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Wing Jet Blowing on the Subsonic High Alpha Research Concept Fighter Configuration

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A large-scale experimental investigation using the 55%-scale Subsonic High Alpha Research Concept (SHARC) was performed in the NASA Ames Research Center 40- by 80-ft Wind Tunnel. The SHARC configuration represents an advanced low-observable fighter aircraft, and features a clipped diamond wing with leading- and trailing-edge sweep angles of ±40 deg, a chined forebody, leading-edge extensions, and a vee-tail. Data covering the angle of attack range from −4 deg to +42.4 deg, and sideslip angles ranging from −10 deg to +10 deg were acquired at a dynamic pressure of 40 psf. Test data are presented for symmetric and asymmetric wing jet nozzle blowing. Blowing coefficient values ranged from a minimum of 0.005 to a maximum of 0.020. The results indicate that wing jet nozzle blowing is an effective lift-enhancement device, giving an across-the-board net increase in lift over the entire angle-of-attack range tested. The jets were also found to improve the aircraft's drag polar. Roll control using asymmetric jet blowing equaled or exceeded that available via the deflection of only a single aileron.

Nomenclature

C_D = drag coefficient, stability axis
C_L = lift coefficient, stability axis
$C_{L_{max}}$ = maximum lift coefficient
C_l = rolling moment, body axis
C_n = yaw moment, body axis
C_μ = blowing coefficient
c = wing mean aerodynamic chord
L/D = lift-to-drag ratio
L/D_{max} = maximum lift-to-drag ratio
V = tunnel freestream velocity, ft/s
α = angle of attack, deg
β = angle of sideslip, deg
Δ = delta or incremental
$\Delta C_L/C_\mu$ = augmentation ratio
δ = control surface deflection angle, deg
Λ_N = jet nozzle orientation angle, deg
ϕ = jet nozzle inclination angle, deg

Introduction

TO survive in the combat arena, modern and advanced fighter aircraft require the ability to aggressively maneuver in flight regimes that are characterized by highly separated flowfields and strong vortical flows. Additional emphasis on signature reduction for fighter aircraft presents a major challenge to the aerodynamicist charged with ensuring that aircraft maneuver performance is not compromised, because these types of flows reduce the effectiveness of conventional aerodynamic controls. Similarly, trends toward reduced speeds and extreme attitudes have increased the demands on aircraft stability and control. However, future military aircraft will require enhanced maneuverability and low observability, necessitating control augmentation devices that are effective at supplementing the aerodynamic control surfaces and restoring or increasing lift and controllability.

The Fighter Lift and Control (FLAC) Program was established as a cooperative research effort between the U.S. Air Force Wright Laboratory and the NASA Ames Research Center in an effort to investigate enhanced maneuver and control concepts for next-generation reduced-observability military aircraft designs. As part of this effort, both small- and large-scale wind-tunnel experiments were performed at the National Full-Scale Aerodynamics Complex (NFAC) that is located at the NASA Ames Research Center on a realistic, near-term technology configuration. Initial testing in the FLAC program was conducted in the NASA Ames Research Center 7- by 10-ft Wind Tunnel involved a 26.3%-scale semispan wing model.[1] That test focused primarily on wing lift-enhancement devices, including vortex generators, Gurney flaps, and wing leading-edge flap hingeline blowing. The second FLAC test[2–4] was conducted in the same tunnel with a three-dimensional 10%-scale model of the FLAC configuration, and focused on lateral/directional control enhancements using mechanical devices, such as forebody strakes, as well as forebody pneumatics. The third test[5] was also with the 10% model in the NASA Ames Research Center 7- by 10-ft Wind Tunnel, with the objective of improving the lift-to-drag ratio (*L/D*) over a range of sustained maneuver lift coefficients. This entry only examined mechanical lift-enhancement devices, in combination with flap settings, including various configurations of vortex generators, Gurney flaps, and other flow control concepts.

The culmination of this program was two tests of a 55%-scale Subsonic High-Alpha Research Concepts (SHARC) model, whose geometry matches that of the earlier FLAC program. This large-scale model was tested at flight-representative Reynolds numbers in two separate tests in the NASA Ames Research Center 40- by 80-ft Wind Tunnel. Each of these entries built on the results of the FLAC testing, providing concept validation of the most promising devices tested on the smaller scale model, while also testing several new concepts. Of the different devices tested on the large-scale model, most of the results have previously been documented.[6] This paper documents the results from the wing jet nozzle blowing investigation that was a part of the second SHARC entry.

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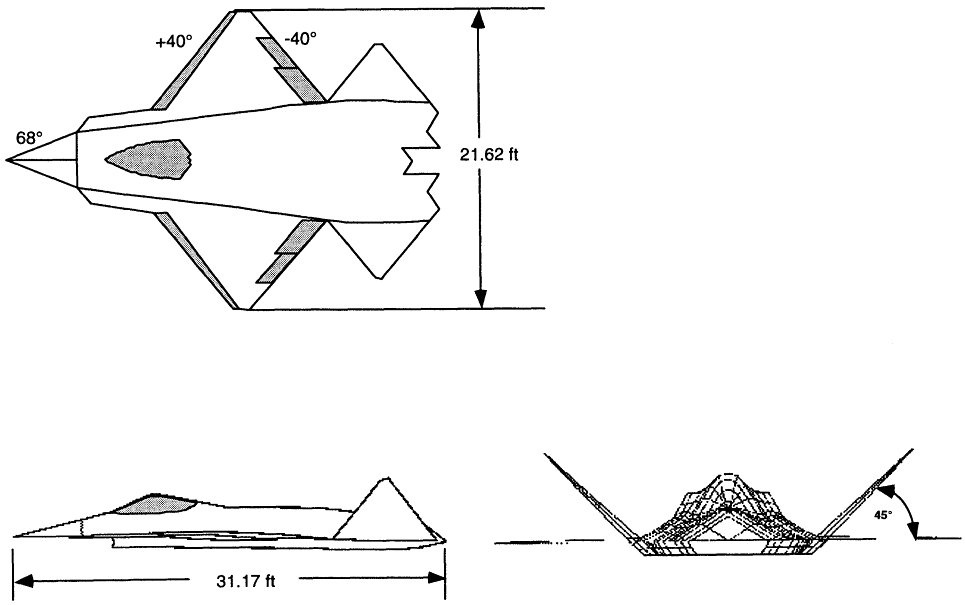

Fig. 1 SHARC 55%-scale configuration.

