Performance Augmentation of a 60-Degree Delta Aircraft Configuration by Spanwise Blowing

A. Seginer* and M. Salomon†
Technion—Israel Institute of Technology, Haifa, Israel

Spanwise blowing (SWB) over the wing and canard of a close-coupled-canard, 60-deg delta fighter-aircraft configuration was investigated experimentally in low-speed flow at angles of attack up to 60 deg and yaw angles of up to 36 deg. Significant improvement in lift-curve slope, maximum lift, drag polar, and lateral/directional stability was found, enlarging the usable flight envelope beyond its previous low-speed/maximum-lift limit. It was shown that SWB can achieve the same lift augmentation produced by a canard, without the drag penalty. Contrary to previous experience with 60-deg swept wings, the efficiency of the lift augmentation by SWB was relatively high and was found to increase with increasing jet-momentum coefficient on the close-coupled-canard configuration. Interesting and promising possibilities of obtaining much higher efficiencies with swirling or multiple nonaligned jets were indicated.

Nomenclature

$\bar{c}$	= mean aerodynamic chord
C_D	= gross drag coefficient, $=D/qS$
C_{D_T}	= net drag coefficient, $=D_T/qS$
C_L	= gross lift coefficient, $=L/qS$
$C_{L_{max}}$	= maximum lift coefficient
C_{L_T}	= net lift coefficient, $=L_T/qS$
ΔC_L	= lift increment due to spanwise blowing
C_N	= gross yawing-moment coefficient, $=N/qS\bar{c}$
C_μ	= jet-momentum coefficient, $=(\dot{m}_j V_j)/qS$
D	= gross drag; jet thrust included
D_T	= net drag; jet thrust removed
L	= gross lift; jet lift included
L_T	= net lift; jet lift removed
$\dot{m}_j$	= jet mass flux
N	= gross yaw moment
q	= freestream dynamic pressure, $=\frac{1}{2}\rho V^2$
S	= wing-planform area
V	= freestream velocity
V_j	= spanwise-blowing jet exit velocity
α	= angle of attack
β	= sideslip angle

Subscripts

c,w	= spanwise blowing over the canard and wing, respectively

Introduction

MOST existing and next-generation advanced tactical fighter aircraft and air-to-air missiles make extensive use of nonlinear vortex lift.[1] The phenomenon of the formation of the leading-edge vortices and of the additional lift they induce has been well understood for the last two decades.[2] It was approximated by Polhamus,[3] and incorporated into predictive computational methods.[4] The utilization of vortex lift is curtailed by vortex bursting or breakdown (VBD), which is characterized by a sudden expansion of the vortex about a rapidly decelerating core, with subsequent vortex disintegration and loss of orderly vortical flow. As the angle of attack is increased, the point of VBD moves upstream, causing loss of lift and, eventually, complete stall.[5]

The main-wing, leading-edge vortices can be stabilized and VBD-induced stall can be postponed to higher angles of attack by another pair of vortices generated by a canard.[6] Such a configuration is used on the Swedish Viggen[7] and on the Israeli KFIR-C2 aircraft, and is being contemplated for most next-generation designs. However, the canard also adds considerable drag, therefore, other means to delay VBD are being sought. One promising vortex stabilization technique is suction or blowing along its core in the two-dimensional case,[8] or spanwise blowing parallel to the leading edge, inboard of the vortex, in the case of a three-dimensional, leading-edge vortex.[9] Reference 10 summarizes the history of spanwise blowing (SWB) and its beneficial effects on lift augmentation, the drag polar, and the lateral/directional stability as measured on many wing planforms and aircraft configurations.

Concerned with the additional drag of the canard in the close-coupled-canard configuration of the KFIR-C2, the present authors decided to investigate SWB on a model resembling this aircraft as a possible alternative to a canard. This, despite evidence in the literature that SWB on a 60-deg delta wing could, at most, increase the maximum lift but not the lift-curve slope.[11,12] Furthermore, also reported in Refs. 11 and 12 was that the efficiency of SWB (defined as $\Delta C_L/C_\mu$, the lift increment ΔC_L due to blowing, divided by the thrust coefficient C_μ of the spanwise jet, which would be the direct jet contribution to the lift when vectored vertically downward) was low on highly swept wings. The authors had some hope that SWB on the aircraft configuration might prove to be more effective and more efficient than on a 60-deg delta wing alone. This hope was based on the better performance of the canard on this configuration[10] than on the wing alone.[6] The main differences between the two configurations, namely, a fuselage and a conical leading-edge droop on the wing, could act beneficially also in the case of SWB. As an alternative for replacing the canard with SWB, it was decided to study also the enhancement of the close-coupled-canard configuration by SWB, including blowing over the canard as well.

A secondary objective of this work was to put to the test Dixon's explanation[13] of the mechanism of vortex control by SWB. Contrary to the model proposed by Cornish,[8] Dixon stated that the jet and vortex did not mix until the jet had expended most of its energy. His explanation was that the jet acted as a barrier to the downstream bending of the leading-

Received Aug. 7, 1983; revision submitted June 1, 1986.

*Professor, Department of Aeronautical Engineering. Member AIAA.
†Consultant, SAL Engineering.

edge vortex and that vortex control was a function of the spanwise entrainment of the freestream flow. Increased entrainment should, therefore, enhance vortex stabilization. To test this model, several SWB experiments were conducted with swirling jets for better mixing and entrainment.

