DEVELOPMENT OF THE CIRCULATION CONTROL WING / UPPER SURFACE BLOWING POWERED-LIFT SYSTEM FOR STOL AIRCRAFT

ICAS-82-6.5.1

M.J. Harris#, J.H. Nichols, Jr.*, R.J. Englar +, and G.G. Huson#

STOL Aerodynamics Group, Aircraft Division
David W. Taylor Naval Ship Research and Development Center
Bethesda, Maryland 20084

ABSTRACT

The Circulation Control Wing/Upper Surface Blowing system is an advanced powered-lift concept currently under development for commercial and military application. High lift is generated by this system through pneumatic control of wing circulation and pneumatic deflection of jet engine exhaust. This potential to generate high lift as required for STOL operation has been confirmed through a series of static and wind tunnel investigations. Static investigations included both small-scale cold gas and full-scale hot gas demonstrations. These investigations have demonstrated that this mechanically simple pneumatic system can generate high lift as effectively as heavier, complex mechanical flap systems. This paper summarizes the technology development of this advanced powered-lift system.

INTRODUCTION

A principle employed by most powered-lift systems is circulation enhancement (or supercirculation). Two such concepts are Upper Surface Blowing (USB) and the Circulation Control Wing (CCW). An advanced powered-lift system currently under development at David Taylor Naval Ship Research and Development Center (DTNSRDC) embodies both these concepts.

In the Circulation Control Wing concept, a small blown circular surface replaces the conventional trailing edge flap. Compressed air is expelled tangentially over a small-radius circular surface from a thin spanwise slot in the aft upper surface of the circulation control airfoil (see Figure 1). This thin jet sheet flows around this curved trailing edge, adhering to this surface. This phenomenon, commonly known as the Coanda effect, results from a balance between the centrifugal force and a reduced static pressure across the jet sheet.

Lift augmentation at lower values of the blowing momentum coefficient, C_μ, is due predominantly to boundary layer control. Higher lift augmentation is achieved through enhanced circulation. Without a sharp trailing edge the Kutta condition no longer fixes the circulation strength. The circulation, and therfore the location of the leading and trailing edge stagnation points, is controlled pneumatically on a circulation control airfoil by varying the momentum of the jet sheet. Increasing the blowing momentum is equivalent to increasing the wing camber near the trailing edge. Lift coefficients in excess of those predicted by potential flow techniques are generated at these higher blowing levels. Therefore supercirculation is achieved.

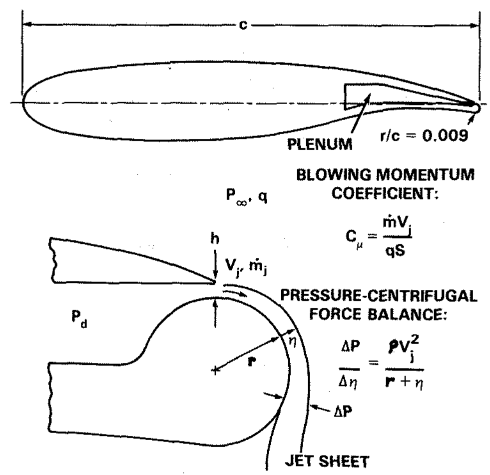

Fig. 1 Circulation Control Airfoil based on a 17-percent thick NASA Supercritical Airfoil

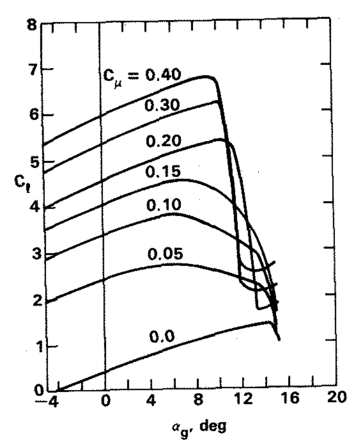

Fig. 2 Sectional Lift Characteristics of a 17-percent thick Supercritical Circulation Control Airfoil

Aerospace Engineer; Member AIAA
* Head, Aircraft Division; Member AIAA
\+ CCW Program Manager; Member AIAA

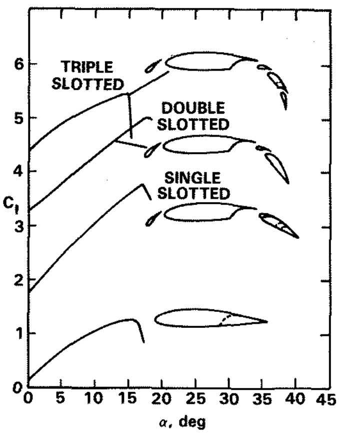

Fig. 3 Multi-Element High-Lift Airfoils with Mechanical Flaps and Slats

Sectional lift characteristics for a 17-percent thick supercritical circulation control airfoil[1] are presented in Figure 2 for constant values of the sectional blowing momentum. Sectional lift coefficients approaching 7 are achieved at relatively low momentum coefficients ($C_\mu = 0.4$). This lift augmentation compares favorably with the lift augmentation of complex multiple-element flap systems. For comparison, lift characteristics for several typical multi-element airfoils[2] are presented in Figure 3.