A number of previous studies[7-9] have demonstrated the effective utilization of wing jets for spanwise blowing to improve the moderate-to-high angle-of-attack aerodynamic characteristics of fighter configurations. The wing jet blowing accomplishes this by energizing the flow in the separated region near the wing-tip and/or trailing edge, thereby delaying separation to higher angles of attack. For this investigation, the primary objectives were to explore the use of the jets as a high-lift device to improve both lift and *L/D* in the moderate-to-high angle-of-attack range, and also to improve the configuration's lateral/directional control through asymmetric (one wing) use of the nozzles. (On the aircraft, the premise is that the wing jets would be deployed when needed, and flush to the wing surface during other phases of flight. However, testing this capability was beyond the scope of this test.) A number of parametrics were studied to quantify the effectiveness of the wing jet nozzles, including nozzle orientation angle, mass flow rate, and nozzle inclination angle.

55%-Scale SHARC Model

The SHARC model used for these tests was a 55%-scale configuration of a near-term technology, low-observable multirole fighter derivative concept that originated from the Innovative Concepts Branch (ASC/XP) at Wright–Patterson Air Force Base. The model features a chined forebody, leading-edge extensions (LEXs), deflectable leading- and trailing-edge flaps, a vee-tail canted 45 deg from the horizontal plane, and a flow-through inlet on the model's underside.

The 55%-scale model has a fuselage length of 31.17 ft, with a wingspan of 21.62 ft (Fig. 1). The wing reference area is 221.06 ft^2, the wing aspect ratio is 2.11, and the mean aerodynamic chord is 12.91 ft. The wing leading- and trailing-edge sweep angles are +40 and −40 deg, respectively. Control surfaces include a full-span constant 12.7%-chord leading-edge flap capable of deflections from 0 through +40 deg, inboard trailing-edge flaps capable of deflections from 0 through +30 deg, and outboard trailing-edge flaps (ailerons) capable of ±30-deg deflections. The vee-tails could also be deflected ±30 deg for lateral/directional control, and rotated about the 50% chord of the vertical tail.

Test Facility

The 40- by 80-ft wind tunnel is part of the NFAC at the NASA Ames Research Center. An overhead view of the facility is shown in Fig. 2, which shows a schematic of the facility as it would be configured to operate as the closed-circuit, 40- by 80-ft wind tunnel. The NFAC can be configured as either a closed-circuit wind tunnel with a 40- by 80-ft test section or an open-circuit wind tunnel with an 80- by 120-ft test section. The maximum dynamic pressure attainable in the 40- by 80-ft wind tunnel is 260 psf, which provides a maximum velocity of approximately 300 kn. The wind tunnel is driven by six 40-ft diam, variable-speed, variable-pitch fans. Each fan is powered by a 22,500-hp electric motor. The test section also features a 6-in. acoustic lining for acoustic research.

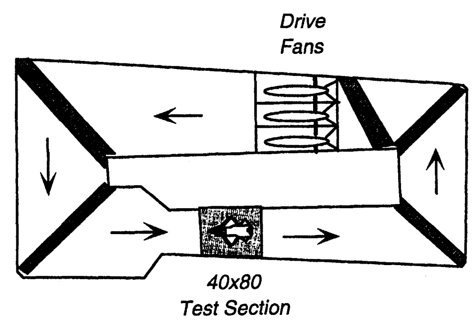

Fig. 2 NASA Ames 40- × 80-ft Wind Tunnel.

SHARC Pneumatic System Description

The SHARC model has several pneumatic systems driven by high-pressure air. The leading-edge flaps have tangentially blowing slots on both inboard and outboard sections; the forebody has three pneumatic slots along both edges; and the chin inlet is pumped by an array of ejectors inside the flow-through inlet. The mass flow rate through each of these systems is measured by means of an orifice plate mass flow meter. The slots on the leading-edge flaps are blown symmetrically, with the same combination of inboard and outboard mass flow rate on both wings. The six forebody slots were fed by a common manifold, and each forebody slot could be opened and closed independently.

Test Approach

Basic aircraft characteristics were determined for high-lift and control work, elevator, rudder, and aileron effectiveness. Flap positions were also varied to determine basic aerodynamic characteristics and for optimizing performance with lift-enhancement devices (aerodynamic interaction of devices with