Experimental Apparatus and Program

SWB was tested over a 1:35-scale model of one of the early versions of the KFIR airplane (Fig. 1). The twin air inlets were faired over. The model had a low delta wing with a relatively sharp leading edge that had a conical droop and was swept back 60 deg. The model could be equipped with a canard mounted on the engine inlets at a height of 0.31 local fuselage diameter above the wing. The canard had a 45-deg leading-edge sweep and a span of 44% of the total wingspan (fuselage included). Four convergent nozzles for SWB (marked by white tufts in Fig. 1) were installed in the model, two on each side of the fuselage. One pair, of 2.3 mm i.d., was located 1 diam above the wing surface at the 10% root-chord station. The second pair, of 1.3 mm i.d., was located 1 diam above the canard surface at the 10% root-chord station of the canard. These locations were determined by preliminary tests on a larger model. It was found that the vertical position of the nozzle affected the SWB results only sightly. The axial location had, however, a strong influence, that was growing stronger as the nozzles were moved aft. The location chosen for these tests was the farthest aft that was consistent with the structural constraints of the inlets of the real airplane. Air, at stagnation pressures of up to 8 atm, could be blown parallel with the leading edges from any desired nozzle combination.

The wind-tunnel experiments were conducted at an airspeed of 30 m/s and a Reynolds number of 1.8×10^5 based on the mean aerodynamic chord. Forces and moments (relative to a reference point at 48% of the root chord) were measured by a six-component balance during angle-of-attack sweeps from -8 to 60 deg at zero sideslip, and during sideslip-angle sweeps from -8 to 28 deg at constant, discrete angles of attack of 0, 10, 20, 25, 30, and 35 deg. Forces and moments were normalized by the freestream dynamic pressure and wing-planform area and also by the mean aerodynamic chord, respectively, to give the aerodynamic coefficients. The longitudinal aerodynamic coefficients (lift, drag, and pitching-moment coefficients) were calculated in the wind-axes system, whereas the lateral coefficients (side-force, yawing-moment, and rolling-moment coefficients) were calculated in the body-axes system. Flow-visualization tests, using a helium-bubble generator, were also conducted in order to compare the characteristics of the flow over the wing and the canard with and without SWB, and to correlate them with the force measurements.

Results and Discussion

Helium-bubble flow visualization was used on both configurations (with and without canard) at the various test conditions (blowing pressure and angle of attack). An example is presented in Figs. 2 and 3, where the model is at an angle of attack of $\alpha = 35$ deg. Without SWB, the flow separates from the leading edge of the wing (marked by a white line in Fig. 2a). The flow is chaotic with some reversed flow over the whole wing. The flow also separates from the canard (Fig. 3a, the leading edge of the canard is also marked by a white line) and does not reattach to the wing. With SWB on ($C_{\mu_w} = 0.07$), the formerly separated flow over the wing rolls up neatly into an orderly vortex (Fig. 2b). The vortex core is clearly defined, and VBD is occurring approximately over the trailing edge. When blowing is also turned on over the canard ($C_{\mu_c} = 0.022$), it induces a vortical motion on the canard flow that reattaches to the wing (Fig. 3b).

In the initial tests, after ensuring that the pressurization of the air-supply system to the nozzles did not load the balance, SWB was turned on without airflow in the wind tunnel. The aerodynamic forces and moments, due to the jet effect only, were recorded. These were later subtracted from the forces and moments measured in the wind-tunnel flow with SWB on, in order to isolate the net aerodynamic contribution of SWB to the aerodynamic coefficients of the configuration. The net aerodynamic coefficients corrected for the jet contribution are marked by the subscript T. It is interesting to note that the lift and thrust resulting from the jets alone (no flow in the tunnel) were larger than the appropriate component of the jet momentum,[10] probably because of the jet-induced suction on the leading-edge droop.

Basic Configuration (No Canard)

Figure 4 shows the effects of SWB on the lift curve. The lift-curve slope is increased contrary to previous experience with wings of high sweep angles.[11,12] The slope increment at low angles of attack is small and is probably due to an increased

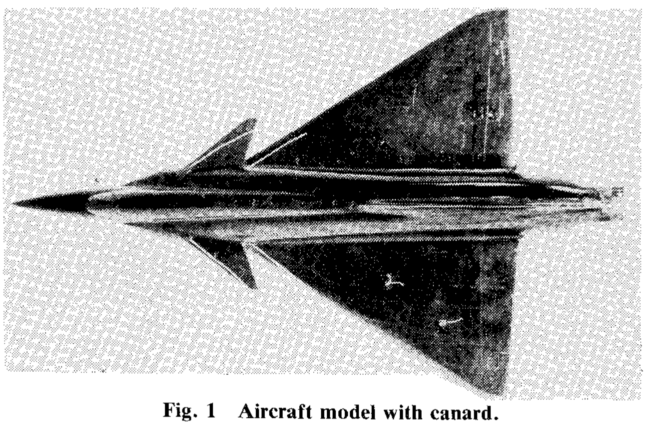


Fig. 1 Aircraft model with canard.

