Aerodynamic Characteristics of a Circulation Control Elliptical Airfoil with Two Blown Jets

J.K. Harvell* and M. E. Franke†
Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio

Effects of two blown jets on the aerodynamic characteristics of a 20%-thick, 8.5%-cambered elliptical airfoil are described. The jet slots are designed so that the jets are tangential to the blunt rear surface of the airfoil. Section lift, drag, and moment coefficients are given for the airfoil at 0-deg angle of attack for a freestream wind tunnel velocity of approximately 30 m/s (98-100 ft/s) and a Reynolds number of 9.5×10^5. Two jets are found to be more effective in producing lift than a single jet at the same total blowing momentum coefficient.

Nomenclature

c	= airfoil chord
C_{d_e}	= section equivalent drag coefficient
C_{d_r}	= section profile (rake) drag coefficient
C_{d_0}	= section corrected profile drag coefficient
C_ℓ	= section lift coefficient
C_m	= section moment coefficient
C_p	= pressure coefficient
C_μ	= section momentum coefficient, $= \dot{m}_j V_j / q_\infty c$
C_{μ_c}	= section cylindrical plenum momentum coefficient
C_{μ_m}	= section main plenum momentum coefficient
C_{μ_T}	= section total momentum coefficient, $= C_{\mu_m} + C_{\mu_c}$
h	= slot height
$\dot{m}$	= mass flow rate
p	= pressure
q	= dynamic pressure
V	= velocity
ϕ	= cylinder rotation angle

Subscripts

c	= cylindrical plenum
j	= jet
m	= main plenum
25	= quarter-chord
∞	= freestream

Introduction

DURING recent years, there has been considerable interest in circulation control techniques that improve the short takeoff and landing capabilities of fixed-wing aircraft. There is also interest in applying circulation control to helicopter rotors. One of the more promising circulation control techniques takes advantage of the Coanda effect. This effect allows a jet to attach to and flow around a curved surface due to a balance between the centrifugal forces in the jet and the reduced pressure on the curved surface.[1] Circulation control airfoils take advantage of this effect by introducing a jet of high-energy air into the suction surface trailing-edge region of a blunt-edged airfoil, thus enabling the flow to remain attached for a greater distance before separation. This moves the trailing- and leading-edge stagnation points toward the lower surface of the airfoil with a corresponding increase in lift.

Comparison of circulation control airfoils with conventional designs points out the advantages and disadvantages of circulation control. For example, conventional airfoils with mechanical flaps usually cannot produce the high-lift coefficients possible with blown airfoils due to the onset of flow separation. Also, blown airfoils are able to vary lift simply by varying the blowing rate. Disadvantages include 1) drag during cruise due to flow separation from the blunt trailing edge unless mechanical configuration changes are made or blowing is used, 2) losses associated with the energy requirements to provide the blowing air, and 3) the negative pitching moment resulting from suction peaks in the upper-surface trailing-edge region of blown airfoils.

A number of studies have been conducted on boundary-layer and flow control. A summary of some of these studies is presented by Lachmann.[2] Also, numerous studies have been conducted on elliptical or modified airfoils with circulation control. Davidson[3] and Kind and Maull[4] have described some of the early work. Kind and Maull[4] showed the potential of blowing on an uncambered elliptical airfoil and reported lift coefficients as high as 3.3. They also found that the drag increased as the blowing rate was increased and concluded that the increased drag was due to large suction peaks in the trailing-edge region of the airfoil and increased viscous losses due to mixing. Following some preliminary work, they postulated that one method of reducing the drag was to use a splitter-plate assembly on the blunt trailing edge. Additional studies have confirmed the effectiveness of a splitter plate.[5] Other work on circulation control airfoils includes that of Williams and Howe,[6] Englar,[7-9] Abramson,[10,11] and Loth et al.[12,13] Also, the circulation control concept was demonstrated in flight tests with the West Virginia University Demonstrator aircraft[12] and, more recently, with a modified A-6A aircraft.[14,15] These flight tests verified the short takeoff and landing application of circulation control lifting surfaces.

