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Design of the Circulation Control Wing STOL Demonstrator Aircraft

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Research and development have been conducted at the David W. Taylor Naval Ship Research and Development Center to develop the STOL capability of the circulation control wing concept. This simple high lift system employs tangential blowing over the wing's rounded training edge, and can more than double the lifting capability of conventional high performance aircraft. Based on the associated STOL benefits, design and flight testing of the concept on a full-scale A-6A flight demonstrator have been completed by Grumman Aerospace Corporation. The present paper addresses experimental development of the vehicle, details of the full-scale aircraft design, predicted STOL performance benefits, and some flight test results.

Introduction

WITH the current growth of interest in advanced aircraft to reduce the deck sizes of aircraft-capable ships, the concept of an effective short takeoff and landing (STOL) configuration may prove very competitive with the presently postulated but rather complex and costly vertical takeoff and landing (VTOL) concepts. To make STOL aircraft feasible, a number of powered lift concepts (see Fig. 1) have undergone development in an attempt to derive maximum lifting benefits from various combinations of advanced lifting surfaces augmented by engine thrust or bleed. Whereas quite large net lift can be generated by many of these designs, a number of compromises are required for actual implementation on high performance Navy aircraft. Several pose rather severe impact on wing complexity and structural design. Engine placement and nacelle design for most of the externally blown configurations are often not compatible with high performance fighter and attack aircraft. A more feasible concept for these aircraft is a high lift system which can be simply incorporated into conventional wing trailing edge structure, and which can be powered by bleed air from existing turbine engines without major modifications or relocation. However, in order to achieve STOL performance, this concept must possess considerably higher lifting capability than the conventional mechanical high lift systems now in use. Technology[1] developed at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) since 1968 has led to the circulation control wing (CCW), a STOL concept offering the previously mentioned potential.

The basic aerodynamics of the circulation control (CC) concept are shown in Fig. 2, and involve the adherence of a thin tangentially ejected jet sheet to the rounded trailing edge of an otherwise conventional airfoil. This phenomenon, frequently identified as the Coanda effect, is produced by a balance within the jet sheet between centrifugal force and the low static pressure produced by the jet velocity. The device initially acts as a boundary-layer control (BLC), but achieves its high lift capability by control of the airfoil stagnation points and thus the circulation around it. Hence, the circulation control wing name. Whereas the CCW does not generate the same ultrahigh lift coefficient (much of which is vertical thrust component) achieved by the externally blown flap and upper surface blowing concepts, it appears to be a very promising concept for high performance attack and fighter aircraft where engine placement below or on the wing may not be practical and where available C_μ may be low.

Exploratory investigations at DTNSRDC of the CCW concept applied to conventional airfoils and wings have demonstrated a threefold gain in lift over the conventional flapped airfoil section[2] and at least a doubling of maximum C_L for a three-dimensional aircraft configuration.[3,4] These results were sufficient to cause initiation of an aircraft design, modification, and flight test program contracted to Grumman Aerospace Corporation to verify the CCW concept on an operational test bed aircraft. Goals of the program were to demonstrate maximum obtainable lift augmentation from the CCW powered by engine bleed air; to evaluate stability, control, and handling characteristics in the STOL regime; and to develop the technology to the point of reducing the risk of application to future STOL designs. The Grumman A-6 was chosen as the test bed demonstrator aircraft because of its excellent aerodynamic configuration, availability of a test aircraft, relative simplicity of trailing edge modifications, twin engines with additional bleed ports available, and predicted STOL performance gains with CCW. The present paper will present experimental wind tunnel results obtained during the flight demonstrator development, predicted full-scale STOL performance gains, details of the demonstrator aircraft, some flight test results, and anticipated benefits for future aircraft employing the concept.