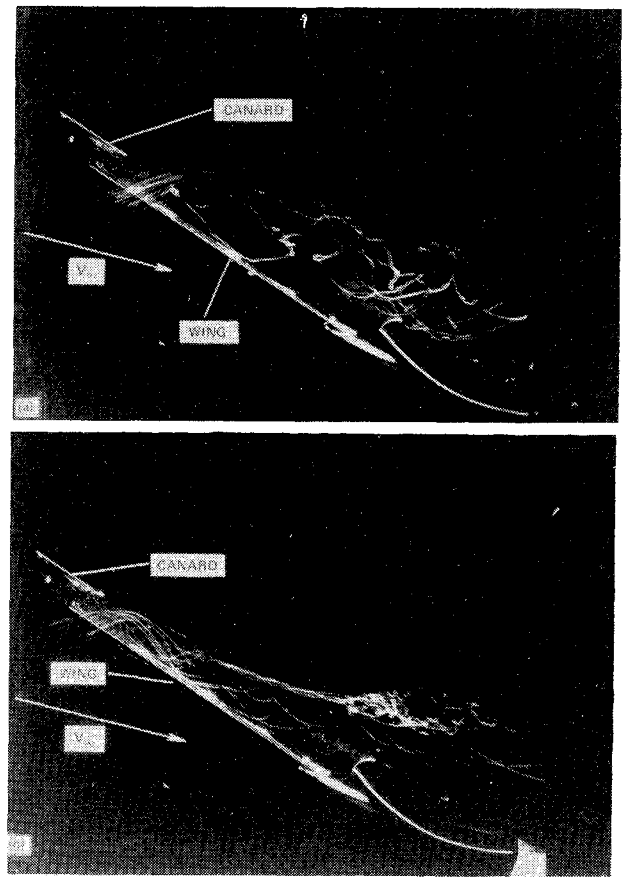


Fig. 2 Main-wing-vortex breakdown and stabilization; $\alpha = 35$ deg, $V = 30$ m/s. a) Breakdown. b) Stabilization by SWB.

effective camber.[12] At higher angles of attack, there is an appreciable increase in the slope and the maximum-lift coefficient is increased by almost 22%. The stall angle is increased by about 1 deg only. An increase in the jet-momentum coefficient from 0.05 to 0.07 affects the results only slightly. The same SWB also improves the drag polar (Fig. 5), even when it is corrected for the jet thrust. SWB affects longitudinal static stability slightly, except for extending the stable region to the new stall angle without the previously experienced pitchup.[10]

In contemplating SWB, one must consider also the performance of the aircraft when the SWB system malfunctions and blows over only one-half of the wing. Therefore, asymmetric blowing was tested,[10] and the results showed that the control surfaces could cope with the small side force, yawing moment, and rolling moment that were due to the asymmetric SWB. The additional rolling moment could even be used to augment the ailerons for rapid roll control. Another interesting result of the asymmetric SWB, because it was done with lower jet-momentum coefficients, was that the contribution of SWB to $C_{L_{max}}$ reached the point of diminishing returns at $C_\mu = 0.045 \div 0.050$.

Another unanswered question was the effect of SWB on the lateral aerodynamic characteristics of the configuration. Many airplanes are limited in high-lift maneuvers by loss of directional stability, and departure occurs below the stall angle. The basic configuration (no canard, no SWB) in the tests described here stalls at $\alpha = 34$ deg, but loss of directional stability is already experienced at $\alpha = 25$ deg. Therefore, increasing the maximum lift by SWB would be meaningless without a concurring lateral stabilization.

The effect of SWB on the lateral aerodynamic characteristics of the basic configuration were, therefore, tested extensively. The only significant effect of SWB was on the yawing moment.[10] The values of the yawing-moment coefficient with SWB are presented in Fig. 6. The basic configuration is directionally statically stable up to $\alpha = 20$ deg at sideslip angles of up to 28 deg. In this case, SWB increases the margin of stability somewhat, but its effect is not significant. At $\alpha \geq 25$ deg, however, the basic configuration is unstable, but is stabilized by SWB at $\alpha = 25$ deg even with a low jet-momentum coefficient, and at $\alpha = 30$ deg only with the highest value of $C_\mu = 0.09$. At $\alpha = 35$ deg, departure occurs even with the maximum SWB.

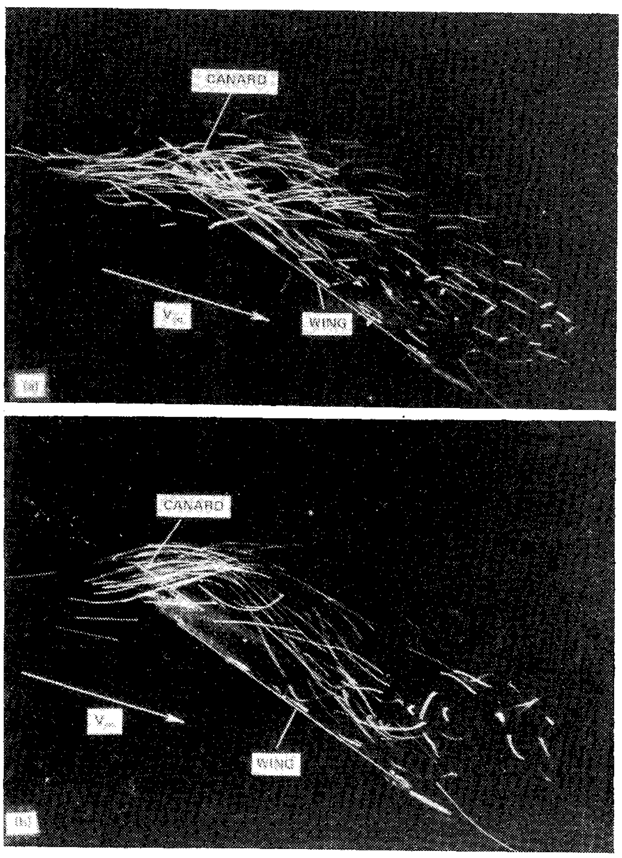


Fig. 3 Canard-vortex breakdown and stabilization; $\alpha = 35$ deg, $V = 30$ m/s. a) Breakdown. b) Stabilization by SWB.