This high-lift capability is achieved without the weight or mechanical complexity of multi-element flap systems. Transformation from high lift to cruise configuration requires only turning off the the circulation control blowing. The cruise configuration drag polar for this supercritical circulation control airfoil is compared in Figure 4 to the drag polar for the baseline conventional supercritical airfoil[3]. With the diameter of the circulation control trailing edge only 1.88-percent of the wing chord, essentially no increase in drag results from leaving this circular surface deployed during cruise flight. Therefore no moving surfaces are required for high lift. Thus, a no-moving-parts high-lift system without a corresponding drag penalty is feasible.

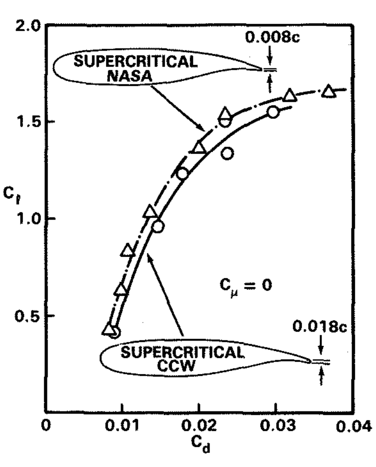

Fig. 4 Cruise Configuration Drag Polars

A Navy A-6 attack aircraft was modified to demonstrate the Circulation Control Wing concept. Based on flight test results[4,5], the A-6/CCW demonstrator aircraft could produce a maximum lift coefficient ($C_{L_{max}}$) of 3.9 at a blowing momentum coefficient (C_μ) of 0.3. This represents an 85-percent increase in $C_{L_{max}}$ when compared to a conventional A-6 with a slotted flap deflected 30 degrees. This increase in lift capability provides a STOL capability or an increase in useful payload of 75-percent while operating with a conventional ground roll.[6]

The Upper Surface Blowing concept is also based on the Coanda effect. In this concept, thick propulsive jets, produced by turbofans mounted above the wing, remain attached to large radius mechanical Coanda flaps and are deflected down at the trailing edge of the wing. In addition to the lift recovered from turning the propulsive jet, this downward momentum enhances fuselage and wing lift. Both the NASA Quiet Short-haul Research Aircraft (QSRA) and the YC-14 have demonstrated this concept.

The QSRA demonstrated several unassisted takeoffs and landings from the aircraft carrier USS Kitty Hawk (CVA-63).[7] Repeated free deck takeoffs and unarrested landings demonstrated the STOL performance and controllability of this aircraft.

The Circulation Control Wing/Upper Surface Blowing (CCW/USB) concept combines propulsive effects with circulation control. The sketch in Figure 5 represents a proposed advanced STOL aircraft embodying the CCW/USB powered-lift concept. In this configuration, turbofans are mounted above a circulation control wing so that the exhaust scrubs the wing inboard upper surface. In addition to controlling the effective wing camber with circulation control blowing, propulsive-induced lift is also generated by deflecting downward the propulsive jet with circulation control blowing over the inboard trailing edge. The degree of deflection of the propulsive jet is controlled pneumatically by the momentum of the circulation control jet sheet. This arrangement of engine and blown trailing edge results in a mechanically less complex and lighter weight system than the mechanical Coanda flap/double slotted flap system normally employed on USB aircraft.

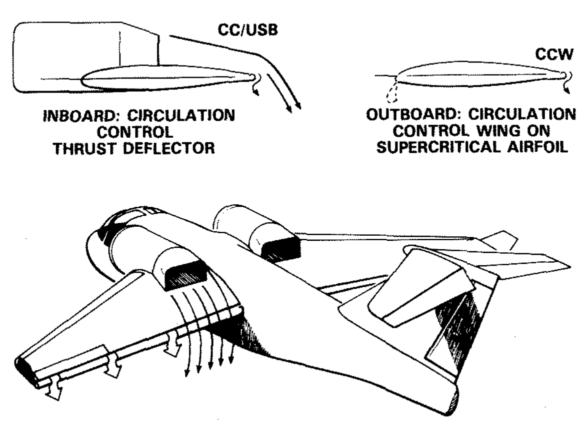

Fig. 5 Proposed CCW/USB STOL Aircraft

The CCW/USB powered-lift system is being investigated concurrently with further development of the circulation control wing. CCW development since the successful A-6/CCW flight demonstration is being incorporated into the CCW/USB concept. Since these new developments are documented in References 1 and 8, this paper will concentrate on the thrust turning with circulation control and how this capability can enhance the high lift generated by the circulation control wing. Initial confirmation of this capability is presented in Reference 6.

Static Thrust-Turning Investigations

The capability to enhance the high lift of the circulation control wing with propulsive-induced lift is dependent on how efficiently the propulsive jet can be turned. An indication of this efficiency is the static thrust deflecting capability of the circulation control trailing edge. A parametric investigation was conducted to determine which parameters influenced the capability of circulation control to deflect a thick propulsive jet. The experimental apparatus used in this investigation is shown in Figure 6.

Tandem tip-turbine fans served as the source of the thick propulsive jet. Three interchangeable two-dimensional nozzles were used to produce an aspect ratio 2,4, or 6 jet. This jet was blown tangentially along a flat plate which formed the lip of the circulation control blowing slot. The distance between the nozzle exit and the blowing slot could be varied. Three interchangeable circulation control trailing edges permitted a trailing edge radius of either 7/32, 7/16, or 7/8 inches to be installed. The entire apparatus was inverted to deflect the thick jet upward avoiding any ground interference.