One area that has not received extensive study is multiple-jet blowing in the trailing-edge region. Kind and Maull[4] tested an airfoil with blowing from two slots in the trailing-edge region. However, in their application, the jets opposed each other, and the lift was lower with blowing from both slots. Smith[16] also tested an airfoil with multiple blowing jets and found some increases in the airfoil lift coefficient. Smith designed his airfoil so that the jet slots could be rotated around the trailing edge, but the slots were fixed relative to each other. Advantageously located multiple-jet slots would appear to provide an effective means for increasing the lift coefficient. Thus, the objective of this study was to investigate the effect of two

Presented as Paper 83-1794 at the AIAA Applied Aerodynamics Conference, Danvers, MA, July 13-15, 1983; received Aug. 1, 1983; revision received April 16, 1985.

*Captain, U.S. Air Force. Member AIAA.
†Professor. Associate Fellow AIAA.

tangentially blown jets on the areodynamic characteristics of an elliptical airfoil at low jet blowing rates.

Model and Test Apparatus

The experimental model, Fig. 1, was a 20%-thick, 8.5%-cambered elliptical airfoil with provisions for two tangentially blown jets. The model had a span of 0.66 m (26 in.), a chord of 0.52 m (20.3 in.), and was designed with a separate plenum for each blown jet. The main plenum contained two screens and a foam block placed along the span that helped to provide a more uniform spanwise pressure distribution and, consequently, a more uniform jet velocity along the span. Three dead stop and three tensioning screws spaced evenly spanwise were used to fix the slot height h at 0.5 mm (0.02 in.). The location for the first (main plenum) blowing slot was fixed at 94.5% chord.

The circular trailing-edge surface and second slot were formed by the surface of the hollow circular cylinder, Fig. 1. The hollow cylinder, which was also used as the plenum for the second slot, could be rotated to vary the position of the second blowing slot from $\phi = 0\text{-}180$ deg. The second slot height was set and maintained at 0.5 mm (0.02 in.) by caps at the ends of the cylinder and by cross members held in place with screws. No screens or foam were used in the cylindrical plenum.

Sixty-seven static pressure taps were distributed along the centerspan of the model; 27 on the suction surface, 23 on the pressure surface, and 17 on the circular trailing edge. Three static pressure taps were located 0.15 m (6 in.) on each side of centerspan to monitor the two-dimensionality of the flowfield.

Testing was conducted in the Air Force Institute of Technology 5-ft-diam. wind tunnel, which is an open-circuit tunnel with a maximum test speed of approximately 134 m/s (300 mph). The model was installed in the wind tunnel with its span vertical and was supported at each end of the span. Circular aluminum plates, 1.22 m (4 ft) in diameter, 5.6 mm (0.22 in.) thick, and beveled 30 deg at the edges, were attached to both ends of the model to reduce the effects of finite span. The combination of the plates and wind tunnel walls formed the 0.66×1.5 m (26×60 in.) test section. The air supplied to the main and cylindrical plena was routed through the supports. The geometric angle of attack was fixed at 0 deg. The tunnel dynamic pressure (tunnel q) was maintained at 0.05 m (2 in.) of water or approximately 30 m/s (98-100 ft/s), and the Reynolds number was approximately 9.5×10^5 The turbulence factor of the tunnel is 1.5, which accounts for the effect of the propeller, guide vanes, and tunnel wall vibrations.[17]

A 12.7 mm (0.5 in.) throat diameter venturi meter, located in each air supply line, was used to measure the mass flow rate to each plenum. Static pressure readings were obtained at taps located at and immediately upstream of each venturi throat. The temperature was measured with a copper-constantan thermocouple located upstream of each venturi meter.

A wake survey rake placed horizontally across the tunnel and 1.48c behind the airfoil was used to measure the momentum deficit in the wake. Ninety-four total head tubes and six static tubes, distributed along the span of the rake, were used to measure the pressure in the airfoil wake.

Alcohol manometers were used to measure static pressure on the airfoil surface. Mercury manometers were used to measure the pressure at the venturi meters, and water manometers were used to measure the total pressure in the main and cylindrical plena.