Swirling Jets (No Canard)

As stated earlier, Dixon[13] postulated that SWB prevented or delayed VBD by acting as a barrier and preventing vortex bending in the downstream direction. He found that the downstream bending of the vortex occurred together with its breakdown and correlated these two phenomena with the ratio of vortex swirl velocity to vortex axial velocity increasing above 1.12 (or the helix angle of the vortex decreasing below 42 deg). Dixon also correlated the effectiveness of SWB with its spanwise entrainment of freestream flow. If Dixon's model

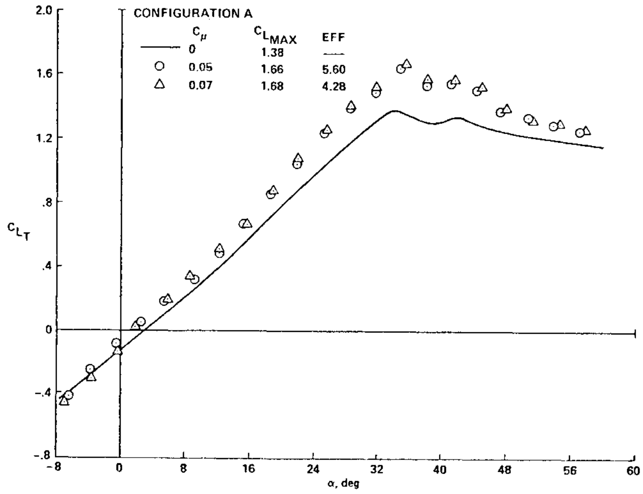


Fig. 4 Lift augmentation by SWB over the wing (no canard); $\beta = 0$ deg, $V = 30$ m/s.

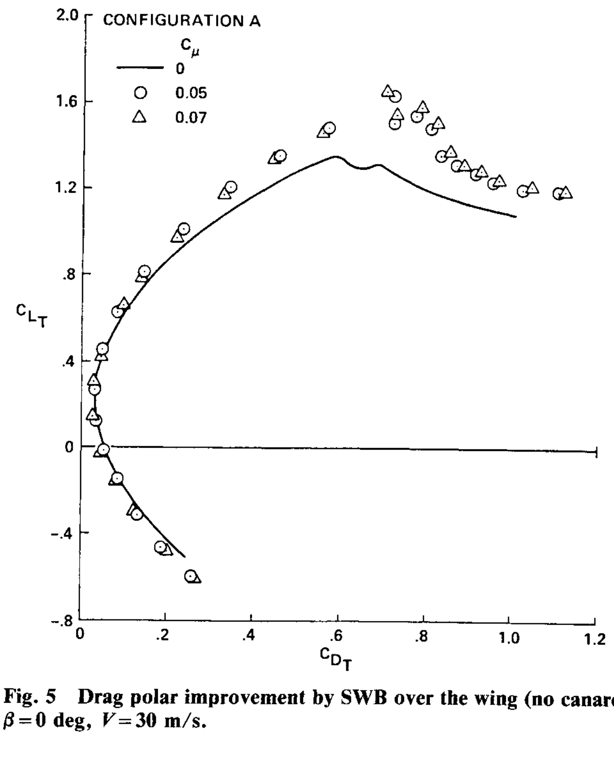


Fig. 5 Drag polar improvement by SWB over the wing (no canard); $\beta = 0$ deg, $V = 30$ m/s.

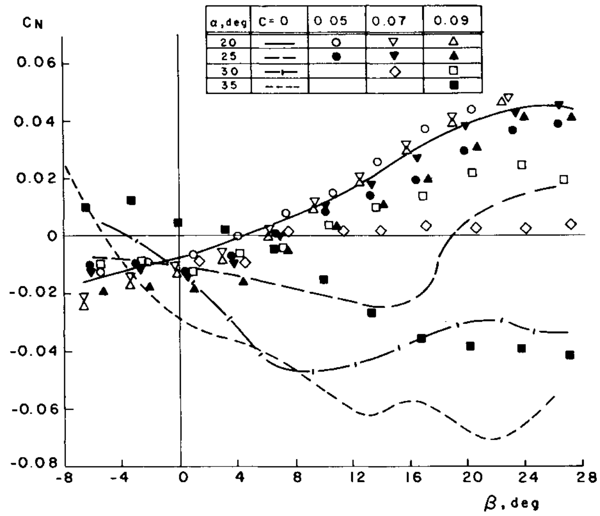
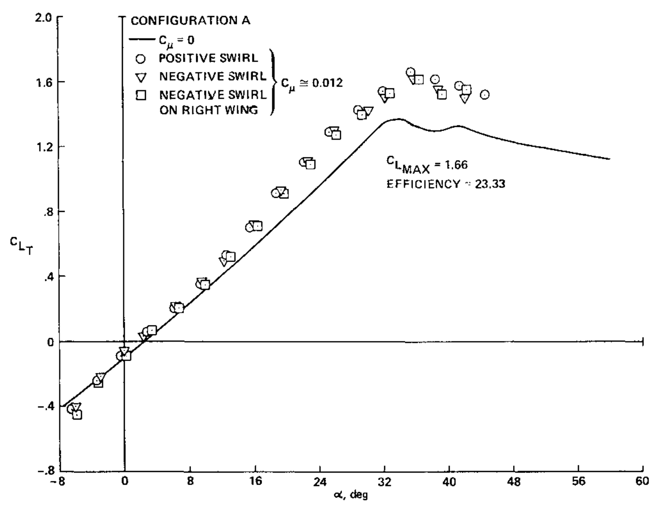
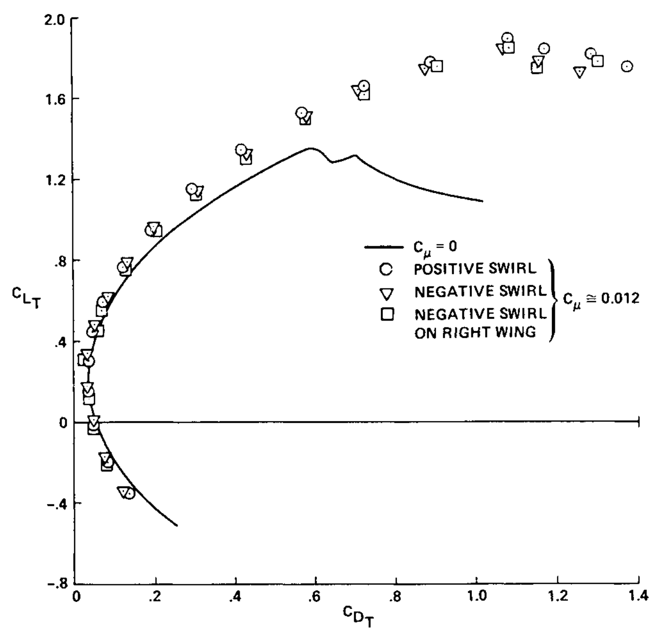