Experimental Development

Airfoil Investigation

Based on knowledge of the trailing edge parameters required to achieve good high lift performance,[1-4] an airfoil section which was characteristic of the A-6 wing was modified to the CCW configuration, where the conventional 30%

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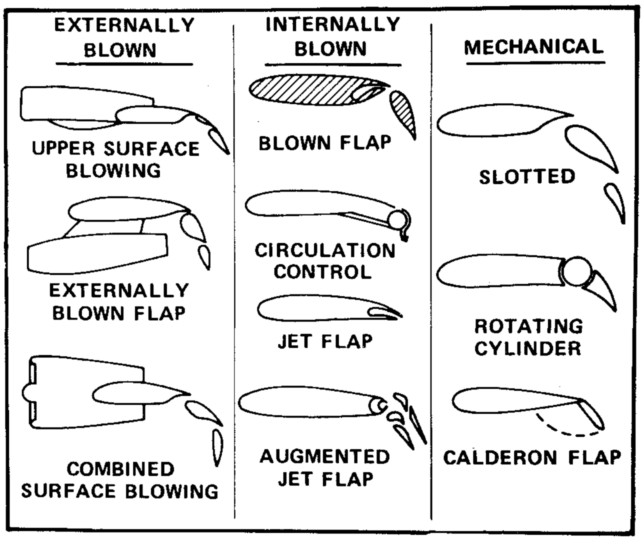

Fig. 1 High lift configurations.

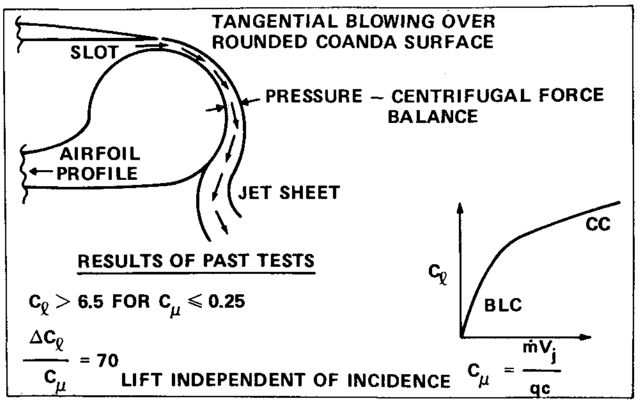

Fig. 2 Basic circulation control aerodynamics.

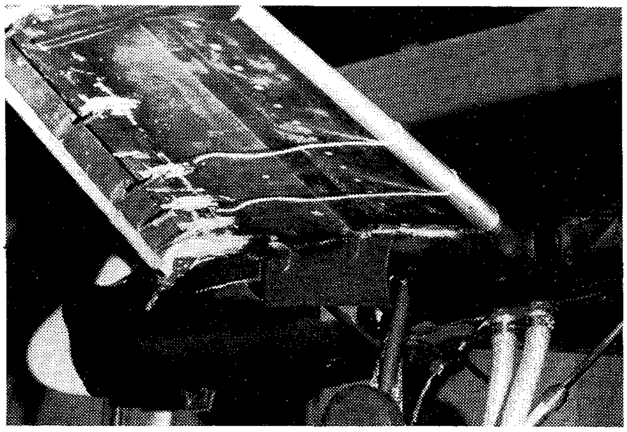

Fig. 3 Trailing edge modifications and jet turning on the A-6/CCW model, wind off.

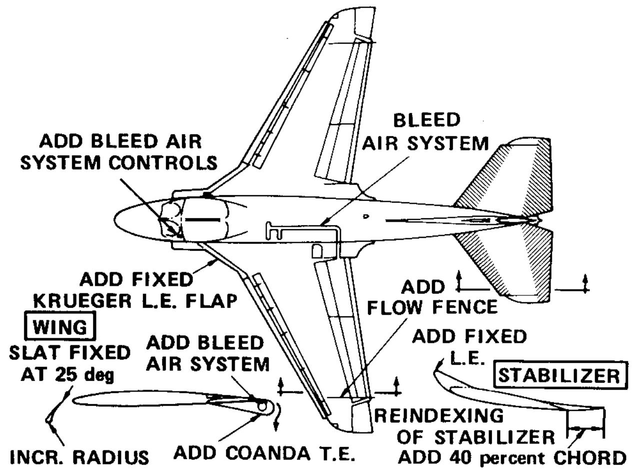

Fig. 4 CCW flight demonstrator airframe changes.