Data Reduction

Following Englar,[1] the jet velocity in the slot exit plane was calculated based on isentropic expansion from plenum total pressure to freestream static pressure. The jet exit velocity, however, actually depends on the local static pressure at the slot exit. Since the airfoil contained two blowing slots, two independent section momentum coefficients were calculated. A total momentum coefficient was defined as the sum of the main plenum and cylindrical plenum momentum coefficients.

$$C_{\mu_T} = C_{\mu_m} + C_{\mu_c} \tag{1}$$

The section lift coefficient C_ℓ and quarter-chord moment coefficient C_{m25} were calculated from the pressure distribution on the airfoil surface. The section profile (rake) coefficient C_{d_r} based on the momentum deficit methods of Betz and Jones,[17,18] was obtained by integration across the airfoil wake. However, this method does not account for the blowing slot jet flow that does not originate upstream of the airfoil. A modification to the section profile (rake) drag coefficient is necessary to correct for this jet flow.[4,6,8] The correction applied to this study subtracts $\dot{m}_j V_\infty / q_\infty c$ from the section profile (rake) drag coefficient to give the section-corrected profile drag coefficient:

$$C_{d0} = C_{d_r} - C_{\mu_m}\frac{V_\infty}{V_{j_m}} - C_{\mu_c}\frac{V_\infty}{V_{j_c}} \tag{2}$$

To facilitate comparison of the circulation control airfoil performance with that of conventional airfoils, the section-corrected profile drag coefficient was modified by the addition of dimensionless terms to account for energy expenditure to produce the high-pressure blowing air and a ram drag effect.[8] This results in the section equivalent drag coefficient, which is defined as

$$C_{d_e} = C_{d_0} + C_{\mu_m}\left(\frac{V_{jm}}{2V_\infty} + \frac{V_\infty}{V_{jm}}\right) + C_{\mu_c}\left(\frac{V_{jc}}{2V_\infty} + \frac{V_\infty}{V_{jc}}\right) \tag{3}$$

This method accounts for the individual penalty generated by each blowing slot. For this study, the lift-to-drag ratio was calculated based on the section equivalent drag.

The manometer data were recorded on film, digitized, and then used to calculate the various section coefficients. Details are given by Harvell.[19] The standard wind tunnel corrections suggested by Pope[17] for solid blockage, wake blockage, and streamline curvature were applied to C_ℓ and C_m. Solid and wake blockage corrections were used to adjust drag, freestream velocity, dynamic pressure, and Reynolds number.

Results and Discussion

Pressure measurements and tuft studies were performed prior to installation of the airfoil in the tunnel. These tests showed that the spanwise pressure distribution in each plenum

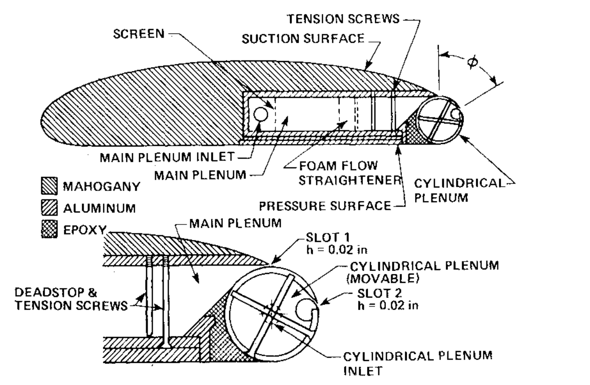

Fig. 1 Schematic of elliptical airfoil with enlarged view of trailing edge.

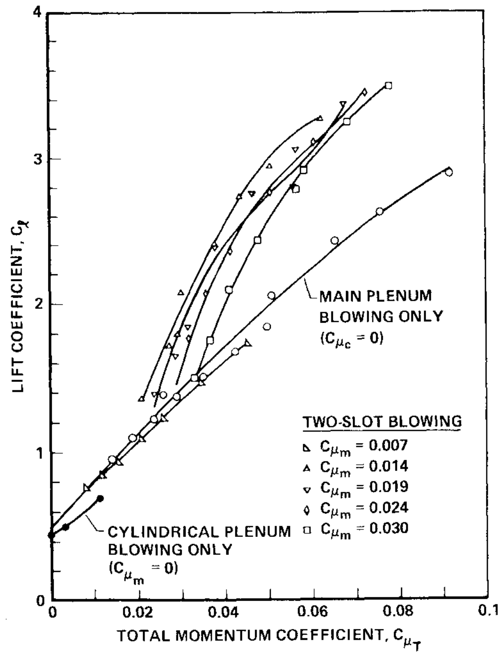

Fig. 2 Lift coefficient as a function of total momentum coefficient, $\phi = 73$ deg.