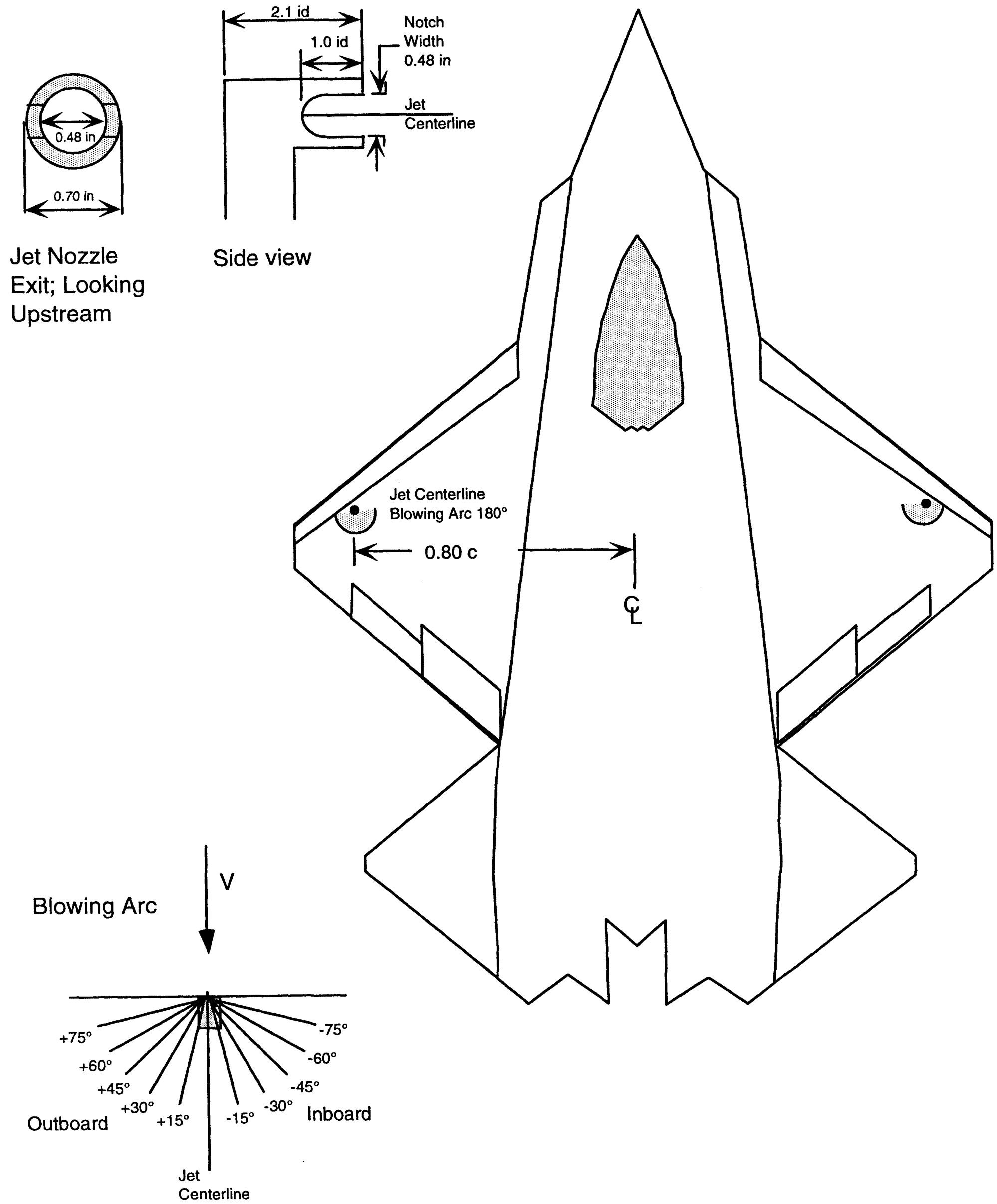

Fig. 3 Jet nozzle placement and definitions.

flowfield for various flap settings). Data covering the angle-of-attack range from −4 to +42.4 deg and sideslip angles from −10 to +10 deg were acquired at a dynamic pressure of 40 psf for all test configurations. The influence of various test devices/geometries was determined by how the force and moment characteristics compared with that of the baseline model (baselines include flaps deflected, but with no devices). In support of these, surface pressure data (over 300 wing pressures were measured with electronic scanning PSI™ modules) were taken, and flow-visualization techniques, including laser light sheets, smoke injection, pressure-sensitive paint, and natural flow condensation, were also used.

Wing Jet Blowing

The design of the jet nozzles used on the SHARC wing was patterned after the slotted nozzle developed as part of the successful X-29 vortex control flight-test program.[10] This nozzle design allows for the nearly two-dimensional expansion of the plume parallel to the wing surface. A schematic of the nozzles is shown Fig. 3. The wing jet nozzles had an i.d. of 0.48 in. and a 0-deg inclination relative to the surface ($\phi = 0$ deg) for the baseline testing. Fixtures with the nozzles inclined ±15

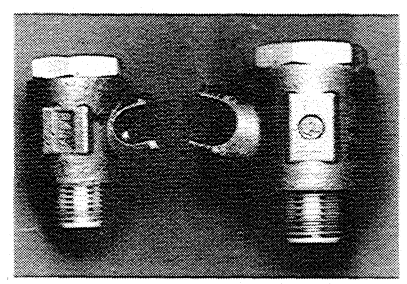

Fig. 4 Closeup of nozzles with $\phi = +15$-deg inclination.

deg to the surface ($\phi = \pm 15$ deg) were also tested (Fig. 4). Nozzle orientation angle has the same definition as wing sweep, that is, $\Lambda_N = 90$ deg corresponds to straight aft. Based on previous flow visualization results,[2–5] the nozzles were located at approximately 25% of the local chord at 80% of the half-span on the wing.

The blowing values were determined using the following relation:

$$C_\mu = \dot{m}V_j/qS_{\text{ref}}$$

Mass flow to the wing jets was limited by a maximum pressure of 1600 psi in the line feeding the two jets. Thus, with both sides running, a maximum mass flow of 5.6 lbm/s could be achieved. The lift-enhancement work was then limited to 109 kn, or a $q = 40$ psf, to achieve maximum blowing coefficient values of $C_\mu = 0.020$. With only one side running, these values were halved, so that the maximum C_μ for the asymmetric blowing was 0.010.

Discussion of Results

In the discussion of results, a reference to a *baseline* refers to an aircraft configuration with identical flap settings, but without the wing jet nozzles. Also, when referring to *flap settings*, the leading-edge deflection is given first, followed by the trailing-edge deflection. For example, 20 deg/0 deg refers to a leading-edge deflection of 20 deg and a trailing-edge deflection of 0 deg.

All longitudinal aerodynamic data are referenced to the stability axis; lateral/directional data are referenced to the body axis. Tare corrections because of the pressurization of the high-pressure air lines and jet thrust effects have been applied so that the data presented would reflect only the aerodynamic effects, unless otherwise noted. Results presented here show the effects a wing jet blowing system has on vehicle aerodynamics. Changes in aircraft performance resulting from engine and airframe installation are not evaluated.

Figure 5 shows a summary of the aerodynamics of the best four flap settings, based on the overall lift and *L*/*D* characteristics in comparison to the baseline 0 deg/0 deg flap setting. The wing jets were subsequently tested on these configurations. Only the 20 deg/0 deg configuration results are presented here because of space limitations. However, it should be noted that the same general trends found in this configuration were also noted at the other flap settings.

Nozzle Orientation Effect

The effects of varying nozzle orientation angle, Λ_N, at a constant nozzle inclination angle, ϕ, are presented in Fig. 6 for the 20 deg/0 deg flap setting at a constant blowing coefficient of $C_\mu = 0.020$. Across the entire angle-of-attack range, the wing jet nozzles contribute significant lift increments in comparison to the baseline, with the greatest improvements at the $\Lambda_N = 40$- and 90-deg orientations. (These orientations correspond to nozzles directed along the leading edge and straight aft, respectively.) The lift increases were largest for angles of attack greater than approximately 10 deg, and can largely be attributed to the ability of the jets to maintain attached flow on the outer portion of the wing.