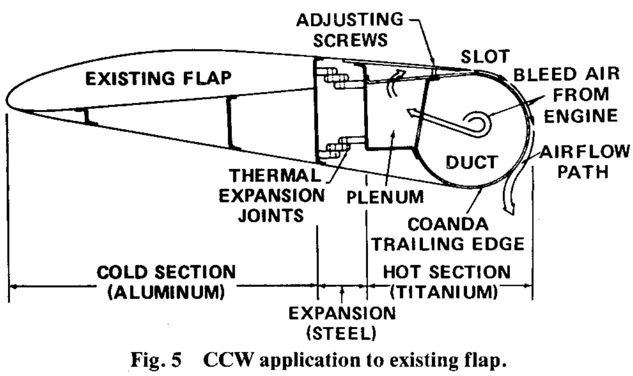

Fig. 5 CCW application to existing flap.

chord single slotted flap was replaced with the rounded trailing edge. Test details and results are presented in Refs. 3 and 5. The section lift coefficient of 6.5 is more than double that of a similar NACA 64A212 airfoil with leading edge slat and double slotted mechanical flap ($C_{l_{max}} = 3.1$).

These results were sufficiently high to warrant modification of a 1/8.5-scale model of the A-6A aircraft and continue the optimization of the configuration on that model.

Investigations of the 1/8.5-Scale A-6/CCW

The majority of configuration development for the flight demonstrator aircraft was conducted on the model shown in Fig. 3. This subsonic model was used by Grumman in development of the standard A-6A aircraft. The trailing-edge parameters developed in the two-dimensional investigation were incorporated to replace the existing single slotted flap with the CCW trailing edge. Roughly 750 h of subsonic wind tunnel investigation were used to optimize the lifting surfaces and the aircraft control surfaces; test results are reported in Refs. 3 and 5.

The effectiveness of the CCW principle on the modified wing is seen in Fig. 3, where the jet slot is just out of view on the upper surface of the rounded trailing edge. The two cotton tufts map the jet flow from the slot, and show turning of more than 180 deg from the slot. This implies large wing circulation and resulting lift, which was confirmed by the generation of trimmed aerodynamic $C_{L_{max}} = 4.3$ compared to 1.9 for the conventional A-6A model,[6] thus displaying a substantial improvement in STOL potential. The test data also show an additional benefit of CCW: lift and drag can both be varied independently of aircraft incidence simply by variation of C_μ.

Thus, pilot visibility on a carrier approach may be improved significantly by use of low angle of attack and blowing to vary the aerodynamic forces. The pilot can obtain at zero incidence and $C_\mu = 0.10$ the same lift coefficient as the conventional flapped A-6A at its stall angle of 20 deg.

Design Features

Based on the promising lift capabilities and STOL performance potential demonstrated during the experimental investigations, a flight demonstration program was undertaken to confirm these characteristics by full-scale flight testing of an A-6A testbed aircraft converted to the CCW configuration by Grumman Aerospace Corporation. Since the test objectives were primarily high lift and STOL performance, the aircraft modifications were designed for speeds less than 250 knots to minimize design scope, complexity, and cost. For this reason, the wing and stabilizer modifications were locked in the deployed positions and did not retract. Figure 4 depicts the modifications incorporated into the testbed aircraft: primarily changes to the wing and bleed system to produce augmented lift, and secondarily changes in the control and flight systems necessary for very low speed flight.