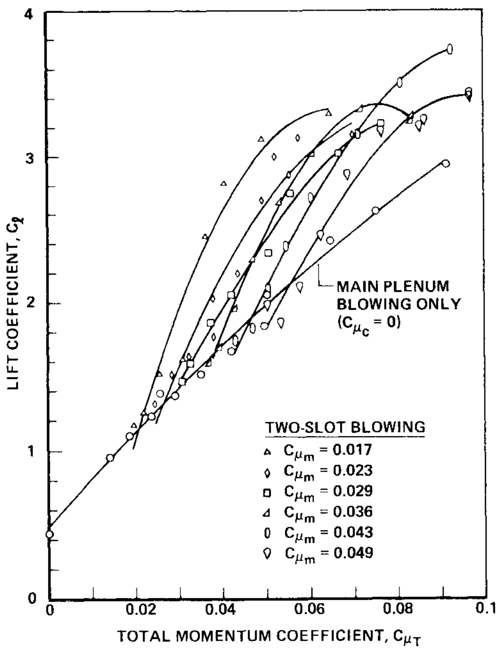

Fig. 3 Lift coefficient as a function of total momentum coefficient, $\phi = 83$ deg.

was uniform within a few percent and that there was good flow attachment of the blown jets around the trailing edge. Also, slot measurements showed that, although the stiffening screws reduced the magnitude of the slot expansion, there was approximately 0.025 mm (0.001 in.) expansion of the slot at the higher blowing rates. This slot expansion was reasonably uniform across the span.

After installation of the airfoil in the wind tunnel, baseline tests were conducted to determine the airfoil performance due to single-slot blowing from the main plenum alone ($C_{\mu_c} = 0$). These tests demonstrated good flow attachment and confirmed a two-dimensional flow about the airfoil. Also, during these baseline tests, the location of boundary-layer separation was identified at angles ranging from $\phi = 70$ to 90 deg based on

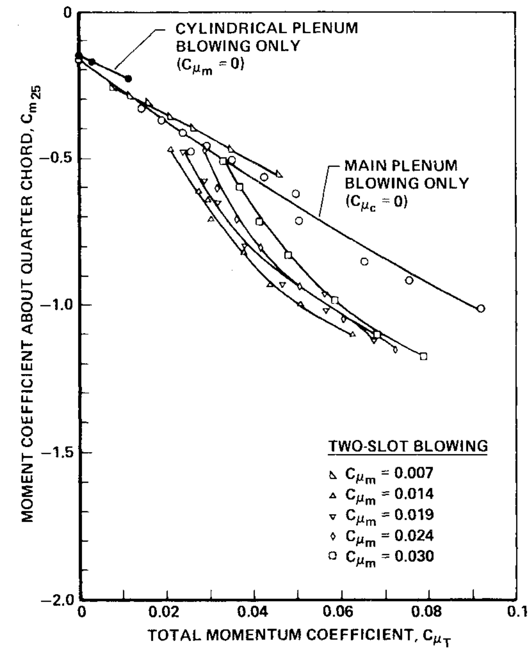

Fig. 4 Moment coefficient as a function of total momentum coefficient, $\phi = 73$ deg.

the manometer readings. This information helped to identify the locations where second-slot blowing would be most promising. Tests were run with the second blowing slot set at $\phi = 73$ and 83 deg. Further preliminary tests with high blowing rates from both slots revealed noticeable three-dimensional flow effects. It is believed that these effects were caused mainly by flow interference with the model sideplates. Without blowing, flow over the majority of the cylindrical trailing edge of the airfoil was separated.

The lift results in terms of C_ℓ as a function of the total momentum coefficient C_{μ_T} are presented in Figs. 2 and 3 for $\phi = 73$ and 83 deg, respectively. For comparative purposes, the baseline curve ($C_{\mu_c} = 0$) with blowing only from the main plenum is repeated in each figure. Loth and Boasson[13] replotted data from Englar[20] and showed that, at constant slot height, ΔC_ℓ increases rather linearly with V_j/V_∞. The results with single-slot (main plenum) blowing in this study showed a somewhat similar relationship.