The thrust of the thick jet was measured with a six-component balance. A second six-component balance measured the net force generated by the entire apparatus. The effective thrust turning angle, θ, was determined from the force components measured with this second balance. Also recorded was the static pressure measured along the flat plate scrubbed by the thick jet and around the circular trailing edge.

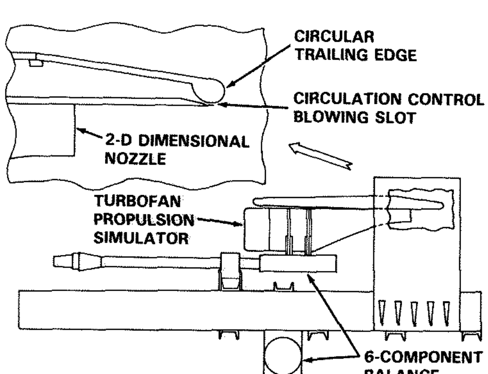

Fig. 6 Test Apparatus for Deflecting a Thick Jet with Circulation Control Blowing

As the momentum of the circulation control blowing increases, the thick jet is entrained and deflected around the circular trailing edge. A region of sub-ambient pressure is generated around that portion of the trailing edge immersed in the thick jet. The force resulting from this region of suction offsets the thrust generated at the nozzle. The net force generated by the entire apparatus is at an angle θ from the initial thrust direction. The angle θ, therefore, represents the effective thrust turning angle.

Deflection angles approaching 180 degrees were achieved when the exit of the highest aspect ratio jet (AR = 6) was located 12.5 trailing edge radii forward of the largest trailing edge (r = 7/8 in). Maps of the static pressure measured around the trailing edge for this configuration are presented in Figure 7. Also presented in Figure 7 are the effective thrust turning angles resulting from this pressure distribution.

Fig. 7 Trailing Edge Static Pressure Maps (Jet AR = 6 and TE r = 7/8 in)

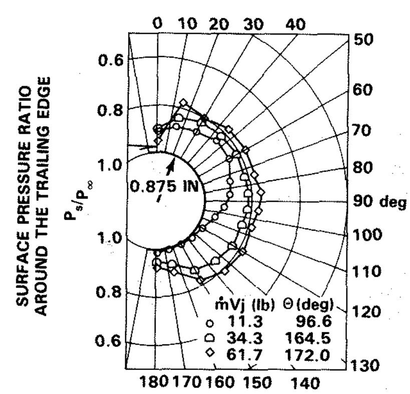

Fig. 7a Jet Pressure Ratio 1.05 and Thrust 28.7 lb

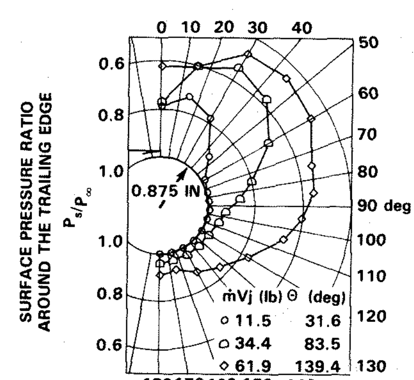

Fig. 7b Jet Pressure Ratio 1.22 and Thrust 91.1 lb

By comparing the pressure maps in this figure several features can be illustrated. The region of suction begins at the circulation control blowing slot (0 deg) and extends partially around the trailing edge. This region extends farther around the trailing edge as the blowing momentum increases. Therefore the thick jet remains attached to the trailing edge and is deflected to a greater angle.

As the pressure ratio, and therefore thrust, of the thick jet increases (now comparing Figures 7a and 7b), the minimum pressure measured around the trailing edge decreases with a resulting increase in the suction force. Increasing the pressure ratio of the thick jet also results in this jet separating from the trailing edge closer to the blowing slot for the same blowing momentum.

Results from this investigation indicate that the maximum jet deflection achievable with circulation control is dependent upon the pressure ratio of the jet, the radius, and the surface area of the trailing edge immersed in the jet. The investigation also demonstrated that this jet deflection was pneumatically controllable over a range of deflection unachievable in conventional USB systems.

The static thrust-turning capability was also evaluated using a model more representative of a turbofan mounted over a circulation control wing. A generic semispan model (Figure 8) previously evaluated in separate USB and CCW configurations[9] was used in these investigations.

