ARTICLE NO. 79-0118R

Effect of Spanwise Blowing on the Aerodynamic Characteristics of the F-5E

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A 1/10-scale F-5E was tested to investigate the spanwise blowing concept to provide improved aerodynamic characteristics with primary emphasis on high angle-of-attack performance and stability. Test data were obtained in the Northrop 7 × 10-ft low-speed facility at a freestream Mach number of 0.18 for a range of model angle of attack, sideslip, jet momentum coefficient, and leading- and trailing-edge flap deflection angles. Spanwise blowing on the 32 deg-swept wing from the wing/leading-edge extension (LEX) junction at a nozzle sweep angle of 55 deg resulted in LEX and wing leading-edge vortex enhancement and large vortex-induced lift increments and drag polar improvements at the higher angles of attack. Spanwise blowing improved the lateral/directional characteristics by delaying wing stall and maintaining vertical tail effectiveness to higher angles of attack. Deflecting the leading- and trailing-edge flaps down to 24 deg and 20 deg, respectively, delayed to higher model attitudes the more beneficial effects of blowing. Blowing reduces the specific excess power available for maneuvering the F-5E.

Nomenclature

C_D = aerodynamic drag coefficient
C_L = aerodynamic lift coefficient
$C_{L,T}$ = total lift coefficient, including nozzle thrust components
$C_{m,T}$ = total pitching moment coefficient, including nozzle thrust components
C_l = rolling moment coefficient
C_n = yawing moment coefficient
C_Y = side force coefficient
C_μ = jet momentum coefficient, $\dot{w}V_j/gq_\infty S_{\text{ref}}$
D = total drag force, including nozzle thrust components
g = gravitational acceleration
L = total lift force, including nozzle thrust components
M_∞ = freestream Mach number
p_t = stagnation pressure at nozzle exit
p_∞ = freestream static pressure
q_∞ = freestream dynamic pressure
S_{ref} = wing reference area
V_j = jet velocity due to isentropic expansion to freestream static pressure
V_∞ = freestream velocity
T = net engine thrust
W = aircraft weight
$\dot{w}$ = nozzle-air weight flow rate
α = angle of attack
β = angle of sideslip
δ_n = leading-edge flap deflection angle
δ_f = trailing-edge flap deflection angle
δ_H = horizontal tail incidence angle
Λ_n = nozzle sweep angle
Λ_{LE} = wing leading-edge sweep angle
ΔC_D = drag increment due to blowing, C_D (jet on) $-$ C_D (jet off)

Presented as Paper 79-0118 at the AIAA 17th Aerospace Sciences Meeting, New Orleans, La., Jan. 15-17, 1979; submitted Feb. 12, 1979.

Index categories: Aerodynamics; Performance.

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Introduction

STABLE leading-edge vortices are characteristic of the flow over thin, highly sweptback wings at moderate-to-high angles of attack. This flow situation is illustrated in the water-tunnel photograph in Fig. 1 and occurs because the favorable spanwise pressure gradient causes the separated leading-edge flow to form into a stable vortex over the wing. For moderately sweptback higher aspect ratio wings suitable for fighter aircraft, however, these vortex-induced lift benefits are not achieved due to vortex breakdown over the wing at moderate angles of attack, as shown in the water-tunnel photograph in Fig. 2. If vortex breakdown could be delayed to higher angles of attack, the resulting vortex lift would significantly improve fighter maneuver performance.

A promising technique that has proven favorable to the formation and control of the leading-edge vortex on moderately swept wings is spanwise blowing, illustrated in the flow visualization photograph[1] in Fig. 3, which consists of blowing a concentrated jet over the wing's upper surface in a direction essentially parallel to the wing leading edge. Spanwise blowing artificially induces spanwise flow gradients similar to those that appear naturally on highly swept wings[2-5] and effectively delays vortex breakdown to higher angles of attack. A stable flow can, thus, be maintained over a wider range of flight attitudes and Mach numbers. Studies which demonstrate the control of separated flow regions by lateral blowing have been made by Werlé[6] and Cornish.[7] Additional research conducted by Dixon et al.,[8-10] Bradley et al.,[11-12] and Campbell[13] applied the spanwise blowing concept to the lifting surfaces of various research model configurations and determined the amount of vortex lift achievable. More recent studies by Erickson and Campbell[14] have determined the effect of blowing on lateral/directional stability of a general research model configuration.