In the tests with two-slot blowing, C_{μ_m} was held constant (within ± 0.002), while the blowing rate from the cylindrical plenum was varied. The value of C_{μ_m} for each curve is identified in each figure. The curves illustrate the advantage of two-slot blowing over single-slot blowing. For example, the lift results in Figs. 2 and 3 at $C_{\mu_T} = 0.05$ show that there was up to a 50% increase in C_ℓ for two-slot blowing depending on C_{μ_m}. The results indicate that once the main plenum blowing was sufficient to keep the boundary layer attached up to the second blowing slot, any additional main plenum blowing in terms of C_μ did not increase lift as much as that for an equivalent incremental amount of blowing (in terms of C_μ) from the second slot. When the value of C_{μ_m} was below that required for boundary-layer attachment up to the second slot, blowing from the second slot was slightly less effective than an equivalent amount of C_μ based on single-slot main plenum blowing. This is illustrated in Fig. 2 by comparing the $C_{\mu_m} = 0$ and 0.007 curves with the baseline $C_{\mu_c} = 0$ curve. The tests with $C_{\mu_m} = 0$ and 0.007 were terminated at $C_{\mu_T} = 0.015$ and 0.05, respectively, due to an unexplained audible resonance experienced at the next test condition for each case. The results for $\phi = 83$ deg shown in Fig. 3 are similar to those for $\phi = 73$ deg; however, the minimum value of C_{μ_m} had to be increased to keep the flow attached up to the second blowing slot. This added main plenum blowing was offset somewhat by the ability of the second blowing slot at $\phi = 83$ deg to produce added circulation due to its position farther around the trailing edge. When the second slot was positioned at $\phi = 93$ deg, high main plenum blowing rates were required to keep the flow attached up to the second slot. This test condition was not investigated further due to limitations of the blowing air supply.

The blown jet velocities at the slot exits were always less than sonic. For the tests conducted at $\phi = 83$ deg (Fig. 3), the approximate maximum blown jet velocities were as follows: for single-slot blowing alone, $V_{jm} = 190.5$ m/s (625 ft/s) at $C_{\mu m} = C_{\mu T} = 0.092$; and for two-slot blowing, $V_{jm} = 137$ m/s (450 ft/s) and $V_{jc} = 145$ m/s (475 ft/s) at $C_{\mu T} = 0.097$ ($C_{\mu m} = 0.047$ and $C_{\mu c} = 0.05$). With low main plenum C_μ, the approximate blown jet velocities were $V_{jm} = 79$ m/s (260 ft/s) and $V_{jc} = 142$ m/s (465 ft/s) at $C_{\mu T} = 0.065$ ($C_{\mu m} = 0.017$ and $C_{\mu c} = 0.048$).

As previously stated, Loth and Boasson[13] found that ΔC_ℓ increases rather linearly with V_j/V_∞ at constant slot height. They also determined that for single-slot blowing at constant C_μ, the maximum value of ΔC_ℓ will be obtained at a V_j/V_∞ value of approximately 4.6. However, at a given C_μ, there is only about a 10% variation in ΔC_ℓ over a range of V_j/V_∞ values between 2.5 and 12. Herein, V_j/V_∞ was varied over a range of approximately 2-7, and, consequently, for single-slot blowing at constant C_μ, less than a 10% variation in ΔC_ℓ would be expected. With two-slot blowing, however, larger increases in ΔC_ℓ at constant $C_{\mu T}$ are shown in Figs. 2 and 3. Apparently, by reducing jet velocity and introducing a second blown jet, the momentum and energy of the two jets are used more effectively in increasing C_ℓ.

The moment results are presented in Figs. 4 and 5 with C_{m25} as a function of $C_{\mu T}$. These curves highlight one of the continuing difficulties with circulation control airfoils in that the lift in the aft section of the airfoil causes a nose-down pitching moment. As a consequence, when these devices are used in conventional aircraft applications, this pitching moment must be offset. As would be expected, higher lift coefficients result in more severe nose-down pitching moments. As shown in Figs. 4 and 5, at equivalent $C_{\mu T}$, more severe nose-down pitching moments were found with two-slot blowing than with the single-slot blowing.

Equivalent drag results in terms of C_{d_e} as a function of $C_{\mu T}$ are presented in Figs. 6 and 7. Before discussing these results, however, it is important to note that, in some cases, the corrections to C_{d_r} are an order of magnitude larger than the actual measured drag. Thus, the effect of calculating C_μ based on expansion to freestream or to local static pressure can introduce variations in C_{d_e} of 25% or more. To be consistent with the lift results, C_μ was based on expansion to freestream pressure.