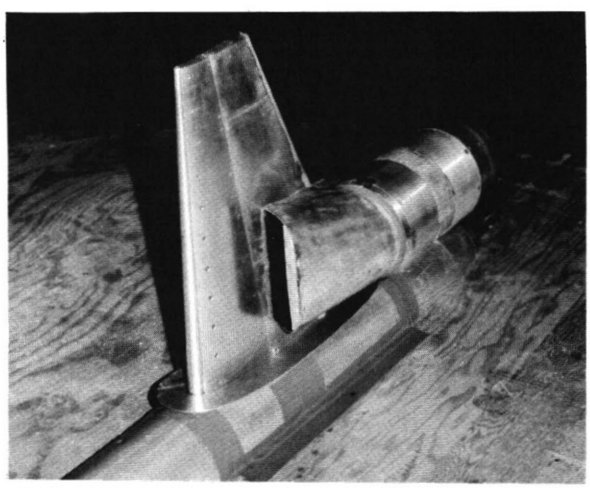

Fig. 8 Generic CCW/USB Semispan Model

The basic wing is a 14-percent thick supercritical airfoil with an aspect ratio of 4.0. This airfoil had a plenum for tangential blowing and a circulation control trailing edge. Trailing edge parameters used for this configuration are based on parameters used during development of the A-6/CCW aircraft. The radius of the circulation control trailing edge was 3.6 percent of the local wing chord. The height of the tangential blowing slot was set at 3.1 percent of the trailing edge radius. Protection against leading edge separation was provided by a 15-percent chord Krueger flap deflected 40 degrees. A turbofan simulator employing tandem 5.5 inch tip-turbine fans was mounted above the wing. This tandem fan arrangement produced a maximum static thrust of 80 lb. For comparison purposes, the maximum thrust of a TF-34 turbofan (installed, sea level tropical day, at 60 knots) is 56.7 lb when scaled to the model, based on thrust loading.

Nozzle geometry is a significant parameter in the thrust turning capability of the circulation control trailing edge. The larger the wing surface that is immersed in the propulsive jet, the more efficiently the lift is generated by turning the propulsive jet. It is therefore desirable to use a nozzle which spreads the exhaust as widely as possible. Initial testing with the semispan model was conducted with a nearly rectangular, D-shaped nozzle with an aspect ratio of 3.3.

The effective thrust turning angle (θ) resulting from this configuration is presented in Figure 9 as a function of the sectional blowing momentum ($\dot{m} V_j/S$), the corresponding blowing plenum pressure (P_{T_D}), and the calibrated static thrust (T_S). To isolate the propulsive effects, only the inboard wing section immersed in the propulsive jet was blown. There was no blowing outboard of this section.

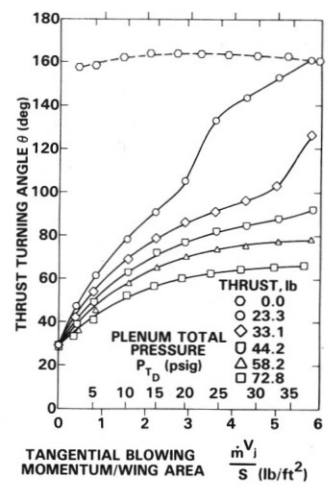

Fig. 9 Static Thrust Turning

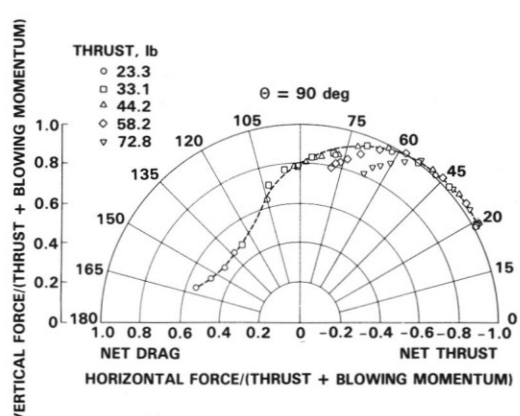

Fig. 10 Thrust Turning Angle and Thrust Recovery

Without tangential blowing, an effective turning angle of 29 degrees resulted from the nozzle geometry and effects of scrubbing the wing upper surface. Increasing the tangential blowing momentum increased the resulting effective turning angle. Also, for a constant amount of blowing momentum, the effective turning angle increased as the thrust decreased.

The efficiency with which this thrust turning is achieved is shown in Figure 10. The measured horizontal and vertical forces were nondimensionalized by the sum of the calibrated static thrust plus the blowing momentum. These forces are plotted to show the turning angle and the percent of the total force recovered. Approximately 100 percent of the thrust and blowing momentum are recovered statically for effective turning angles through 55 degrees. Although less efficient, acceptable thrust recovery is achieved beyond 55 degrees. At lower thrust levels 80-percent thrust recovery is achieved at angles through 90 degrees.

A reasonable thrust deflection during a STOL landing approach would be approximately 60 degrees. During takeoff, a thrust deflection at aircraft rotation much greater than 20 degrees results in an unacceptable decrease in horizontal acceleration at lower thrust-to-weight ratios. While the unblown thrust deflection in the configuration tested should be reduced for any practical installation, the circulation control trailing edge clearly demonstrated an effective thrust turning capability.

Although early static investigations proved the principle of operation, limitations in the maximum turning angle achieved at high thrust levels indicated that further static testing was required. Additionally, the need for a full scale, hot gas demonstration was required for assurance that scale and temperature effects would not render the system ineffective or inoperable.

Full-Scale Investigation

As a courtsey of the NASA Ames QSRA Project Office, manpower and test facilities were provided to conduct a full-scale static investigation of the CCW/USB concept applied to their existing USB research aircraft[10]. This aircraft had been mounted on static thrust stands for engine calibration. The CCW/USB investigation was intended primarily to determine thrust deflecting capability when operating in the mixed flow exhaust of a USB state-of-the-art turbofan engine and D-nozzle, and to compare those results to existing small-scale data. Since no flight testing was intended at this point, the test configuration was designed as a simple bolt-on device to be installed behind one engine only. This configuration was based on parameters found effective in past development, and is shown installed behind the left inboard YF-102 engine in Figure 11. For simplicity, the device was attached to the existing USB flap and powered by external air-start ground carts rather than engine bleed.