The objectives of the current investigation are unique in that they are designed to provide a comprehensive data base on the effect of spanwise blowing on the aerodynamic characteristics of a model of an existing fighter configuration with particular emphasis on high angle-of-attack performance and stability and to provide a realistic evaluation of the effect of blowing on fighter maneuver performance. Accordingly, a low-speed wind-tunnel investigation was conducted in the Northrop 7 × 10-ft facility using a 1/10-scale F-5E. Six-component force and moment data were acquired at a freestream Mach number of 0.18 for a range of model angle

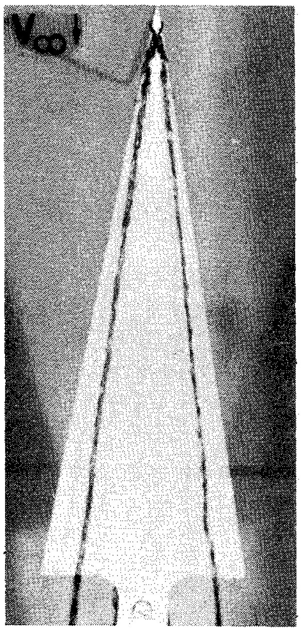


Fig. 1 Stable leading-edge vortices on a slender planform; $\alpha = 35$ deg.

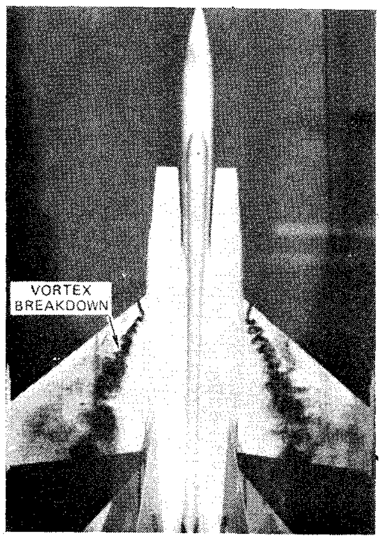


Fig. 2 Leading-edge vortex breakdown on a moderately swept wing; $\alpha = 20$ deg.

Fig. 3 Spanwise blowing on a 44 deg swept trapezoidal wing; $\alpha = 20$ deg (from Ref. 1).

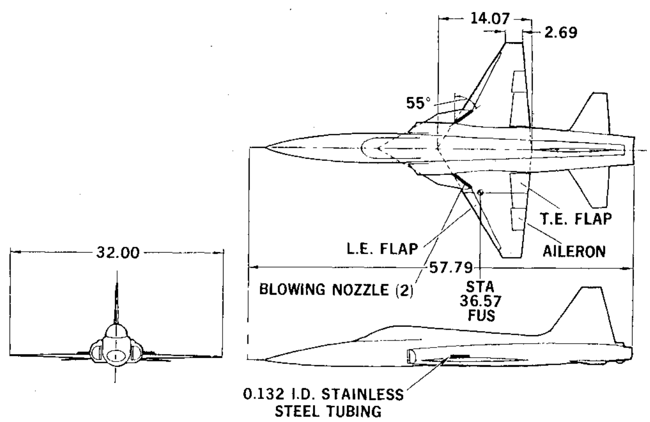


Fig. 4 F-5E three-view drawing (all dimensions in inches).

of attack, sideslip, jet momentum coefficient, and leading- and trailing-edge flat deflection angles.

Wind-Tunnel Model and Apparatus

A three-view drawing of the 1/10-scale F-5E wind-tunnel model is shown in Fig. 4. A photograph of the model mounted in the Northrop 7×10-ft low-speed facility is presented in Fig. 5.