Fig. 6 Yawing-moment coefficients with SWB (no canard); $V=30$ m/s.

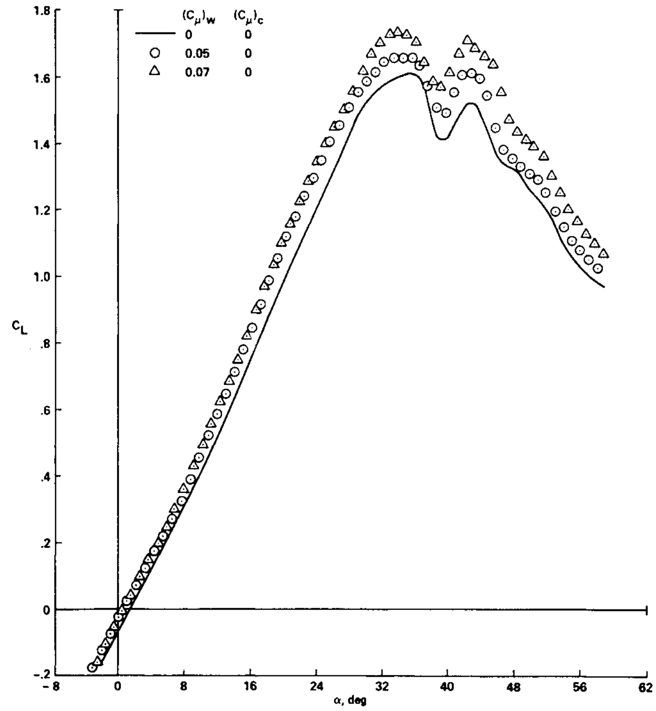


a) Corrected lift curve (jet lift removed).

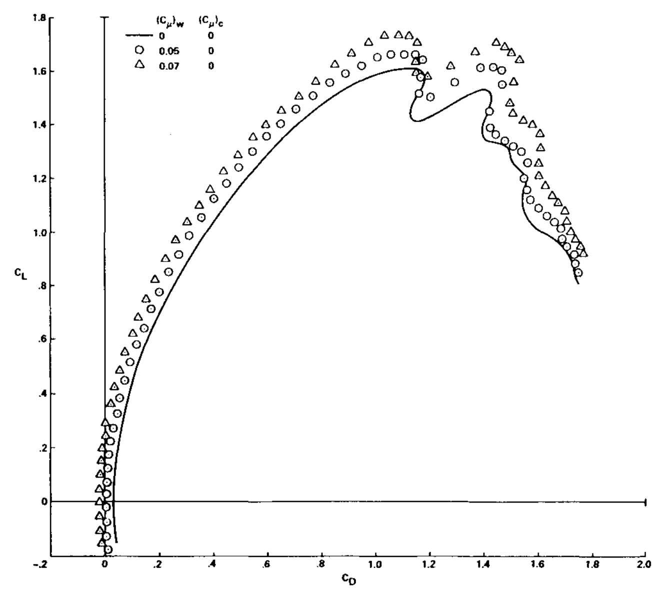


b) Corrected drag polar (jet thrust removed).

Fig. 7 SWB with "swirling" jets; $V=30$ m/s, $\beta=0$ deg.



a) Lift curve.

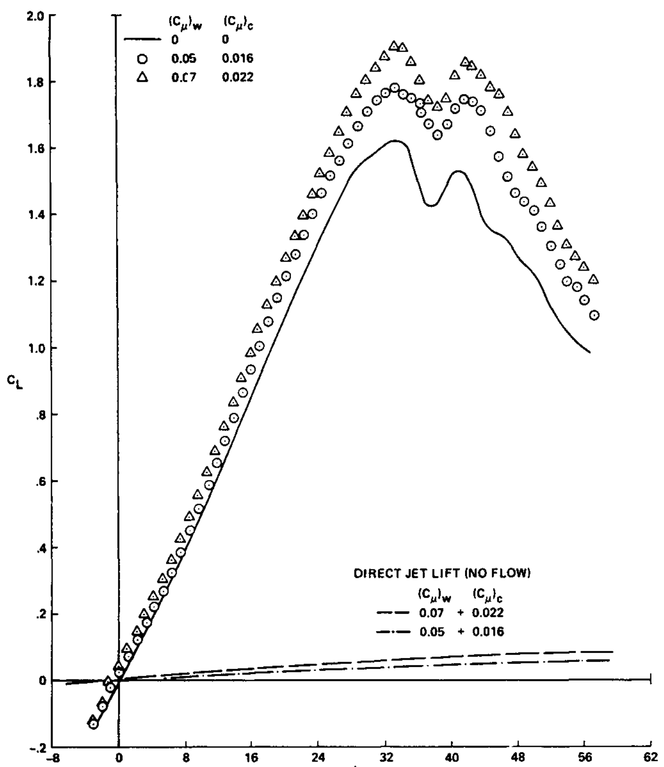


b) Drag polar.