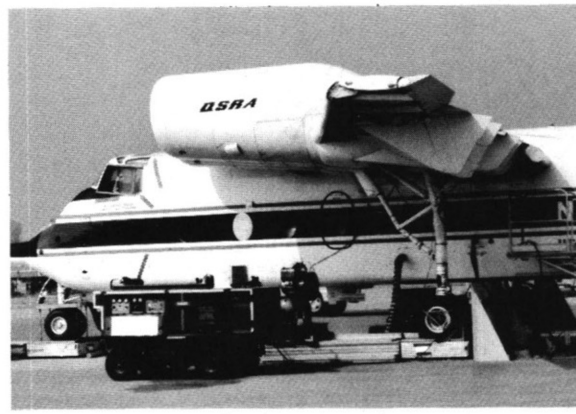

Fig. 11 Circulation Control Trailing Edge Installed inboard on the NASA QSRA

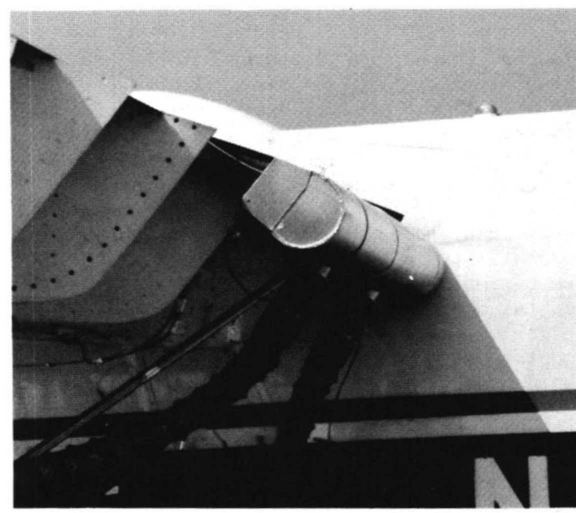

Fig. 12 Thrust Deflection at the Circulation Control Trailing Edge (Blowing on)

Visualization of the flow deflection capability of this 6 ft span CCW/USB trailing edge is provided in Figure 12, where the flow field on the section is mapped by tufts. With CCW blowing on, these tufts were seen to turn nearly to the horizontal, leading forward under the wing, while a tuft outboard of the round trailing edge continued to trail aft at roughly the flap upper surface deflection angle. Further implications that large portions of the engine exhaust were being entrained to large deflections were provided by observations of a grassy field behind the aircraft, where the grass was strongly deflected aft by the engine exhaust with CCW blowing off, but became still as blowing was turned on. As the blowing was increased, objects on the ground below and ahead of the round trailing edge became visibly disturbed.

Resolved thrust deflection angle is presented in Figure 13 as a function of resulant engine thrust for three values of CCW blowing pressures, and includes the unblown case. Also shown is basic USB thrust deflection with the flap retracted to 0 degrees. Trailing edge camber produced by addition of the CCW device alone with

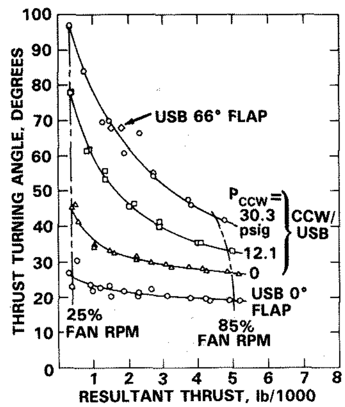

Fig. 13 QSRA CCW/USB Static Thrust Turning

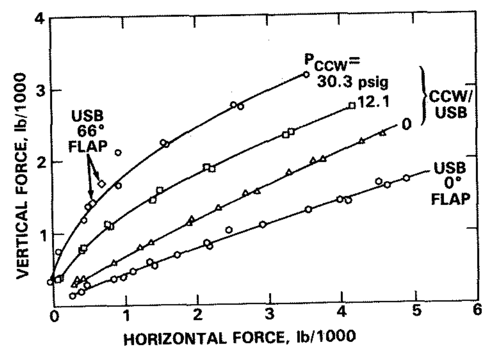

Fig. 14 QSRA CCW/USB Static Thrust Components

no blowing yielded an additional 7 to 20 degrees in thrust turning over the basic flap, depending on thrust setting. Addition of blowing produced thrust deflection angles up to 97 degrees at low power settings, and 42 degrees at maximum thrust. This built-in reduction in deflection at high thrust is quite effective in producing thrust recovery when needed during takeoff or waveoff. The versatility in STOL operation of the CCW/USB system is implied in Figure 14 where the static horizontal and vertical thrust components are shown for various blowing levels. In flight, the horizontal and vertical thrust components plus the downward momentum of the turbofan exhaust provide additional lift and drag. Thus, operation in flight at a constant vertical (or lift) force could be maintained, while horizontal force was being converted from low to high thrust recovery by reducing blowing. This represents conversion from a landing to a takeoff mode. Generation of these forces is possible without any change in angle of attack, and without requiring any moving parts to be deflected.

These data presented were compared to similar data for the semispan model (Figure 9) and were found to be slightly lower in thrust turning angle. This was thought to be due more to the length of the trailing edge span and the existing vortex generators than to scale or temperature effects. In fact a portion of the exhaust was not deflected since it was outboard of the blown trailing edge. This can be seen by examining the tufts in Figure 12. The tuft beyond the round trailing edge is being blown straight back while the others are wrapped around the trailing edge. A longer span blown trailing edge and improvements in test configuration trailing edge geometry should produce thrust deflection results comparable to or exceeding the small-scale test results.