The two wing blowing nozzles shown in Fig. 4 were 0.132-in. inner diam stainless steel tubing. The tubing was routed through each wing at the intersection of the wing leading edge and fuselage to extend spanwise on the wing upper surface to the wing/LEX junction. The nozzle sweep angle Λ_n was 55 deg.

Instrumentation and Calibration

Six-component force and moment data were recorded by means of an internally mounted strain-gage balance. High-pressure air was routed through stainless steel tubing from below the model and connected to the blowing nozzles mounted on the wing upper surface by means of swage-lock fittings.

The jet momentum coefficient C_μ is defined as:

$$C_\mu = \dot{w} V_j / g q_\infty S_{\text{ref}} \tag{1}$$

where $\dot{w}$ is the measured air weight flow rate and V_j is the jet velocity reached by isentropic expansion from the stagnation pressure at the nozzle exit to freestream pressure, given by

$$V_j = 109.6 \sqrt{T_t [1 - (p_\infty / p_t)^{2/7}]} \tag{2}$$

T_t and p_t are the measured upstream total temperature and jet exit total pressure, respectively. In order to insure equal flow rates through each nozzle, static pressure taps were installed

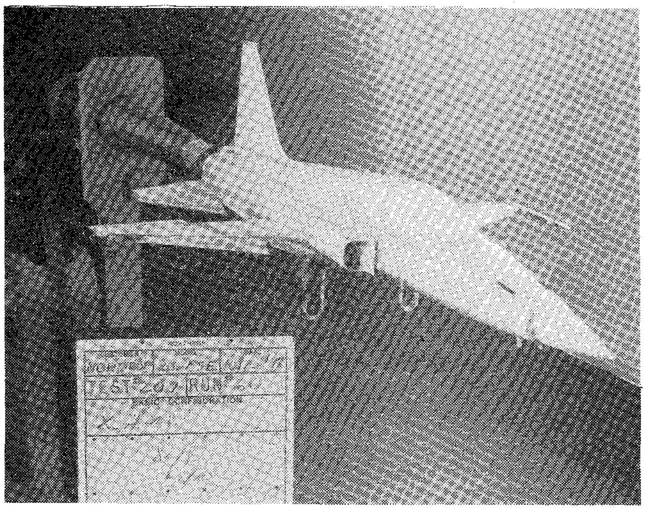


Fig. 5 Photograph of 1/10-scale F-5E mounted in Northrop 7 × 10-ft wind tunnel.

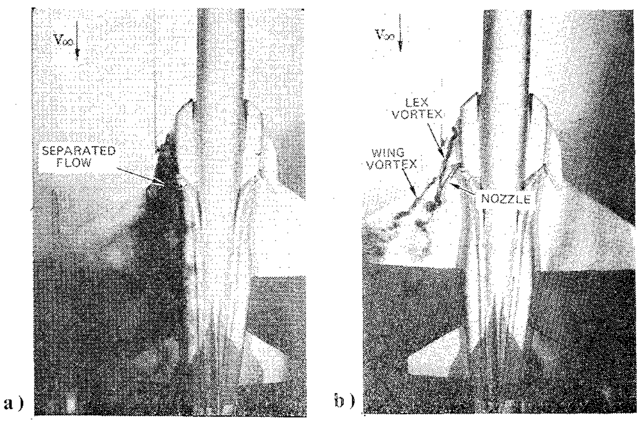


Fig. 6 Water-tunnel photograph of 1/40-scale F-5F; a) blowing off, $\alpha = 24$ deg; and b) blowing on, $\alpha = 24$ deg.

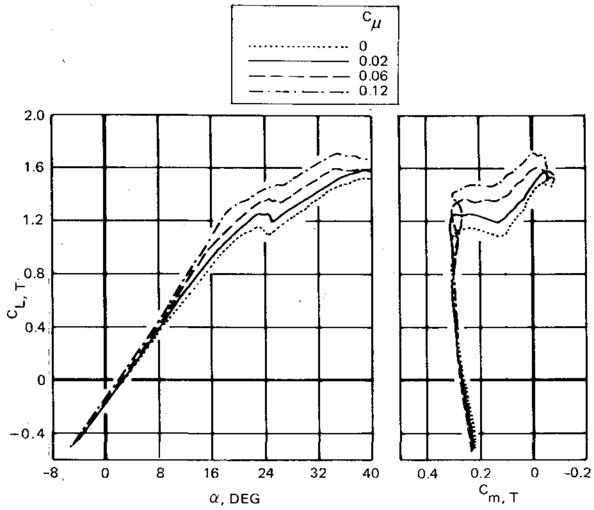


Fig. 7 Effect of spanwise blowing on the longitudinal characteristics; $\delta_n/\delta_f = 0/0$.