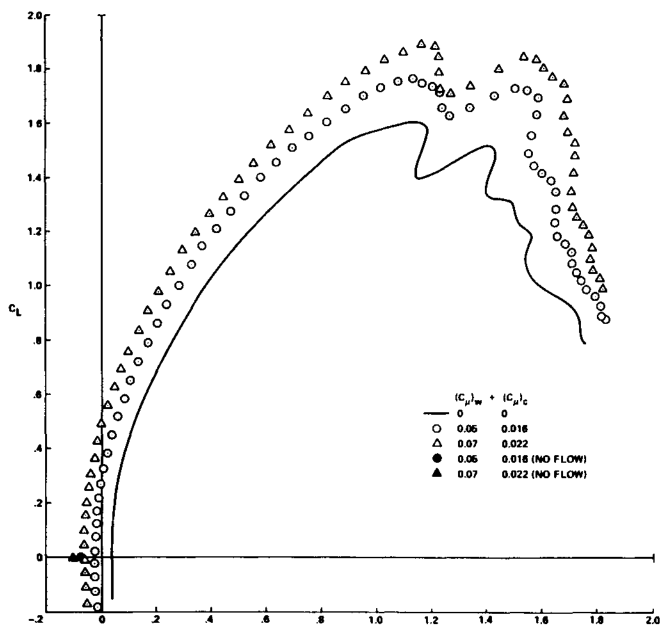
Fig. 8 SWB over the wing of the wing-canard configuration; $V=30$ m/s, $\beta=0$ deg.

describes the flow correctly, then introducing swirl into the SWB jets should have several effects on the jet-vortex interaction. Swirl increases mixing and should increase the effectiveness of SWB due to enhanced entrainment. Also, since the helix angle of the vortex plays an important role in the VBD, vortex stability could be controlled by the direction of swirl in the SWB jet. When the vortex and jet are counterrotating, the jet increases the swirl velocity of the vortex, thus, contributing to its destabilization. Conversely, a jet having the same sense of rotation as the vortex should reduce its swirl velocity and, thus, contribute to its stabilization.

To put these ideas to the test, an effort was made during this work to introduce swirl into the jets. Good swirl nozzles could not be manufactured for the small-diameter SWB nozzles. As a compromise, drill bits were sunk into the SWB tubes and nozzles over the wing with the idea of forcing the air to swirl in



a) Lift curve.



b) Drag polar.

Fig. 9 SWB over the wing and canard; $V=30$ m/s, $\beta=0$ deg.

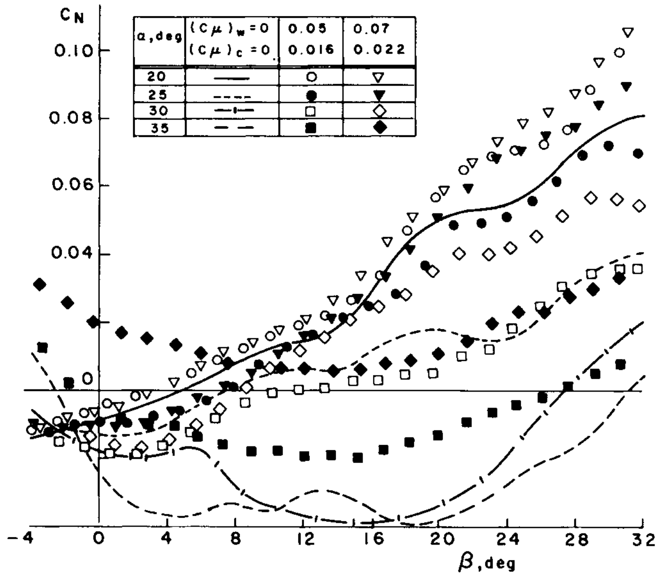


Fig. 10 Yawing-moment coefficients with SWB over wing and canard; $V=30$ m/s.

the tubes around the drill bits along their grooves. The cross section of the passage open to the air (the grooves) was only about 25% of the cross section of the SWB nozzles, thus, the jet-momentum coefficient in these tests was correspondingly reduced.