Flow visualization performed in earlier FLAC testing[2–6,11] showed a strong forebody/LEX vortex that moves the wing leading-edge vortex outboard as the angle of attack increases. By $\alpha = 12$ deg, this wing vortex has broken down, and flow separation and reversed flow are evident. At $\alpha = 20$ deg, these flow patterns become even more apparent (Fig. 7). The wing jets provide favorable pressure gradients on the outer portion of the wing, allowing the flow to remain attached until higher angles of attack. It is also speculated that the jets enhance the existing wing vortex, delaying its breakdown to higher angles of attack as well.

The wing jets' lifting effectiveness is highlighted in Fig. 8. The jets were most effective in providing lift increments for

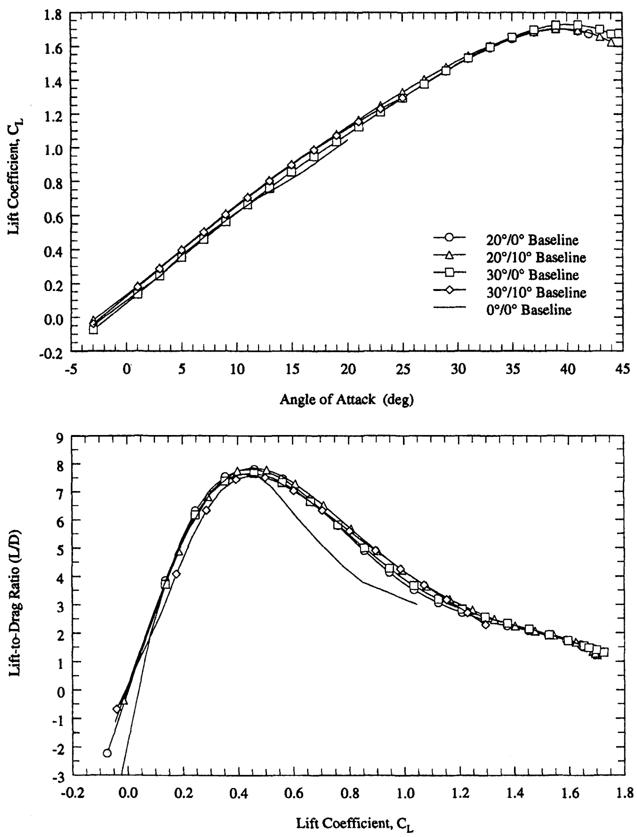

Fig. 5 Baseline flap setting comparison.

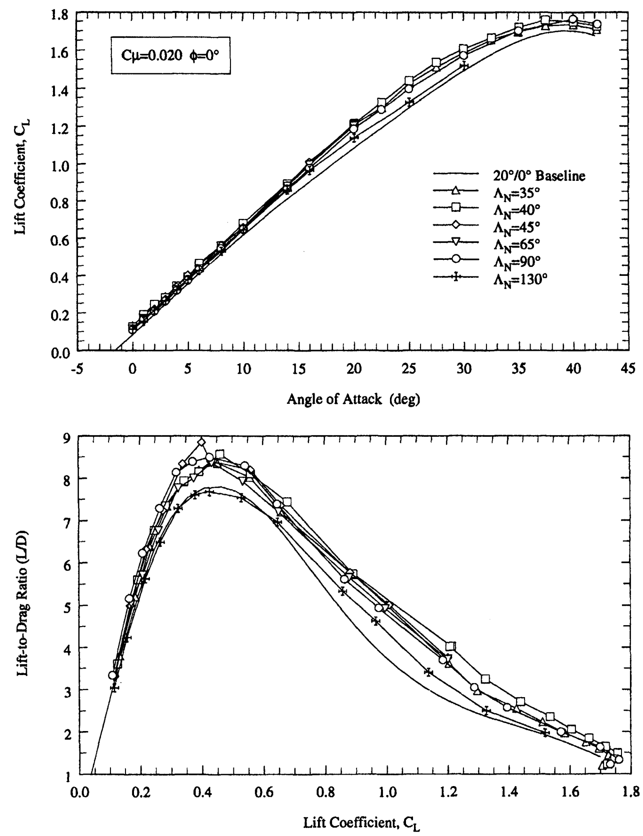

Fig. 6 Nozzle orientation (Λ_N) effects.

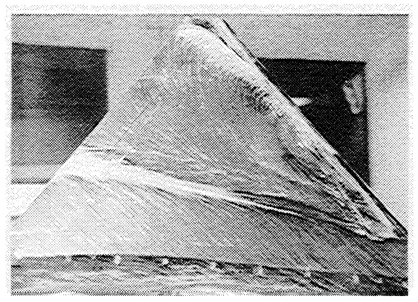

Fig. 7 FLAC 10%-scale model titanium dioxide flow visualization for 20 deg/0 deg flap setting at $\alpha = 20$ deg.

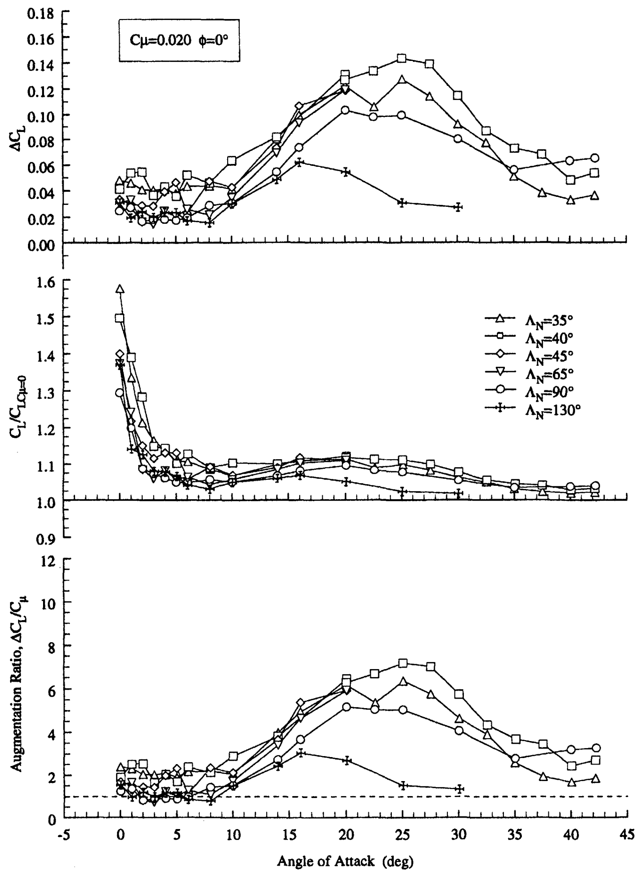

Fig. 8 Nozzle orientation effect on lifting effectiveness.