In general, the QSRA results confirmed full-scale static thrust deflection greater than 90 degrees as functions of thrust and blowing only, without the use of external moving parts. This implies a significant versatility for STOL operation.

Static thrust turning is an indication of the propulsive lift that can be generated by a configuration. Static investigations, however, cannot properly indicate the propulsive effects on total system lift during flight. During takeoff, when thrust-turning is restricted by acceleration requirements, circulation enhancement can be the major propulsive contribution. Wind tunnel investigations were conducted to evaluate the total system and its operation.

WIND TUNNEL TEST RESULTS

The CCW/USB semispan model (shown in Figure 8 and described in the small scale static thrust-turning discussion) was evaluated in the wind tunnel for total system performance. This model does not properly represent the proposed CCW/USB configuration of Figure 5 due to the low aspect ratio of the model wing. This investigation did, however, indicate the high lift performance that can be generated by the CCW/USB concept in flight. A D-nozzle representative of an efficient cruise design was used during this wind tunnel investigation. A description of this nozzle is presented in Figure 15.

The contributions of thrust, tangential blowing, and angle of attack to total system lift are shown in Figure 15. Corresponding drag polars are presented in Figure 16. The results presented in these figures are typical of the results achieved over the entire thrust and blowing range.

In these figures, the lower dashed curve presents the lift and drag generated by the wing alone without thrust or blowing. Both lift and drag increase as the effective wing camber increases with circulation control blowing. This effect is illustrated by the lower solid curve, which was generated without thrust but with blowing along the entire semispan. At an angle of attack of 25 degrees the wing alone (lower dashed curve) produced a lift coefficient of 1.6. At the same angle of attack, a lift coefficient of 3.0 is

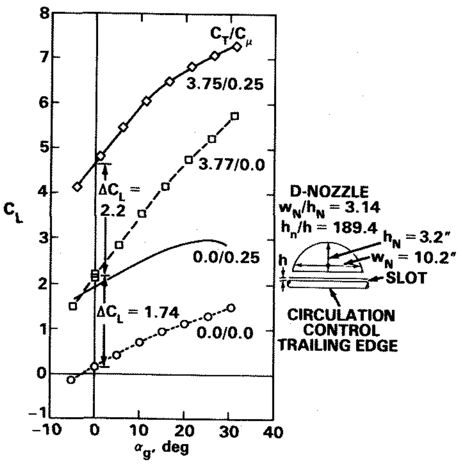

Fig. 15 Typical CCW/USB Lift Characteristics

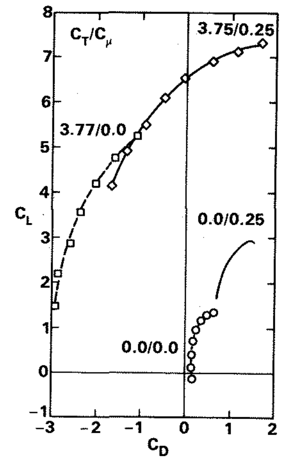

Fig. 16 Typical CCW/USB Drag Polar

produced at a blowing momentum coefficient of 0.25 ($C_\mu = \dot{m}V_j/qS$). While blowing tends to reduce the stall angle, the maximum lift coefficient at this blowing level increased by 1.74.

With the turbofan simulator mounted above the wing, the propulsive jet also contributes to lift. Entrainment properties of the propulsive jet enhance the local dynamic pressure and provide boundary layer control which delays wing stall. Some thrust deflection is also produced without blowing due to the geometry of the wing (including the round circulation control trailing edge) and the engine nozzle geometry. This higher lift is generated for a modest reduction in horizontal thrust. These propulsive effects are illustrated by the upper dashed curve in Figures 15 and 16.

The combined effects of thrust, blowing and angle of attack are illustrated by the upper solid curve in Figures 15 and 16. Tangential blowing generates sub-ambient pressure along the trailing edge as in the case without thrust. On the inboard wing section influenced by the higher dynamic pressure of the propulsive jet, even lower static pressures are generated. As tangential blowing increases, the distance around the trailinge edge over which these sub-ambient pressures are generated also increases. This low aspect ratio model produced a lift coefficient of 6.5 with a net balance between horizontal thrust and total system drag ($C_D = 0$) at a thrust coefficient of 3.75, a blowing coefficient of 0.25 and an angle-of-attack of 16.6 degrees. Note that the lift increment due to $C_\mu = 0.25$ has now increased from 1.74 without thrust to approximately 2.2 with $C_T = 3.75$, thus confirming the additional lift augmentation due to circulation control flow entrainment behind the nozzle.

A clear understanding of the potential of combining propulsive and circulation control effects is illustrated by comparing the lift and drag generated at a constant angle of attack when varying the levels of thrust and blowing. Lift coefficients for constant thrust values are presented in Figure 17 as a function of the blowing momentum coefficient, C_μ. Corresponding drag polars are presented in Figure 18. In both figures the solid symbols (dashed curves) represent only inboard blowing, as in the static investigation. The open symobls (solid curves) represent blowing over the entire wing span.