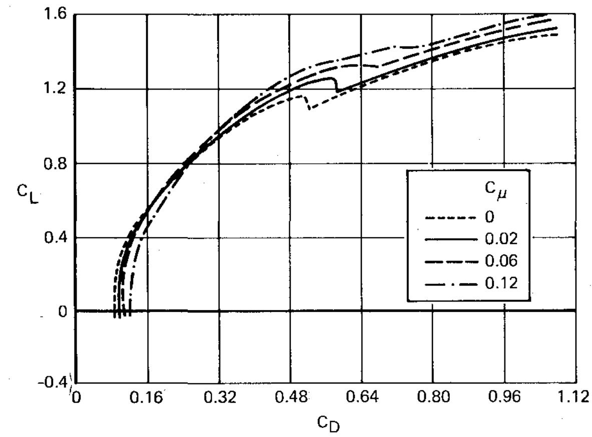


Fig. 8 Effect of spanwise blowing on the aerodynamic drag characteristics; $\delta_n/\delta_f = 0/0$.

upstream of the nozzle exits and throttle values were used to equalize static pressures.

It should be noted that wind-tunnel data obtained for $C_\mu = 0.02$-0.12 correspond to 7-33% of the F-5E engine airflow for the test Mach number of 0.18. Although these rates are not viable for the F-5E, these C_μ values may be acceptable for future aircraft with engines designed for high bleed rates with relatively low sensitivity of thrust loss to engine bleed.

Water-Tunnel Studies

Preliminary flow visualization studies were made in the Northrop water-tunnel facilities of a 1/40-scale F-5F. Results from this investigation indicated that blowing from the wing/LEX junction at a nozzle sweep angle of approximately 55 deg enhanced both the LEX and wing leading-edge vortices at moderate-to-high angles of attack. A typical result from this study is shown in Fig. 6 which illustrates the effect of blowing at $\alpha = 24$ deg.

The water-tunnel investigation stimulated a low-speed test in the Northrop 7 × 10-ft wind-tunnel using a 1/10-scale F-5E. Results from this test are presented in the following sections.

Wind-Tunnel Studies

The longitudinal characteristics presented in the following sections include nozzle thrust components, except where otherwise indicated. The longitudinal data presented in this report are referred to the stability-axis system, whereas the lateral/directional data are referred to the body-axis system. The moment reference center is taken to be at 25% of the mean aerodynamic chord, which is illustrated in Fig. 4. Data presented in this paper were obtained with a horizontal tail deflection angle δ_H of -17 deg.

Flaps Undeflected ($\delta_n/\delta_f = 0/0$)

Figure 7 illustrates the effect of spanwise blowing on the longitudinal characteristics at $\beta = 0$ deg. Blowing results in vortex-induced lift increments, particularly at higher angles of attack, which increase with increased blowing rate. In addition, blowing delays wing stall to slightly higher angles of attack. The significant point to note is that spanwise blowing is quite effective on the F-5E wing, which has a relatively low leading-edge sweep angle of 32 deg. Blowing results in essentially no effect on the stability level and an extension of the linear pitching moment to higher values of lift.

The effect of blowing on the aerodynamic drag characteristics (thrust effects excluded) is shown in Fig. 8. Spanwise blowing improves the drag polar shape relative to that obtained with no blowing. Increased blowing rate results in a slight increase in drag at low lift levels and a significant drag reduction at moderate-to-high values of lift.