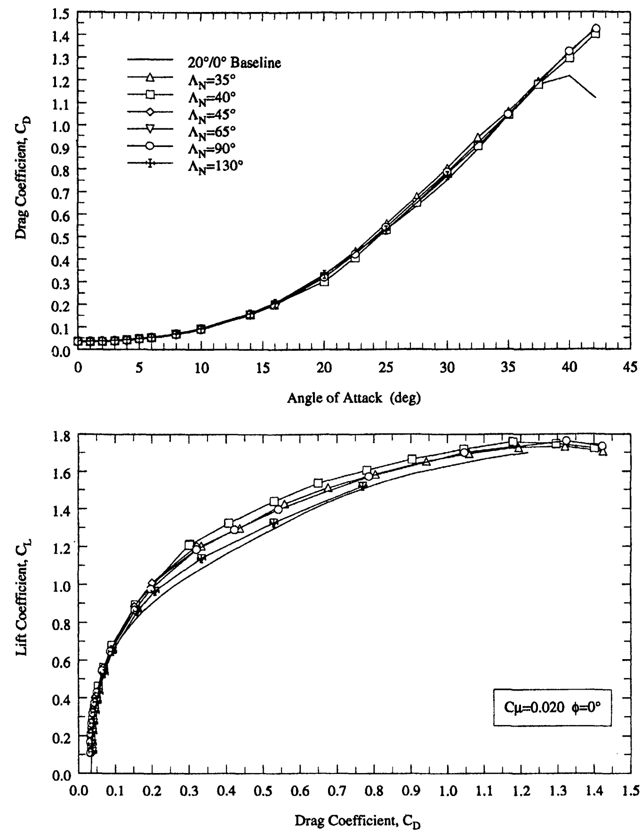

Fig. 9 Nozzle orientation effect on drag.

angles of attack between 10 and 35 deg. The best orientation angle was $\Lambda_N = 40$ deg, which provided a $\Delta C_L = 0.144$ at $\alpha = 25$ deg, an 11% increase. $C_{L_{max}}$ was also increased with the wing jets, by as much as 6.5% in the best case. No change, though, was found in the angle of attack for maximum lift.

The ratio of C_L with blowing to C_L, without blowing ($C_L/C_{LC_{\mu=0}}$), is a measure of merit representing lift effectiveness, and indicates the percentage increase in lift available with blowing. A near-constant increase of approximately 10–12% is seen for angles of attack between 5 and 35 deg for the best orientations of $\Lambda_N = 35$, 40, and 90 deg.

The lift augmentation ratio, $\Delta C_L/C_\mu$, also shows the lift effectiveness of the wing jet blowing by comparing how well the blowing increases the wing lift compared with simply vectoring the blowing in the direction of lift for thrust lift. Thus, for augmentation ratios less than 1.0, the jets would be more effective used as direct lift devices. Again, it was found that a nozzle orientation of $\Lambda_N = 40$ deg was most effective, with the jets most effective between 10 and 35 deg angle of attack. A surprising result was that the nozzle directed straight aft ($\Lambda_N = 90$ deg) was ineffective ($\Delta C_L/C_\mu < 1.0$) below $\alpha = 10$ deg.

A key benefit of the wing jets is the lowering of the angle of attack necessary to achieve a given lift. An examination of the lift curves in Fig. 6 shows a small shift in lift-curve slope for $\alpha > 12$ deg, resulting in approximately a 3 to 4 deg lowering of the angle of attack required for a given C_L. (For example, for $C_L = 1.0$, $\alpha = 16$ deg was required with blowing vs $\alpha = 19$ deg without blowing.) A direct result of this shift is a large reduction in drag for lift coefficients in the moderate-to-high-angle-of-attack range (Fig. 9). It should be noted, however, that while achieving a drag reduction for a given C_L, the wing jet blowing did not decrease drag at a given angle of attack (Fig. 9). Thus, because the angle of attack required with blowing was lower for a given lift, the corresponding drag at that angle of attack was smaller. This drag reduction becomes even more evident when we examine the L/D (Fig. 10). L/D was improved by as much as 49% for lift coefficients values above 0.8 on the 20 deg/0 deg flap settings. L/D_{max} was also increased by as much as 8.5% for the 40- and 90-deg nozzle orientation angles. As a result of the preceding comparison, the 40- and 90-deg orientation were selected as the optimum.

It must be noted that these aerodynamic improvements do not come without paying a penalty. A recent study, looking at the practicality of incorporating pneumatic control technology into future aircraft, indicated that engine bleed flow rates of up to 6 lbm/s were maintainable throughout the flight envelope. However, specific fuel-consumption impacts on the order of 10% were noted when utilizing the pneumatics; likewise, weight increases on the order of 450 lb because of pneumatic device installation were noted. (This study highlighted the impact of incorporating pneumatic devices onto existing aircraft configurations. No effort was made to account for weight reduction because of control surface reduction or elimination.) Thus, while potentially beneficial, the proper integration of pneumatics into the design at the earliest stages of the concept definition is paramount to achieve the greatest benefit.

Mass Flow Rate Effect

Having determined the optimal nozzle orientation angle(s), the effects of variable mass flow rate were investigated next. Here, the objective was to maximize the effectiveness while minimizing mass flow requirements. As expected, an increase in the mass flow rate (C_μ) produced a proportional increase in lift, as shown in Fig. 11 for $\Lambda_N = 40$ deg and the 20 deg/0 deg flap setting. Again, the jet blowing was most effective in the moderate-to-high-angle-of-attack range, 15 deg $< \alpha <$ 30 deg.

However, in terms of lift effectiveness, an examination of the lift augmentation ratio curves in Fig. 12 indicates that the smaller blowing coefficients were much more efficient in providing increased lift for angles of attack between 10 and 16 deg. (This was true for both nozzle orientations investigated.)