For a constant angle of attack, higher lift results from increasing either thrust or circulation control blowing. There is also a corresponding change in drag. By pneumatically controlling the horizontal thrust recovery, both positive and negative values of C_D are produced.

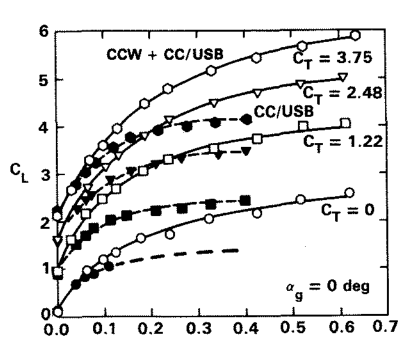

Fig. 17 Effect of Thrust and Circulation Control on Lift for a constant angle of attack

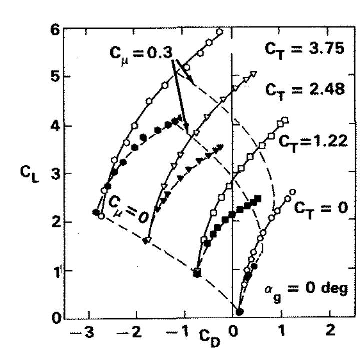

Fig. 18 Effect of Thrust and Circulation Control on Drag for a constant angle of attack

Higher lift is also generated for the same blowing momentum if circulation control blowing is spread over the entire wing span than if confined inboard. For a constant blowing coefficient of 0.30, this effect can be seen by comparing the lift and drag generated for a constant thrust. With only inboard blowing (solid symbols and dashed curves) a C_L of 3.4 and a C_D of -0.4 (a net positive thrust) is produced with a C_T of 2.48. For the same blowing coefficient but full span blowing, a C_L of 4.4 and a C_D of -0.3 is produced with a C_T of 2.48. This is an increase in C_L of 1.0 and C_D of 0.1 produced by increasing the percent of the wing span having circulation control blowing.

A wide range of flight conditions can be produced by controlling the thrust and blowing levels, the distribution of blowing along the wing span, and the angle-of-attack. High lift can be generated along with a high horizontal thrust recovery along the full span to achieve short takeoff runs and acceptable rates-of-climb by blowing along the full span. Relatively steep and slow landing approaches can be flown by increasing the inboard blowing level, minimizing the horizontal thrust recovery. A high thrust level can be maintained during the approach. Thus, reducing the blowing inboard and increasing the blowing outboard again provides high horizontal thrust recovery to accelerate and climb if the approach must be aborted.

The 7.3-percent-thick circulation control trailing edge employed in this low-aspect-ratio semispan model was based on the successful A-6/CCW design. Any operational use of this particular design would require some mechanization to convert to a sharp trailing edge for cruise flight. Certainly a smaller diameter (1.88-percent-thick) as used on the Supercritical Circulation Control airfoil[1] can be employed outboard where the wing is not immersed in the turbofan exhaust. However, the impact of the smaller radius on the propulsive-induced lift needs further analysis. The Circulation Control Wing/Upper Surface Blowing powered-lift concept promises significant lift augmentation without the mechanical complexity and weight of powered-lift systems with multi-element flaps.

FUTURE PLANS

The capability of circulation control as a high lift system has been demonstrated in full-scale flight with the A-6/CCW aircraft being flown in 1979. Additional wind tunnel experiments have shown that such a CCW system can operate effectively with a cruise-configured trailing edge on a thick supercritical airfoil without any external moving parts being required. Also, wind tunnel and static full-scale data have substantiated the thrust turning potential of a circulation control thrust deflector (CCUSB) when a turbofan engine is configured in an Upper Surface Blowing arrangement. The ultimate benefits of these two systems can apparently be achieved when combining them together in a single powered high lift system, allowing each to operate indepently or together as desired flight conditions dictate. This has been shown to a limited extent on a low-aspect-ratio semi-span wind tunnel model. Further experimental development is being pursued in each of these three areas: the circulation control high lift wing, the circulation control thrust deflector, and the integration of both systems.

Wind tunnel experiments are planned to evaluate the effectiveness of a cruise-configured small trailing edge incorporated in a conventional airfoil using a 2-D model. An even greater challenge is to integrate CCW into a thin high performance airfoil. This is being addressed as part of a Defense Advanced Research Project Agency (DARPA) sponsored program to assess the potential of CCW on a Forward Swept Wing (FSW) configuration. Initial experimental results have confirmed a beneficial reduction in the nose-down pitching moment for such a configuration. Two-dimensional airfoil experiments have been proposed as a next step in this program which will require solving the thin airfoil challenge. Some progress to this end has been made in developing an alternate partially rounded trailing edge design.

Success of the full-scale static tests on the QSRA have encouraged a second series of NASA/Navy static tests on this aircraft. A smaller trailing edge radius will be used. Improved hardware design, construction and testing methods will be employed based on the experience gained from the first tests. In addition, a joint Air Force/Navy effort is in progress to evaluate the effectiveness of circulation control in deflecting a high temperature, high pressure ratio turbojet exhaust using a Teledyne CAE J402-CA-400/660 lb. thrust engine. These tests are imminent as this paper is being prepared.