Wing Trailing Edge

For simplicity, the wing flaps were locked in their tracks in the fully retracted position and the round trailing edge, blowing slot, and duct were attached, as shown schematically in Fig. 5. High temperature bleed air from the J52-P-8B engines reached the inboard ends of the trailing edge ducts at 640° F maximum. To permit the resulting spanwise thermal expansion, each 18 ft titanium trailing edge hot structure is mounted on a system of six steel links in the horizontal plane with a vertical fixed pin at the inboard end. Thus, the trailing edge is free to move spanwise as it expands without imposing buckling stress on the forward structure of the flap. The sliding external upper surface skin joint is sealed with a thin overlapping titanium strip. The round trailing edge blowing surface structure also serves as the spanwise air supply duct feeding plenum and nozzle chambers, and is designed to 50 psig internal pressure. A thermal barrier isolates the hot sections from the aluminum forward flap structure.

In addition to the high temperature design problems, the nozzle slot is a critical area. The desired nozzle slot height tapers spanwise as a fixed percentage of wing chord, as does the entire trailing edge geometry. The nozzle upper plate is essentially 0.25 in. thick titanium machined to taper to a thickness of 0.02 in. at the slot opening. The actual slot height expanded under deflections due to temperature and pressure, the maximum heights ranging from 0.094 in. inboard tapering to 0.047 in. outboard, an average of 0.070 in. Ground adjustment was provided by a spanwise row of screws at 3 in. spacing. Aircraft ground tests determined that the unpressurized cold setting had to be nominally 0.015 in. inboard tapering to 0.007 in. outboard. Since the circulation control concept was to be demonstrated at low takeoff and landing speeds, flight airloads on the nozzle plate were very small. However, the effects of wing bending on the nozzle gaps and the stiff thick trailing edge were of concern. Here, building the modification into the existing flaps turned out to be an advantage since the inboard and outboard flap sections are each mounted on only two tracks, permitting each to remain essentially straight elements, not being forced to follow the wing spanwise deflection curve. This deflection pattern did, however, require that a "flexible" joint be provided to permit a "kink" in the trailing edge at the wing fold joint area. It may be of further interest to note that the nozzle slot is located essentially at the original wing trailing edge and, therefore, also in the wing box beam chord plane, basically the neutral axis of the wing. Figure 6 shows the rounded trailing edge installed on the test aircraft. Also visible are the slat increased radius, the Kruger leading edge flap on the strake, and the outboard wing fence, all as depicted in Fig. 4. In also should be mentioned that the nozzle slot on a production aircraft would probably be preset, not requiring adjustment, once the desired gap was determined. In addition, recent tests indicate that the radius of the trailing edge could be significantly reduced with virtually no loss in augmented lift, but with significant benefits in drag reduction and trailing edge retraction and storage.

Blowing System

Requirements for the bleed air system were primarily twofold: 1) the system must provide balanced air flow of 10% of single engine airflow to each wing at a pressure ratio no greater than 4.5, and balanced supply with loss of one engine; and 2) engine power setting and blown lift must be independently variable. Figure 7 shows a schematic of the Grumman-designed system incorporated in the aircraft to fulfill these requirements, and Fig. 8 shows the cost-reducing external installation. Pipe cross-sectional area, pressure losses, and slot area control the desired 10% maximum mass flow, while values less than that are set by the two throttle valves. The pressure regulators limit the maximum pressure in the plenums to 50 psig (4.4 pressure ratio at sea level) and

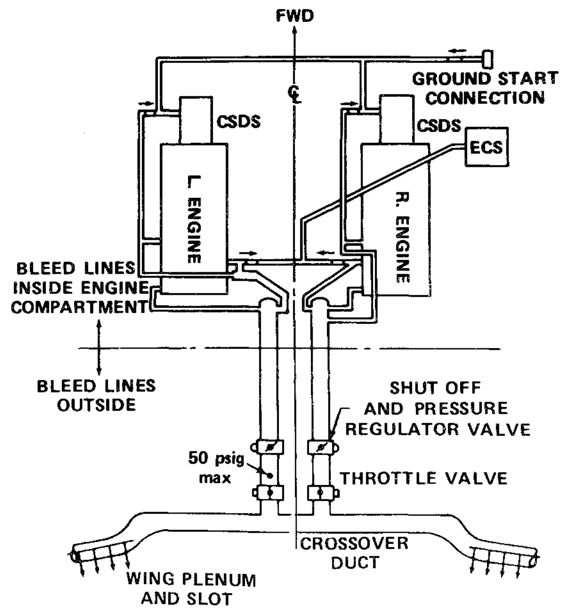

Fig. 7 CCW bleed air system.