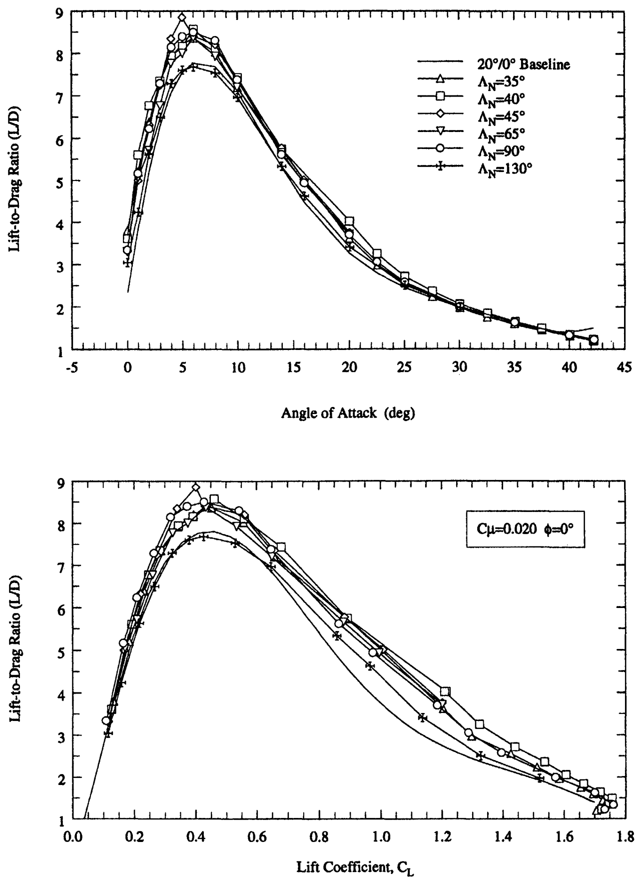

Fig. 10 Nozzle orientation effect on L/D.

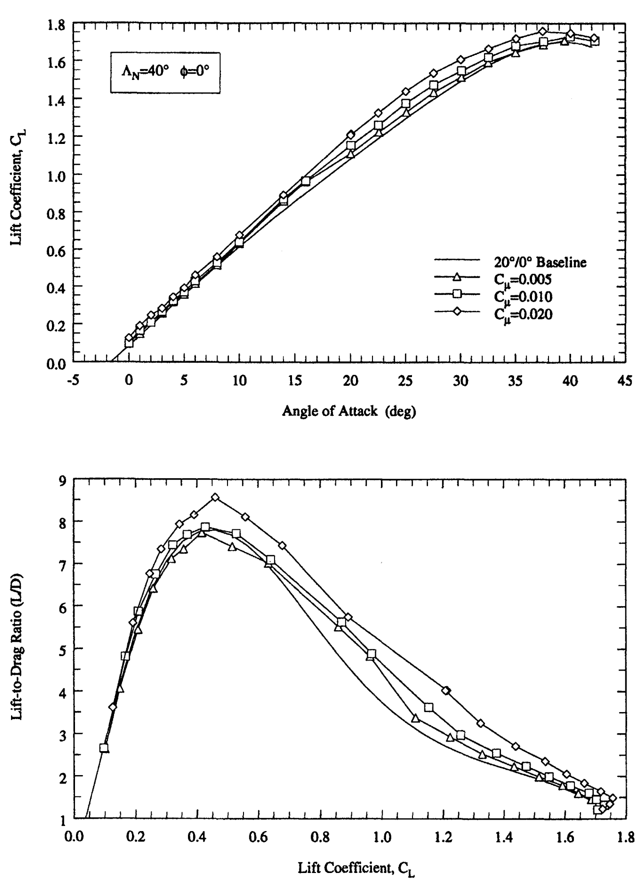

Fig. 11 Blowing rate effect.

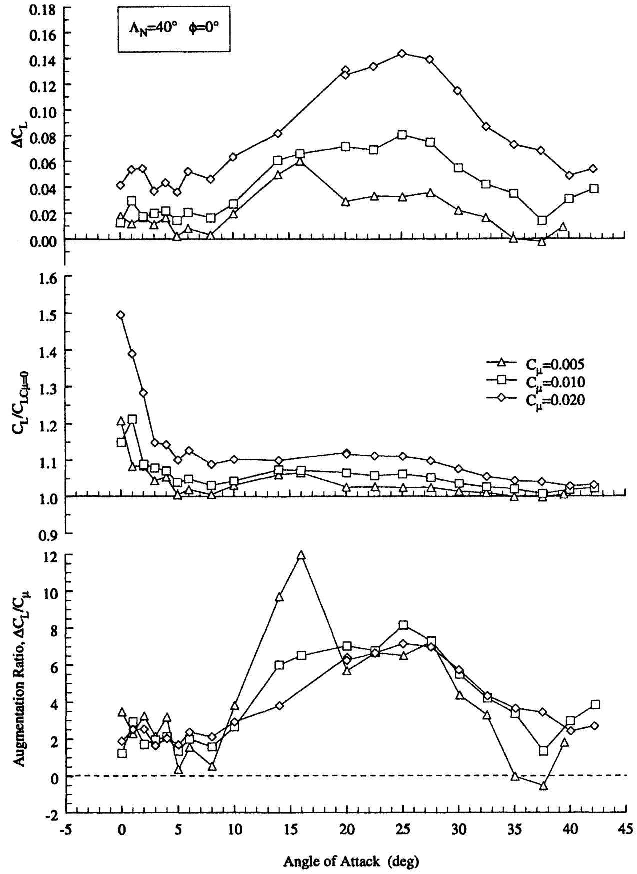

Fig. 12 Mass flow rate effect on lifting effectiveness.