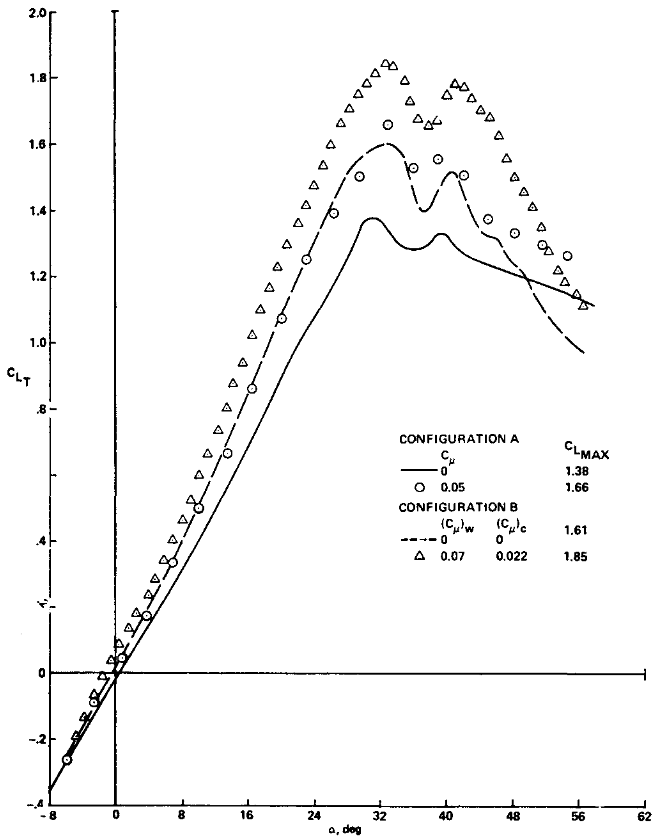
Three tests were conducted with different swirl directions (the swirl direction could be controlled by using right- or left-hand drill bits). In one test, the swirl of the jets over both wings had the same sense as the adjacent vortices ("positive" swirl in Fig. 7); in another, the jets and vortices were counter-rotating ("negative" swirl); in a third, there was negative swirl over the right wing and positive over the left. Figure 7 shows that, despite the greatly reduced jet-momentum coefficient ($C_\mu \cong 0.012$), the effect is essentially equal to that of SWB with a single axial jet with $C_\mu \cong 0.05$ (Figs. 4 and 5). The relatively small effect that the direction of swirl had on the results made the authors reconsider their apparatus and assumptions. In hindsight, they realized that the jets that emerged from the drill-bit grooves were not actually swirling, but consisted, rather, of two discrete jets at cross angles. Gersten[14] reported that SWB with multiple jets was more effective than with a single jet, but that the effect was not dramatic. However, his multiple jets were parallel and not at cross angles, therefore, his results are not directly comparable.

Wing-Canard with SWB

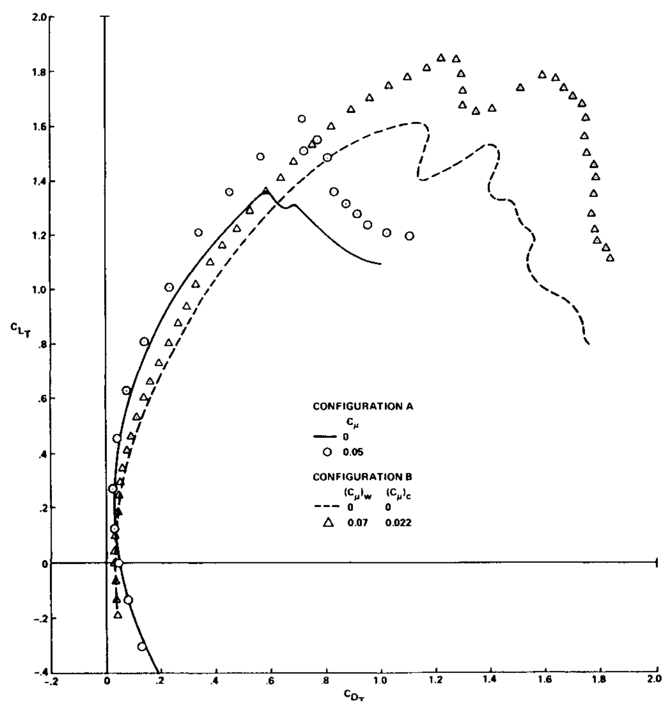
As the aircraft model with the close-coupled wing-canard configuration also was available for the purpose of comparing canard and SWB effects, it was decided to study SWB effects on the combined configuration. Testing was done with blowing over the wing alone and over both the wing and canard.

SWB only over the wing increases the slope of the lift curve above $\alpha=8$ deg, and also increases the maximum lift coefficient (Fig. 8a). It also improves the drag polar of the configuration (Fig. 8b). This, however, is done with a lower efficiency than that of SWB on the model without the canard (Figs. 4 and 5). There the efficiency, defined as $(\Delta C_L)_{\max}/C_\mu$, was 5.60 for $C_\mu=0.05$, and 4.29 for $C_\mu=0.07$, whereas on the wing-canard configuration (Fig. 8a) it is 0.60 and 1.57 for $C_\mu=0.05$ and 0.07, respectively. As expected, the efficiency is lower than without a canard, because the canard itself intensifies and stabilizes the vortex. Yet, if one is determined to increase the maximum lift at any cost, then SWB can augment even other high-lift devices. Another unexpected result is the increasing efficiency of SWB over the wing-canard configuration with the higher jet momentum, contrary to the wing-alone results presented previously, and to the results reported by Campbell.[12] Note that in Fig. 8, the lift and drag coefficients were not corrected by removing the jet thrust because the gross performance of two configurations is compared and not the net effect of SWB on the aerodynamic characteristics.

Simultaneous SWB over the wing and canard (Fig. 9) not only increases the lift augmentation and drag polar improvement above those of SWB over the wing alone, but does so with a higher efficiency, $(\Delta C_L)_{\max}/C_\mu$, of 2.27 with a total jet-momentum coefficient of $C_\mu=0.066$ ($C_{\mu_w}=0.05$ plus $C_{\mu_c}=0.016$), and of 3.04 with $C_\mu=0.092$ ($C_{\mu_w}=0.07$ plus $C_{\mu_c}=0.022$). The efficiency is again increasing when the blowing rate is increased. As in Fig. 8, here too the lift and drag



a) Lift curve.



b) Drag polar.

Fig. 11 Comparison of SWB and canard effects; $V = 30$ m/s, $\beta = 0$ deg.

coefficients are not corrected for jet thrust, but the components of the jet thrust in the lift and drag directions are presented in Fig. 9, so that the pure aerodynamic effects of SWB also can be evaluated.