The third area of technology development is in the integration of the two systems. The Lockheed California Co., under contract to the Navy, is designing and constructing a full-span wind tunnel model. This model will be used in a series of Navy wind tunnel experiments to thoroughly evaluate the various circulation control and aircraft performance, stability, and control parameters. Although the model and test data will be generic in nature, there is a distinct resemblance to the S-3 aircraft. These data will provide a substantial technology base for further military and commercial applications, and for any desired full-scale vehicle demonstrations.

During this technology development effort, several areas of technology risk will be addressed wherever possible. These will include 1) leading edge devices or blowing to maintain flow and help reduce the nose-down pitching moment, 2) internal ducting arrangements and weights, 3) internal ejectors used to alleviate high slot exit temperatures and improve Coanda performance, 4) methods to improve tail trim effectiveness, 5) cross-ducting for engine out performance and control enhancement, 6) cockpit and black-box control simplification to minimize pilot workload, 7) differential blowing (from side to side) to provide roll control, 8) circulation control thrust recovery methods to counteract adverse yaw, and 9) alternative trailing edge shapes to facilitate efficient installation in cruise-configured thinner airfoils.

The emphasis in this technology development program may appear to be favoring an effective powered high lift system developed from combining the CCW and CCUSB systems. However, it is not the intent of this paper to detract from the use of each system independently. It is particularly important to remember that a substantial part of the development effort is toward CCW as used by itself. The CCW technology is at a more mature stage and studies supported by the Naval Sea Systems Command are in progress to evaluate the feasibility and impact of installing a CCW high lift system on combat aircraft now in the fleet to improve takeoff, landing, and overload performance. Consideration of other military and commercial applications should also be given in view of the potential payoffs that have been shown.

SUMMARY AND CONCLUSIONS

An advanced high-lift system which embodies elements of both Upper Surface Blowing and the Circulation Control Wing concept is currently under development at DTNSRDC. Circulation Control Wing/Upper Surface Blowing combines propulsive induced lift with the lift augmentation of circulation control. This highly effective high-lift system is also mechanically simple. Investigations conducted indicate that CCW/USB can generate the high lift coefficients required for STOL operation or to increase the useful payload of an aircraft while operating with a conventional ground roll.

Some conclusions drawn from these investigations are:

- The lift augmentation of the circulation control wing can be enhanced by mounting the propulsive system over the wing and deflecting the propulsive jet with the circulation control trailing edge.

- Lift augmentation and horizontal thrust recovery can be controlled pneumatically, which offers increased versatility during STOL flight with a simple conversion from a high lift to a cruise configuration.

- Deflection of the propulsive jet in excess of 90 degrees using a circulation control trailing edge has been demonstrated in both small-scale and full-scale hot gas (QSRA) investigations.

- At higher blowing levels, lift augmentation of the circulation control wing is equal to or frequently exceeds the lift augmentation of multi-element flap systems.

- Without external flap hinges, tracks, or hydraulic actuators, the circulation control concept offers a simple, light-weight high-lift system with few moving parts.

REFERENCES

1. Englar, R.J., "Low-Speed Aerodynamic Characteristics of Small, Fixed-Trailing-Edge Circulation Control Wing Configuration Fitted to a Supercritical Airfoil," DTNSRDC Report ASED-81/08, March 1981.

2. Ljungstrom, B.L.G., "Experimental High Lift Optimization of Multiple Element Airfoils," in AGARD Conference Proceedings No. 143 on V/STOL Aerodynamics, April 1974.

3. McGhee, R.H. and G.H. Bighan, "Low-Speed Aerodynamic Characteristics of a 17-percent Thick Supercritical Airfoil Section, Including a Comparison Between Wind-Tunnel and Flight Data," NASA Technical Memo X-2571, Jul 1972.

4. Englar, R.J., et al, "Design of the Circulation Control Wing STOL Demonstrator Aircraft," Journal of Aircraft, Vol. 18, No. 1, Jan 1981, pp. 51-58.

5. Pugliese, A.J. and R.J. Englar, "Flight Testing the Circulation Control Wing," AIAA Paper No. 79-1791 presented at the AIAA Systems and Technology Meeting, New York, Aug 1979.

6. Nichols, J.H. Jr, and R.J. Englar, "Advanced Circulation Control Wing System for Navy STOL Aircraft," AIAA Paper No. 80-1825 presented at the AIAA Aircraft Systems Meeting, Anaheim, California, Aug 1980.

7. Cochrane, J.A., et al, "Quiet Short-Haul Research Aircraft - The First Three Years of Flight Research," AIAA Paper No. 81-2625 presented at the AIAA/NASA Ames VSTOL Conference, Palo Alto, California, Dec. 1981.

8. Nichols, J.H. Jr., et al, "Experimental Development of an Advanced Circulation Control Wing System for Navy STOL Aircraft," AIAA Paper No. 81-0151 presented at the AIAA 19th Aerospace Sciences Meeting, St. Louis, Missouri, Jan 1981.

9. Trobaugh, L.A., et al, "Low Speed Aerodynamic Characteristics of Wing of Aspect Ratio 3 and 4 Equipped with High Lift Systems," DTNSRDC Report ASED 80/09, May 1980.

10. Eppel, J.C., et al, "Static Investigation of the Circulation Control Wing/Upper Surface Blowing (CCW/USB) Concept Applied to the Quiet Short-Haul Research Aircraft (QSRA)," NASA Technical Memo 84232, 1982.