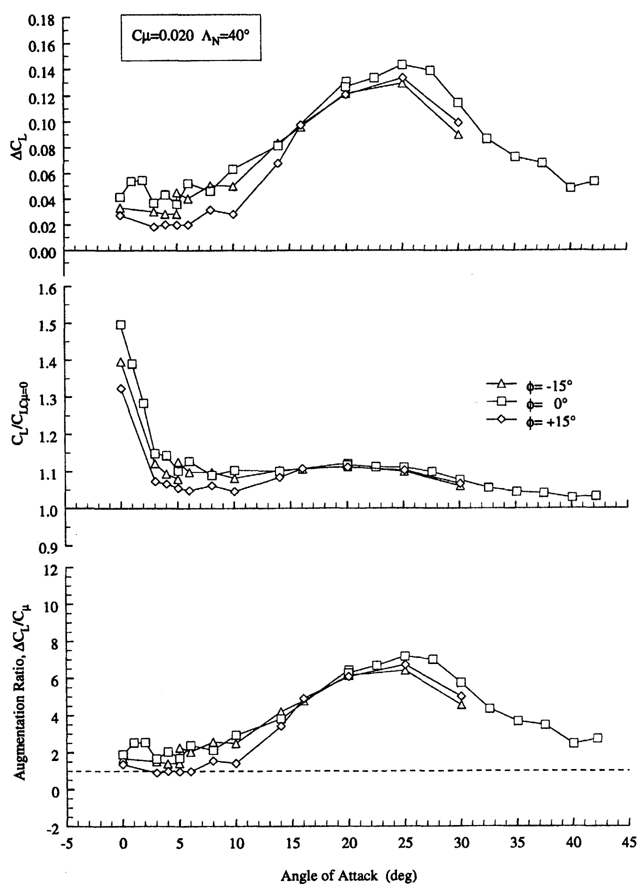

Fig. 13 Nozzle inclination angle effects.

In the angle-of-attack range of 16 deg < α < 30 deg, all three blowing rates were comparable. This result suggests that the lowest blowing rate was sufficient enough to enhance the wing vortex, while higher rates were not as effective.

Inclination Angle Effects

The effects of nozzle inclination angle (ϕ) are shown in Fig. 13 for three nozzle inclination angles investigated, at the maximum blowing coefficient of $C_\mu = 0.020$ and a nozzle orientation angle of $\Lambda_N = 90$ deg. The nozzle inclination angle showed little effect on lift, although at low angles of attack the ϕ = 0-deg inclination was slightly better. In terms of L/D, all inclination angles provided improvement, though none outperformed the baseline elevation of 0 deg.

Asymmetric Wing Jets

A number of runs were made to determine the effectiveness of asymmetric jet blowing as a roll and/or yaw control device. For this investigation only the right-hand wing nozzle was used, with $\Lambda_N = 90$ deg and $\phi = 0$ deg. Figure 14 summarizes the results for the 20 deg/0 deg flap setting. It should be noted that the rolling and yawing moment data are presented in body axes, and have not been corrected for jet thrust effects.

A significant result from the asymmetric jet blowing was the jet's ability to provide rolling moment equal to or greater than that of single-side (one wing) aileron deflections. Earlier testing of the SHARC model showed that a single-side aileron deflection of $\delta_A = 30$ deg produced a maximum rolling moment of $C_l = 0.011$ in the 10 deg < α < 16 deg range, with effectiveness dropping off rapidly above α = 16 deg. (For $\delta_A = 20$ deg, the maximum increment was 0.008.) With the asymmetric jet blowing, a maximum rolling moment increment of $C_l = 0.020$ was achieved at the maximum $C_\mu = 0.010$, as shown in Fig. 15.

One might expect that the single jet would also provide a significant yaw moment. However, the jets did not prove to be

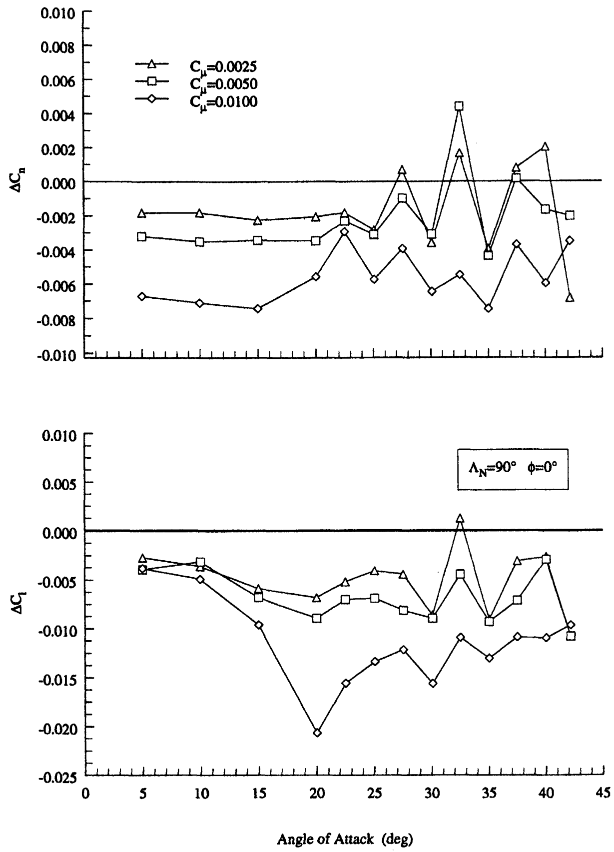

Fig. 15 Incremental yaw/roll moments using asymmetric wing jet blowing.

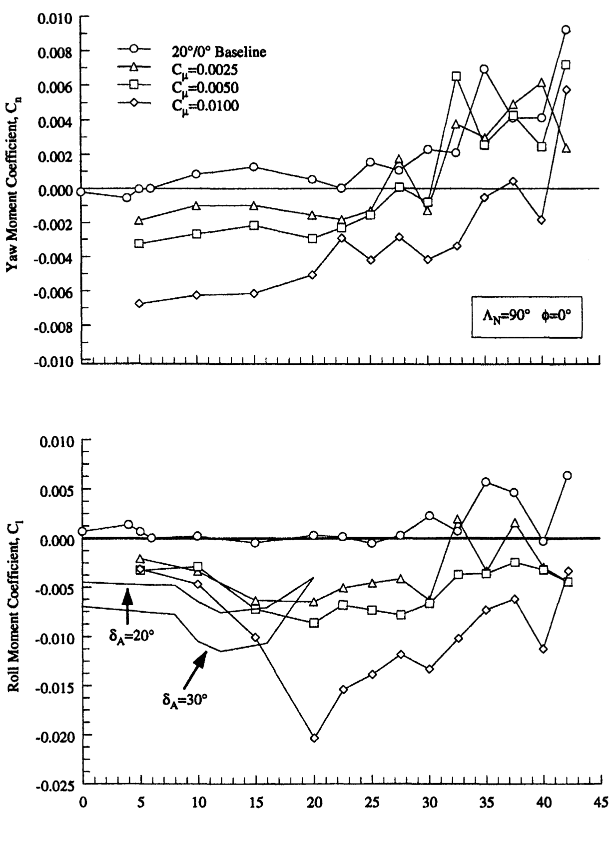

Fig. 14 Yaw/roll effectiveness of asymmetric wing jets.