Figure 9 presents the effect of blowing on the lateral/directional characteristics at $\beta = -10$ deg. Spanwise blowing results in favorable increments in rolling moment

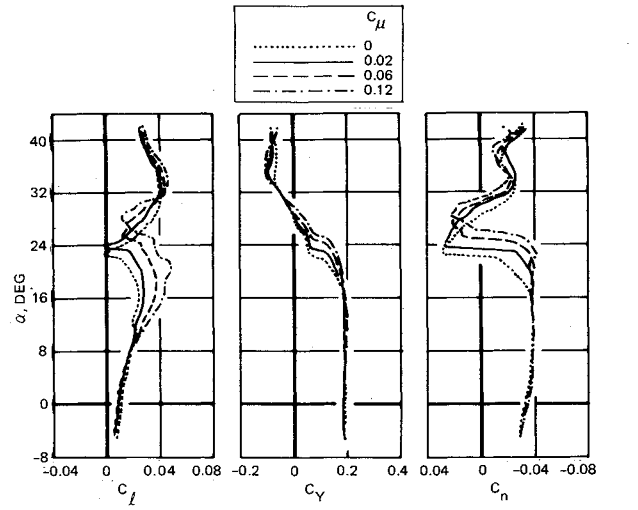


Fig. 9 Effect of spanwise blowing on the lateral/directional characteristics; $\beta = -10$ deg; $\delta_n/\delta_f = 0/0$.

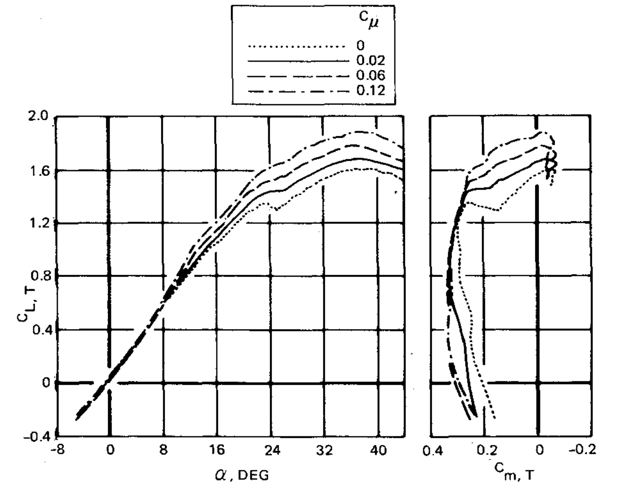


Fig. 10 Effect of spanwise blowing on the longitudinal characteristics; $\delta_n/\delta_f = 24/20$.

and yawing moment coefficients up to angles of attack of approximately 24-26 deg, depending on blowing rate. Figure 9 indicates that rolling moment is very dependent on jet momentum coefficient. Blowing is undoubtedly resulting in differential lift increments, the greater increments being generated on the advancing wing, which has lower effective sweep angle and, hence, benefits more from spanwise blowing. This asymmetry of forces creates a stable rolling moment increment which increases with increased blowing rate. The favorable yawing moment increments due to blowing, which are most significant in the wing stall region ($C_\mu = 0$), can be attributed to a delay to higher angles of attack of the dynamic pressure loss at the vertical tail that is associated with LEX and wing leading-edge vortex breakdown.

Flaps Deflected ($\delta_n/\delta_f = 24/20$)

The effect of spanwise blowing on the longitudinal characteristics at $\beta = 0$ deg is presented in Fig. 10. Deflecting the leading-edge flap down to 24 deg delays leading-edge flow separation and, hence, the more beneficial effects of blowing, to higher angles of attack. The lift increments due to blowing at the moderate angles of attack are undoubtedly due to enhancement of the LEX vortex and, in part, to an improvement in trailing-edge flap effectiveness. At the higher angles of attack at which flow separation occurs either at the leading edge or the leading-edge flap knee, a leading-edge vortex is generated on the wing. Blowing effectiveness is limited, however, due to the excessive angle of attack and the adverse pressure gradient associated with the deflected trailing-edge flap.