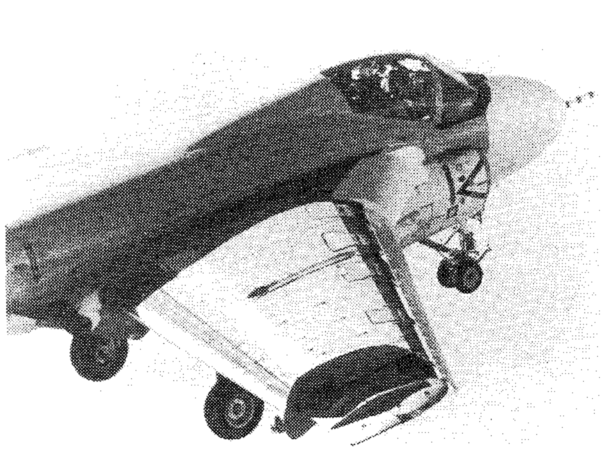

Fig. 6 Wing modifications on testbed aircraft.

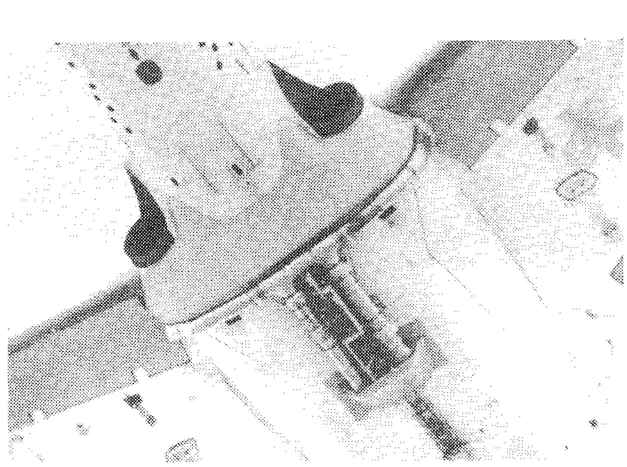

Fig. 8 External bleed air ducting and control valves.

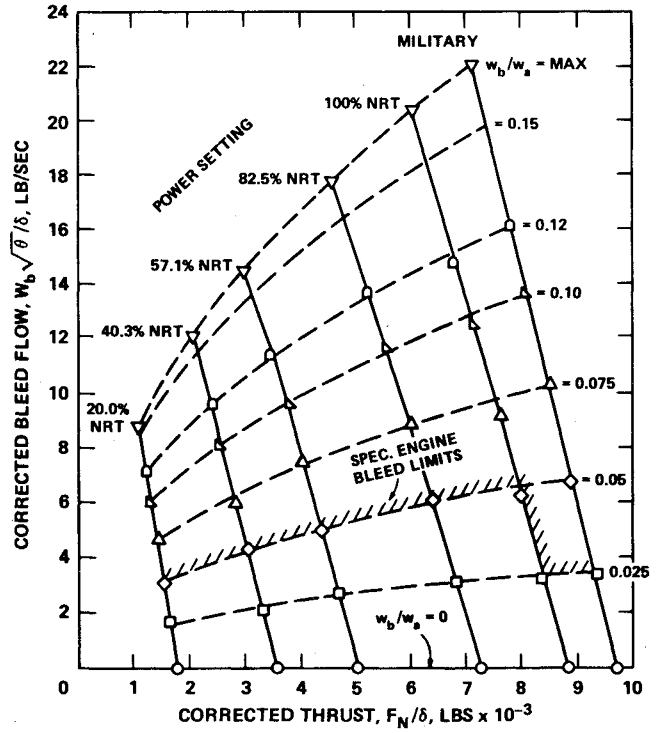

Fig. 9 Thurst performance of uninstalled J52-P-8A engine with bleed.

provide a one-way flow check valve should one engine be out. In the engine-out case, the remaining engine is automatically connected in equal proportion to both wing plenums by the common crossover duct, and since the combined slot area can now accommodate the equivalent of as much as 20% bleed from one engine, that engine's output will approach its 16% maximum. Since pressure at the bleed ports exceeds 50 psig at almost all power settings for level flight, the regulators thus cause pressure in the wing to be independent of throttle position, and thrust and lift are decoupled.