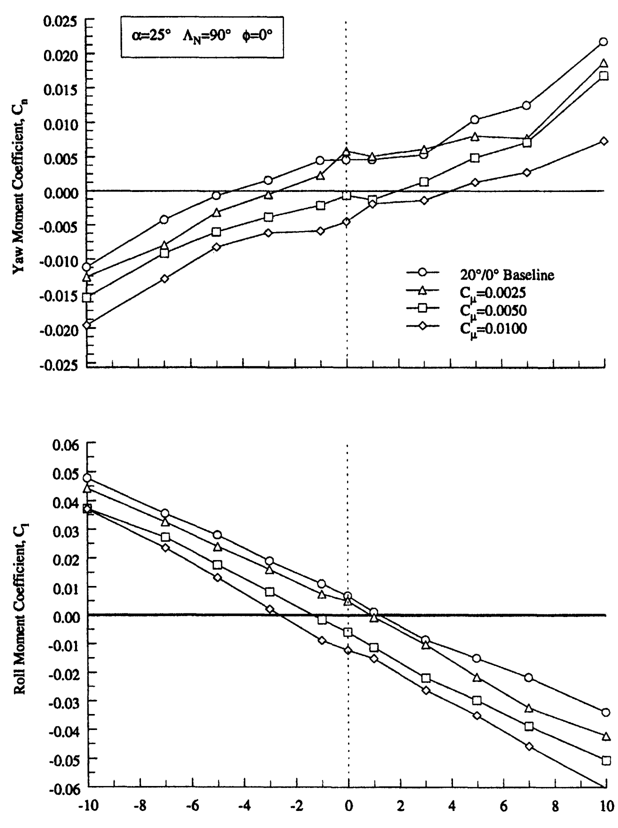

Fig. 16 Asymmetric jet blowing effectiveness at sideslip for α = 25 deg.

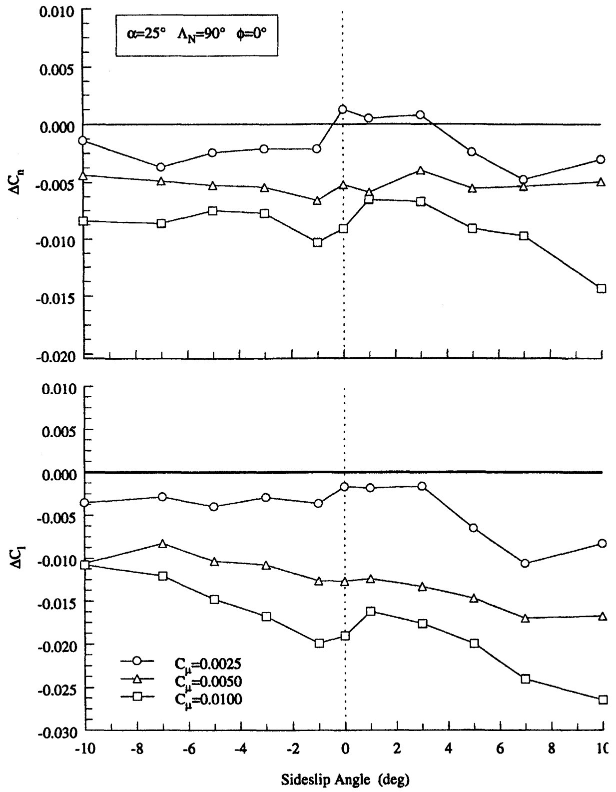

Fig. 17 Incremental yawing and rolling moment at sideslip for $\alpha = 25$ deg.

effective as yaw control devices (Fig. 15). The right-hand jet produces more lift on the right-hand wing, generating a negative rolling moment. This increase in lift comes with a very small increase in drag, generating a (small) positive yawing moment, while the jet thrust produces a (large) negative yawing moment. The net result is a low level of proverse yawing moment ($|C_N| < 0.006$), which is desirable.

The asymmetric jet blowing effectiveness at sideslip is shown in Figs. 16 and 17 for $\alpha = 25$ deg and a varying blowing rate. The wing jet showed no significant effect on the aircraft's lateral/directional stability, while maintaining its effectiveness through sideslip angles of ± 10 deg. The jet provided near-constant increments across the sideslip range tested (-10 deg $< \beta < +10$ deg), in direct proportion to the blowing rate, although it was more effective at positive sideslip, where the natural tendency of the aircraft to roll away from sideslip and the wing jet blowing are working together.

Summary and Conclusions

A large-scale experimental investigation using the 55%-scale SHARC was performed in the NASA Ames Research Center 40- by 80-ft Wind Tunnel. The results indicated the following conclusions.

1) Wing jet nozzle blowing is an effective lift-enhancement device, giving an across-the-board net increase in lift of approximately 10% for the entire angle-of-attack range tested, with jet thrust effects removed.

2) The wing jets were found to improve the aircraft's drag polar. By allowing a given level of lift to be achieved at a lower angle of attack, the resulting drag at that angle of attack was lower, thus resulting in a drag reduction for a given lift.

3) The wing jets were most effective either when directed along the wing leading edge ($\Lambda_N = 40$ deg) or directed straight aft ($\Lambda_N = 90$ deg). Increasing the mass flow increased the lift, but lower blowing coefficients were more efficient in providing increased lift. The nozzle inclination angle had only minor effects.

4) The wing jet nozzles, when used asymmetrically, provided roll control that equaled or exceeded that available via the deflection of only a single aileron, and also gave a low level of proverse yawing moment with the roll when thrust effects were included.

5) Wing jet blowing, while effective as a lift and/or control device, must be considered during aircraft development, particularly for concepts that already have engine bleed systems and/or engines designed to provide high-pressure air without a significant loss of thrust.

Acknowledgments

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