A second problem is that pointed out by Pope[17] in his explanation of the use of a wake rake and the momentum deficit method in general. Pope states that the wake rake, when used with the momentum deficit method, is only accurate when measuring drag on an airfoil that is not stalled. His explanation is that the previously stated method only resolves the linear variation in momentum and that in the

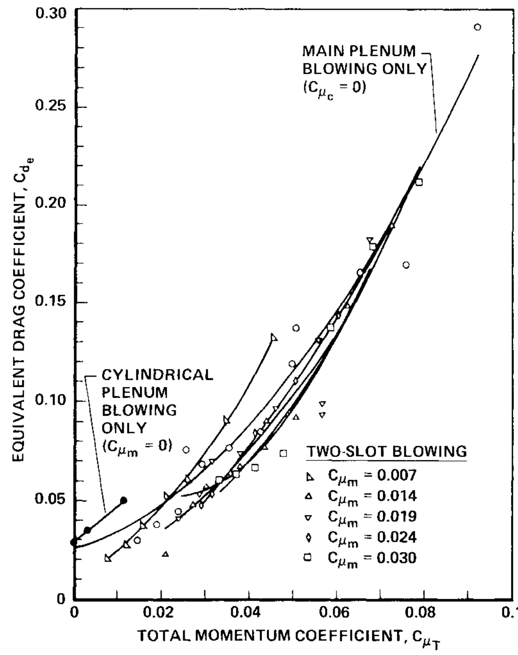

Fig. 6 Equivalent drag coefficient as a function of total momentum coefficient, $\phi = 73$ deg.

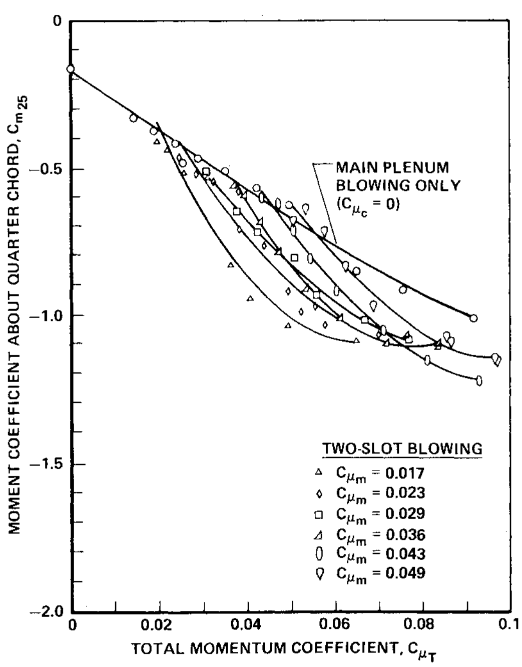

Fig. 5 Moment coefficient as a function of total momentum coefficient, $\phi = 83$ deg.

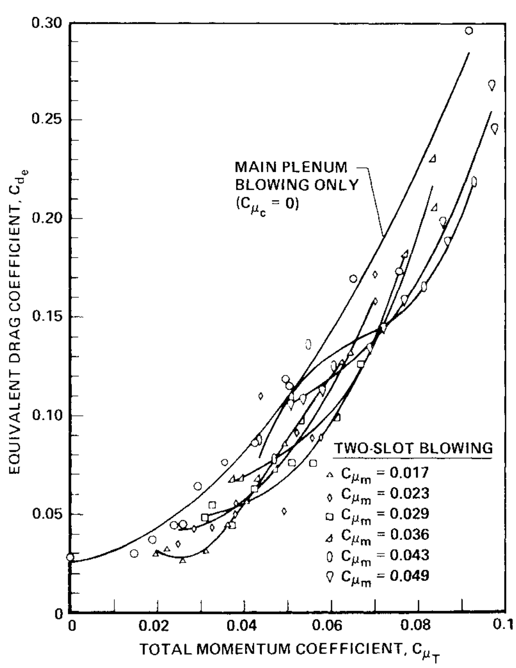

Fig. 7 Equivalent drag coefficient as a function of total momentum coefficient, $\phi = 83$ deg.