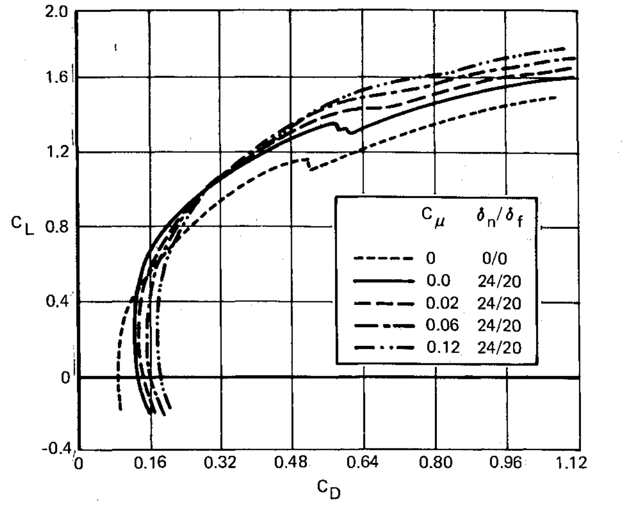


Fig. 11 Effect of spanwise blowing on the aerodynamic drag characteristics; $\delta_n/\delta_f = 24/20$.

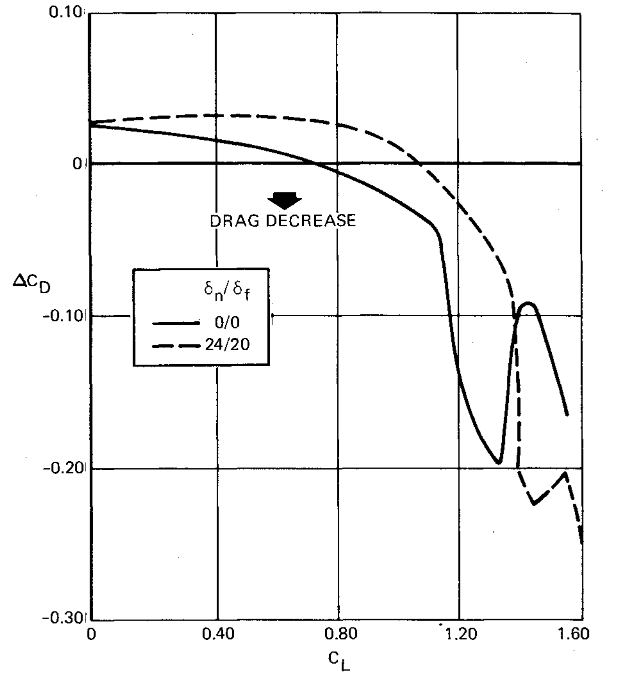


Fig. 12 Effect of C_L and δ_n/δ_f on the drag increments due to blowing; $C_\mu = 0.06$.

Increased downwash on the horizontal tail with blowing on at the low to moderate lift levels is reflected in the pitching moment curves. Blowing results in a noseup pitching moment increment, the magnitude of which is dependent on blowing rate.

The effect of blowing on the aerodynamic drag characteristics (thrust effects excluded) is shown in Fig. 11. The data suggest that blowing in conjunction with leading- and trailing-edge flaps results in greater improvement in the drag polar shape relative to that obtained with flaps retracted. Figure 12 illustrates the effect of C_L and δ_n/δ_f on the drag increments due to blowing at $C_\mu = 0.06$. As might be expected, extending the flaps delays the more significant drag reductions due to blowing to higher values of lift. The large drag benefits with