The pilot controls for the blowing system were placed on the throttle grip with an emergency shutoff feature on the control stick. The system modulating valves and pressure regulators were energized electrically. To assure the electrical functioning of all necessary components, including instrumentation, an emergency battery system was provided since the basic aircraft electrical ram air turbine would not be effective below 105 knots.

After a short feasibility study, the decision was reached to utilize the high temperature bleed air directly from the engine's twelfth compressor stage to provide the required blowing air. The study also considered the use of heat exchangers, air flow multipliers, and turbo compressors in the bleed system, and augmenting the twelfth stage bleed with the fifth stage bleed air. Tests conducted by DTNSRDC at the Naval Air Propulsion Test Center (NAPTC), Trenton, indicated that the twelfth stage bleed ports fully open would provide 16% of the total engine airflow, more than necessary, without exceeding critical temperatures in the engine. The engine is normally rated at 5 percent of the total airflow at or below normal rated thrust (NRT) and 2.5 percent at military power. A 50-h engine endurance test run at maximum bleed conditions and cyclic power variations verified that no engine damage due to this high excess bleed would result over the planned 50-h flight demonstration program. Figure 9 presents the test data in the form of corrected bleed mass flow and engine thrust as functions of power setting and bleed ratio. Here, bleed flow W_b is a function of total engine airflow W_a at that bleed setting. Thrust loss due to bleed at power settings of 0.40 NRT and above averaged about 132 lb of thrust per pound per second of bleed air. This is favorable in the equilibrium flight approach, where reduced thrust allows increased glide slopes or reduced velocity, but is somewhat undesirable on takeoff due to resulting reduced acceleration. It is for this latter reason that optimized STOL takeoff was made at a reduced blowing rate initiated at airplane rotation, utilizing full engine thrust, blowing off, for the takeoff run. Additional engine test results are reported in Ref. 7.

In order to determine the aerodynamic performance capability of the A-6A/CCW aircraft, it was first necessary to estimate the quantity and characteristics of the flow that could be provided at the Coanda duct, and the effects of extracting that flow on the engine performance. Since engine performance affects the flow available and vice versa, a complicated iterative solution is required. A computer program was designed to calculate the performance of two J52-P-8B engines installed in the A-6A/CCW aircraft while simultaneously simulating the CCW internal flow system. The computer program, in essence, consisted of two integrated parts: an engine performance program based on test data generated during J52 engine tests conducted at NAPTC,[7] and a flow matching program simulating the characteristics of the CCW internal flow system and matching flow through the ducting system to the demand of the blowing slot (based on assumed Coanda duct plenum pressure). During the flight test the system performed as predicted by this program. There was no detectable pressure drop, inboard to outboard, in the Coanda duct. In the one-engine-out tests the Coanda plenum pressure equalized side to side, providing balanced flow through the slots. However, the supply duct pressure drop calculations were found to be optimistic, thus requiring higher engine speed before the pressure regulator became active.

Secondary Modification to the Aircraft

A number of additional modifications to the aircraft were necessary to provide control, flight, and instrumentation systems plus system safety and reliability in order to fly the aircraft at the low speeds associated with CCW. In addition to those changes shown in Fig. 4 the following modifications were made:

1) Horizontal stabilizer: addition of balance weights to retain existing static balance, and actuator instrumentation to measure tail loads in flight.