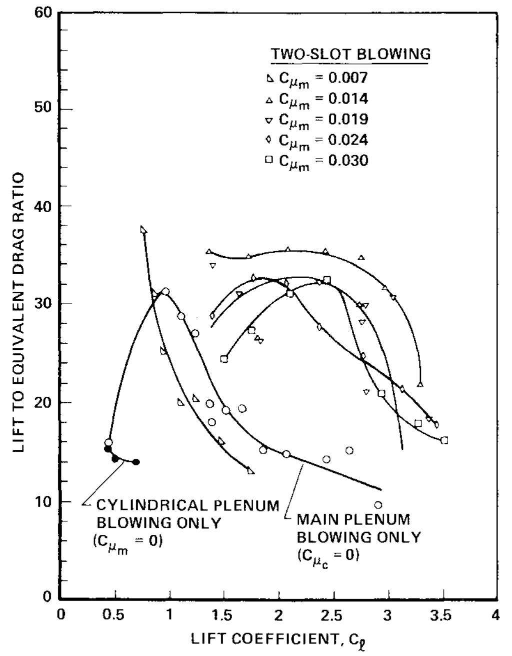

Fig. 8 Lift-to-equivalent-drag ratio as a function of lift coefficient, $\phi = 73$ deg.

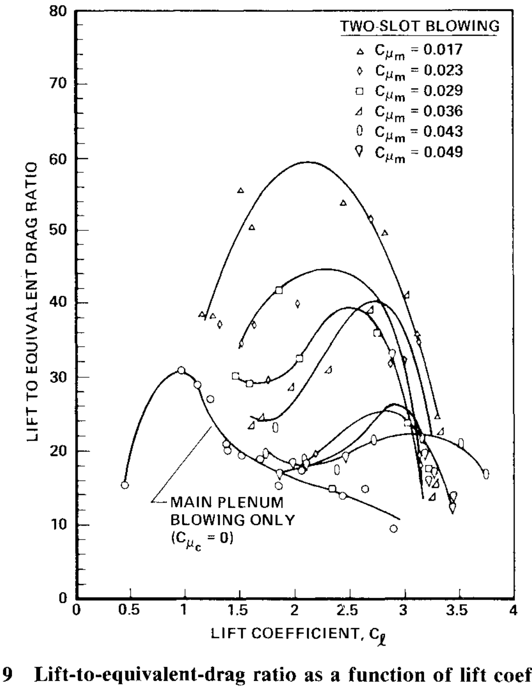

Fig. 9 Lift-to-equivalent-drag ratio as a function of lift coefficient, $\phi = 83$ deg.

case of separated flow there are significant losses of a rotational nature. With circulation control airfoils, it is possible for the upper-surface air to flow around the trailing edge and impinge upon the lower-surface freestream flow. Under these conditions there are undoubtedly considerable rotational effects in addition to linear momentum effects.

There are other considerations as well. One is that a wake rake, used in conjunction with a manometer bank, is a time-averaging device. As a consequence, any unsteady condition in the region of the wake is essentially lost and readings of a cyclic behavior may be affected by the response time of the system. Another is that drag results have been reported in numerous ways in the literature, therefore, care must be taken when comparing results from different sources. Also, the penalties applied to the profile drag for energy expenditure and ram drag may not be appropriate in all cases.

Given the equivalent drag qualifications, C_{d_e} with single-slot blowing was found to be slightly greater than that of the two-slot configurations at equivalent C_{μ_T}. Since lift as a function of C_{μ_T} was significantly enhanced with two-slot blowing, lift-to-drag ratios C_ℓ/C_{d_e} shown in Figs. 8 and 9 were higher for two-slot blowing than for single-slot blowing. Comparing Fig. 8 with Fig. 9 shows that values of lift-to-drag ratio with $\phi = 83$ deg were higher than with $\phi = 73$ deg for the lower values of C_{μ_m} at an equivalent C_ℓ. At the higher values of C_{μ_m}, the results were about the same at $\phi = 73$ and 83 deg.

Conclusions

This experimental investigation of a two-dimensional, circulation control airfoil showed that

1) An airfoil using two blowing slots produced higher overall C_ℓ and C_ℓ/C_{d_e} than the same airfoil using single-slot blowing alone for the same C_{μ_T}.

2) When using two slots, maximum C_ℓ/C_{d_e} can be obtained by limiting the blowing from the primary slot to just the amount needed to ensure good flow attachment up to the secondary slot. However, too little blowing from the primary slot can reduce the effectiveness of blowing from the second slot to being equivalent to or less than that for a single slot.

References

[1]Englar, R. J., "Experimental Investigation of the High Velocity Coanda Wall Jet Applied to Bluff Trailing Edge Circulation Control Airfoils," Naval Ship Research and Development Center, Bethesda, MD, NSRDC Rept. 4708, Sept. 1975.

