel size ratio testing environment with those acquired in a near free air testing configuration. Experiments proved the results of this simplified method to be equivalent or superior to those of the classical method.

Experimental Facility and Models

The entire experimental study was conducted at the University of Washington Aeronautical Laboratory, 8- × 12-ft (2.438- × 3.658-m) low-speed wind tunnel. Features of the airplane models used are shown in Table 1.

The rectangular wing model was constructed so that it could be built up from the wing to the complete airplane during the test. Twenty percent chord zap flaps were available for this model. The delta wing model was not designed to be built up in the tunnel. Combinations of configurations shown in Table 1 were tested in the 8- × 12-ft (2.438- × 3.658-m) test section, which was considered to be near free air, and in a 2.5- × 3.75-ft (0.726- × 1.143-m) insert to simulate a more realistic wind-tunnel model to tunnel size ratio. Reference 2 describes

Table 1 Features of models tested

	Rectangular wing	Delta wing
Wing area S, ft^2 (m^2)	1.50 (0.139)	1.86 (0.173)
Wing span b, in. (m)	36.0 (0.914)	22.66 (0.576)
MAC, in. (m)	6.0 (0.152)	16.49 (0.419)
Aspect ratio, AR	6.0	1.92
Flaps, 100% b and 40% b, deg	30, 45, 60	Fixed
Leading-edge sweep-back angle, deg	0	68.48

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