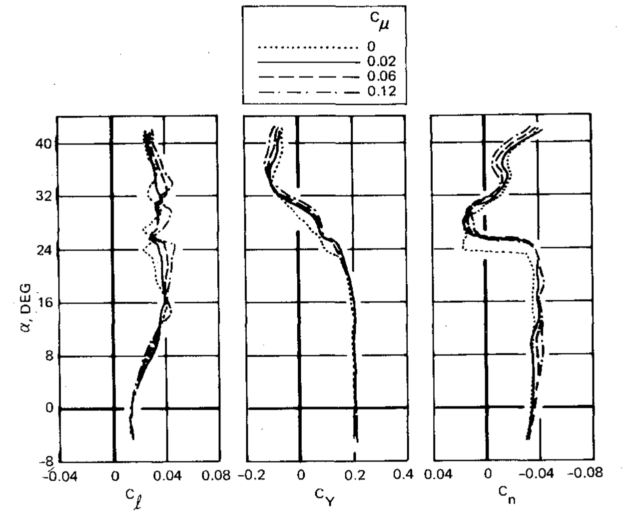
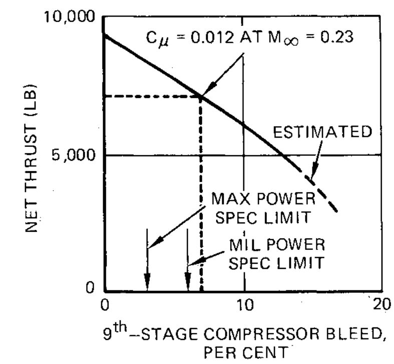


Fig. 13 Effect of spanwise blowing on the lateral/directional characteristics; $\beta = -10$ deg; $\delta_n/\delta_f = 24/20$.



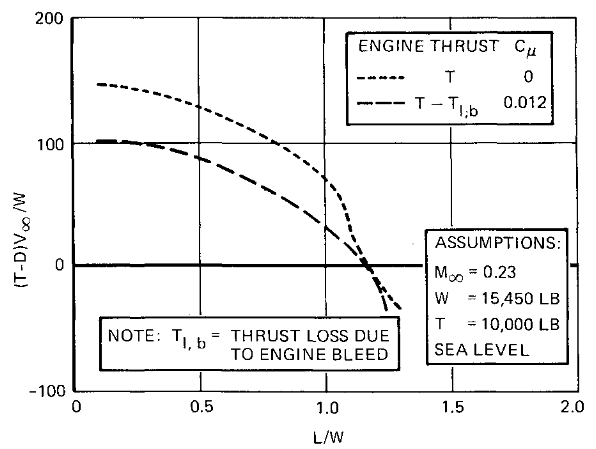


Fig. 14 Effect of spanwise blowing on specific excess power; $\delta_n/\delta_f = 0/0$.

blowing on at the higher lift values may be due, in part, to the suction pressures associated with the augmented wing leading-edge vortex acting on the extended leading-edge flap.

Figure 13 illustrates the effect of blowing on the lateral/directional characteristics at $\beta = -10$ deg. Deflecting the leading-edge flap down delays leading-edge flow separation to higher angles of attack and thereby improves the lateral/directional characteristics that were obtained with flaps retracted (Fig. 9). As a result, the favorable increments in rolling moment and yawing moment due to blowing are reduced. It is of interest that the lateral/directional characteristics obtained at the higher blowing rates ($C_\mu = 0.06$ and 0.12) and with flaps retracted (Fig. 9) are comparable to those obtained without blowing ($C_\mu = 0$) and with flaps extended (Fig. 13).

Specific Excess Power

An attempt to demonstrate the effect of spanwise blowing on F-5E performance is made in Fig. 14 for $\delta_n/\delta_f = 0/0$ where the specific excess power available for maneuvering is presented as a function of load factor. The source of blowing is assumed to be engine compressor bleed air. Engine thrust of 5000 lb/engine (sea-level static rating; maximum after burner) and takeoff gross weight of 15,450 lb have been assumed, in addition to a Mach number of 0.23. Taking into account the thrust loss associated with 7% engine bleed, which corresponds to the lowest blowing rate considered in the present studies, net thrust is 7200 lb. This value of net thrust is considerably less than the value that would be obtained if engine thrust were reduced by $C_\mu q_\infty S_{ref}$ ($T = 9825$ lb). The lift L and drag D forces are the total loads measured on the F-5E and, therefore, include the spanwise thrust components in the lift and drag directions.

The results show that spanwise blowing reduces the specific excess power available for maneuvering the F-5E. The data, therefore, indicate that the reduction in thrust associated with blowing exceeds the improvements in aerodynamic characteristics due to blowing. It should be noted, however, that spanwise blowing may have practical application in future aircraft with engines designed for high bleed rates with relatively low sensitivity of thrust loss to engine bleed.