The effects of SWB over the wing and canard on the directional stability of the wing-canard configuration also were studied (Fig. 10). The configuration with SWB off develops directional instability already at $\alpha = 25$ deg and $\beta \geq 10$ deg, and is completely unstable at $\alpha \geq 30$ deg. With SWB on, the configuration is stable up to $\alpha = 30$ deg at least, and departs at $\alpha = 35$ deg.

SWB Compared with the Canard

Figure 11 summarizes the results of this investigation. The lift curve and drag polar of the baseline configuration (no canard, SWB off) are compared with those of the wing-canard configuration without blowing, with SWB over the wing only, and SWB over the wing and canard. Thus, the contribution of each configuration change can be evaluated separately and compared with the others. All the results are presented with jet thrust removed.

SWB with a jet-momentum coefficient of $C_\mu = 0.05$ over the basic configuration (no canard) generates about the same lift augmentation as does the canard with blowing off (Fig. 11a, circles and dashed line, respectively). This, however, is achieved at a much lower drag (Fig. 11b, circles vs dashed line). The canard increases the drag of the basic configuration, whereas SWB reduces it (except at zero lift where the basic configuration and the one with SWB have the same parasitic drag). When the jet thrust is not removed, the zero-lift drag is much lower. Furthermore, whereas the SWB can be turned on or off as required and can thus conserve energy during most phases of a mission profile, the penalty of increased drag and additional deadweight of the canard persists throughout the flight envelope, even when the canard is not needed. The lateral/directional stabilization of the basic configuration by SWB (Fig. 6) also is better than that by the canard (Fig. 10). If one is carrying the canard anyway, then SWB over the wing alone (Fig. 8a) or over both wing and canard greatly increases the lift coefficient (Fig. 11a) with an impressive improvement of the lift-to-drag ratio (Fig. 11b, triangles vs dashed line).

Conclusions and Recommendations

Spanwise blowing over the wing and canard of a close-coupled-canard, 60-deg delta fighter-aircraft configuration was studied experimentally in low-speed flow. It was shown that, contrary to previous experience with highly swept wings, SWB not only increased the maximum lift but also increased the lift-curve slope, improved the drag polar, and increased the usable flight envelope by improving the lateral/directional stability to higher angles of attack and sideslip angles. All of the preceding was achieved with a relatively high efficiency. When SWB was used on the wing-canard configuration, the efficiency increased with increasing jet momentum.

It was shown that two adjacent jets at cross angles greatly increased the efficiency of SWB. The possible roles of the number of jets, the relative angles between the jets, and swirl in the jets on the results have to be investigated further.

Acknowledgment

The first author was a National Research Council Senior Research Associate at NASA Ames Research Center when this paper was written and first presented.

References

[1]Küchemann, D., "On the Possibility of Designing Wings That Combine Vortex Flows with Classical Airfoil Flows," RAE TM, Aero 1363, Oct. 1971.

[2]Stanbrook, A. and Squire, L. C., "Possible Types of Flow at Swept Leading Edges," *The Aeronautical Quarterly*, Vol. 15, Feb. 1964, pp. 72–82.

[3]Polhamus, E. C., "Predictions of Vortex-Lift Characteristics by a Leading-Edge Suction Analogy," *Journal of Aircraft*, Vol. 8, April 1971, pp. 193–199.

[4]Rusak, Z., Wasserstrom, E., and Seginer, A., "Numerical Calculation of Nonlinear Aerodynamics of Wing-Body Configurations," *AIAA Journal*, Vol. 21, July 1983, pp. 929–936.

[5]Wentz, W. H. and Kohlman, D. L., "Wind-Tunnel Investigations

of Vortex Breakdown on Slender, Sharp-Edged Wings," NASA CR-98737, 1969.

[6]Er-El, J. and Seginer, A., "Vortex Trajectories and Breakdown on Wing-Canard Configurations," *Journal of Aircraft*, Vol. 22, Aug. 1985, pp. 641–648.

[7]Behrbohm, H., "Basic Low-Speed Aerodynamics of the Short-Coupled Canard Configuration of Small Aspect Ratio," SAAB, Sweden, Rept. TN-60, July 1965.

[8]Cornish, J. J., III, "High Lift Applications of Spanwise Blowing," ICAS Paper 70-09, 7th Congress of ICAS, Rome, Italy, Sept. 1970.

[9]Poisson-Quinton, P., "Contrôle D'ecollement D'use Surface Portante par un Jet Transversal," 7th Congress of ICAS, Rome, Italy, Sept. 1970.

[10]Seginer, A., and Salomon, M., "Augmentation of Fighter-Aircraft Performance by Spanwise Blowing Over the Wing Leading Edge," NASA TM 84330, March 1983.

[11]Bradley, R. G. and Wray, W. O., "A Conceptual Study of Leading-Edge-Vortex Enhancement by Blowing, " *Journal of Aircraft*, Vol. 11, Jan. 1974, pp. 33–38.

[12]Campbell, J. F., "Augmentation of Vortex Lift by Spanwise Blowing," *Journal of Aircraft*, Vol. 13, Sept. 1976, pp. 727–732.

[13]Dixon, C. J., "The Mechanism of Vortex Control by Spanwise Blowing and Wing Geometry," Lockheed-Georgia Co., Marietta, GA, Engrg. Rept. LG 78-ER-0187, June 1978.

[14]Gersten, K., "Vortex Breakdown Control by Jet Injection," Colloquium on Vortex Breakdown, RWTH Aachen, FRG, Feb. 1985, verbal presentation.