[2]Lachmann, G. V., ed., *Boundary Layer and Flow Control,* Vols. I and II, Pergamon Press, New York, 1961.

[3]Davidson, I. M., "Aerofoil Boundary-Layer Control System," British Patent 913754, 1960.

[4]Kind, R. J. and Maull, D. J., "An Experimental Investigation of a Low-Speed Circulation-Controlled Aerofoil," *The Aeronautical Quarterly,* Vol. 19, May 1968, pp. 170-182.

[5]Stevenson, T. A., Franke, M. E., Rhynard, W. E. Jr., and Snyder, J. R., "Wind-Tunnel Study of a Circulation-Controlled Elliptical Airfoil," *Journal of Aircraft,* Vol. 14, Sept. 1977, pp. 881-885.

[6]Williams, R. M. and Howe, H. J., "Two-Dimensional Subsonic Wind Tunnel Tests on a 20-Percent Thick, 5-Percent Cambered Circulation Control Airfoil," Naval Ship Research and Development Center, Bethesda, MD, NSRDC Tech. Note AL-176, Aug. 1970.

[7]Englar, R. J., "Two-Dimensional Subsonic Wind Tunnel Tests of Two 15-Percent Thick Circulation Control Airfoils," David Taylor Naval Ship Research and Development Center, Bethesda, MD, DTNSRDC Tech. Note AL-211, Aug. 1971.

[8]Englar, R. J., "Two-Dimensional Subsonic Wind Tunnel Investigations of a Cambered 30-Percent Thick Circulation Control Airfoil," Naval Ship Research and Development Center, Bethesda, MD, NSRDC Tech. Note AL-201, May 1972.

[9]Englar, R. J., "Subsonic Two-Dimensional Wind Tunnel Investigations of the High Lift Capability of Circulation Control Wing Sections," David Taylor Naval Ship Research and Development Center, Bethesda, MD, DTNSRDC Tech. Rept. ASED-274, April 1975.

[10]Abramson, J., "Two-Dimensional Subsonic Wind Tunnel Evaluation of a 20-Percent Thick Circulaton Control Airfoil," David Taylor Naval Ship Research and Development Center, Bethesda, MD, DTNSRDC Rept. ASED-311, Code 1619, June 1975.

[11]Abramson, J., "Two-Dimensional Subsonic Wind Tunnel Evaluation of Two Related Cambered 15-Percent Thick Circulation Control Airfoils," David Taylor Naval Ship Research and Development Center, Bethesda, MD, DTNSRDC Rept. ASED-373, Sept. 1977.

[12]Loth, J. L., Fanucci, J. B., and Roberts, S. C., "Flight Performance of a Circulation Controlled STOL Aircraft," *Journal of Aircraft,* Vol. 13, March 1976, pp. 169-173.

[13]Loth, J. L. and Boasson, M., "Circulation Controlled STOL Wing Optimization," *Journal of Aircraft,* Vol. 21, Feb. 1984, pp. 128-134.

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

[15]Nichols, J. H. Jr., Englar, R. J., Harris M. J., and Huson, G. G., "Experimental Development of an Advanced Circulation Control Wing System for Navy STOL Aircraft," AIAA Paper 81-0151, Jan. 1981.

[16]Smith, R. V., "A Theoretical and Experimental Study of Circulation Control with Reference to Fixed Wing Applications," University of Southampton, United Kingdom, Research Paper 582, July 1978.

[17]Pope, A., *Wind Tunnel Testing*, John Wiley and Sons, Inc., New York, 1954.

[18]Schlichting, H., *Boundary Layer Theory*, 7th Ed., McGraw-Hill Book Co., New York, 1979.

[19]Harvell, J. K., "An Experimental/Analytical Investigation into the Performance of a 20-Percent Thick, 8.5-Percent Cambered, Circulation Controlled Airfoil," M.S. Thesis, Air Force Institute of Technology, Wright-Patterson AFB, OH, AFIT/GAE/AA/82D-13, Dec. 1982.

[20]Englar, R. J., "Low-Speed Aerodynamic Characteristics of a Small Fixed Trailing-Edge Circulation Control Wing Configuration Fitted to a Supercritical Airfoil," David Taylor Naval Ship Research and Development Center, Bethesda, MD, DTNSRDC Rept. ASED-81/08, March 1981.