Conclusions

A 1/10-scale F-5E was tested to investigate the effect of spanwise blowing on the aerodynamic characteristics with primary emphasis on high angle-of-attack performance and stability. Test data were obtained in the Northrop 7×10-ft low-speed wind tunnel at a freestream Mach number of 0.18 for a range of model angle of attack, jet momentum coefficient, and leading- and trailing-edge flap deflection angles.

The results of this investigation indicate that spanwise blowing from the wing-LEX junction with a nozzle sweep angle of 55 deg generates significant vortex-induced lift increments at the higher angles of attack, improves the drag polars, and extends the linear pitching moment to high lifts. Spanwise blowing improves the lateral/directional characteristics by delaying wing stall and maintaining vertical tail effectiveness to higher angles of attack. The more significant blowing-induced benefits in longitudinal characteristics are delayed to higher angles of attack by deflecting the leading-edge flap. Furthermore, since a deflected leading-edge flap delays flow separation at the leading edge to higher α's, the subsequent improvement in lateral/directional characteristics without blowing limits the beneficial effects when blowing is applied. Spanwise blowing reduces the specific excess power available for maneuvering the F-5E, assuming that the source of blowing is engine compressor bleeding air.

References

[1] Erickson, G.E. and Campbell, J.F., "Flow Visualization of Leading-Edge Vortex Enhancement by Spanwise Blowing," NASA TMX-72702, July 1975.

[2] Wentz, W.H., Jr. and Kohlman, D.L., "Wind Tunnel Investigations of Vortex Breakdown on Slender Sharp-Edged Wings," NASA CR-98737, 1969.

[3] Bartlett, G.E. and Vidal, R.J., "Experimental Investigation of Influence of Edge Shape on the Aerodynamic Characteristics of Low Aspect Ratio Wings at Low Speeds," *Journal of Aeronautical Sciences*, Vol. 22, Aug. 1955, pp. 517-533, 588.

[4] Tosti, L.P., "Low-Speed Static Stability and Damping-in-Roll Characteristics of Some Swept and Unswept Low-Aspect Ratio Wings," NACA TN 1468, 1947.

[5] Polhamus, E.C., "Charts for Predicting the Subsonic Vortex-Lift Characteristics of Arrow, Delta, and Diamond Wings," NASA TN D-6243, April 1971.

[6]Werlé, H., "Division and Coming Together of Fluid Flows," *La Recherche Aeronautica*, No. 79, 1960.

[7]Cornish, J.J., III., "High Lift Applications of Spanwise Blowing," *Seventh ICAS Congress*, ICAS Paper No. 70-09, Rome, Sept. 1970.

[8]Dixon, C.J., "Lift Augmentation by Lateral Blowing Over a Lifting Surface," AIAA Paper 69-193, Feb. 1969.

[9]Dixon, C.J., "Lift and Control Augmentation by Spanwise Blowing Over Trailing Edge Flaps and Control Surfaces," AIAA Paper 72-781, Aug. 1972.

[10]Dixon, C.J., Theisen, J.G., and Scruggs, R.M., "Theoretical and Experimental Investigations of Vortex-Lift Control by Spanwise Blowing," Experimental Research, LG73ER-0169, Vol. I, Sept. 1973.

[11]Bradley, R.G., Whitten, P.D., and Wray, W.O., "Leading-Edge Vortex Augmentation in Compressible Flow," AIAA Paper 75-124, Jan. 1975.

[12]Bradley, R.G., Smith, C.W., and Wray, W.O., "An Experimental Investigation of Leading-Edge Vortex Augmentation by Blowing," NASA CR-132415, April 1974.

[13]Campbell, J.F., "Effects of Spanwise Blowing on the Pressure Field and Vortex-Lift Characteristics of a 44° Swept Trapezoidal Wing," NASA TN D-7907, 1975.

[14]Erickson, G.E. and Campbell, J.F., "Improvement of Maneuver Aerodynamics by Spanwise Blowing," NASA TP-1065, Dec. 1977.