2) Fuselage: removal of nose-located avionics, addition of ballast weight for c.g. control, addition of zero-zero ejection seats, addition of flight test instrumentation, and emergency electrical system to replace ram air turbine which is ineffective at low speeds.

3) Aerodynamic controls: provision for full control surface travel throughout entire flight range by neutralization of high speed limited travel devices, fuselage and wing tip speed brakes deactivated, stability augmentation system (SAS) modified for low speed control, and addition of wing tip yaw jets for adverse yaw control.

4) Engine: addition of bleed line check valves to connect ground start CSDS and ECS to modified bleed system, flow instrumentation in bleed lines, and pressure ratio gage in cockpit, as well as temperature sensing wires along bleed ducts and fire warning lights in cockpit.

Potential Problem Areas

A number of potential problems and design criteria were considered early in the demonstrator aircraft design stage, and corrections or solutions were incorporated into the aircraft modification and test procedures. The necessity of accurately setting the tapered slot height was accommodated by use of closely spaced adjustment screws at the entrance to the converging nozzle. Measurement of expanded slot height exposed to high temperature air and design pressure was handled by solenoid-operated tapered pin gages remotely inserted in the slot during ground tests. Ground vibration surveys conducted prior to flight indicated that the critical flutter speeds of the modified flap area and horizontal stabilizer were well above the upper speed limit of 250 knots. Predicted loads on the modified leading edge slat were found to be higher than anticipated, and the slat support structure was strengthened. Ground testing of the longitudinal control system verified that a suspected structural coupling instability due to the enlarged stabilizer was not present. However, to insure that loads on that enlarged aerodynamic surface did not exceed design limits, the stabilizer actuator was instrumented so that loads could be monitored real time on the ground during flight. Aircraft control and handling qualities at flight speeds considerably lower than those of the conventional A-6 were improved by a directional reaction control system and by increased authority to the stability augmentation system, as discussed in the following section.

Stability and Control

The nonlinear aerodynamic characteristics of the CCW aircraft required an analysis that investigated interaxis coupling and pilot opinion ratings throughout the flight envelope. A six-degree-of-freedom man-in-the-loop simulation was supported by a digital computer program to evaluate the following: primary handling qualities; control system analysis and design; failure effects; and procedure for transition from blowing off to blowing on. The main goal of this study was to establish handling quality levels sufficient to allow the primary task of evaluating the performance of the CCW system in flight.

Preliminary analysis indicated that a modification would be required to the basic A-6 SAS. The lower speeds and the anticipated levels of lateral-directional aerodynamic derivatives obtained in the tunnel tests implied the need for a SAS that could provide increased directional "stiffness," positive dutch-roll damping and roll coordination to contain the adverse yaw anticipated at low speeds. The implementation of this system was simplified by obtaining an EA-6B yaw SAS amplifier and modifying it to accept dynamic pressure gain scheduling down to the lowest speed expected, and installing appropriate filtering to prevent structural mode coupling. Since the A-6 series autopilot is of the single thread variety (no redundancy), all superfluous functions were eliminated to raise the level of reliability for the task at hand. Aerodynamic tunnel data predicted severe adverse yaw accompanying flaperon (spoiler) deflection, due to high induced drag on the opposite (upgoing) wing. Since rudder authority was limited by existing hardware, off-the-shelf valves were installed at the outboard end of the blowing ducts, pointing aft, to produce a reaction jet moment to help cancel the adverse yawing moment produced by the flaperons. These reaction control tip jets, shown in Fig. 10, are fed from the blowing ducts, and provide thrust in direct proportion to blowing pressure, lift, and thus adverse yaw. They operate automatically when blowing is activated and spoiler deflection on the opposite wing exceeds 5 deg. The pitch axis SAS was not modified, but the stabilizer was incremented 2.5 deg trailing-edge-down to provide additional nosedown trim capability up to 250 knots airspeed, blowing off.

The six-degree-of-freedom motion simulation with the pilot in the loop provided lead time evaluation to the test pilots for the CCW task. Projected flight profiles and handling quality tasks were placed on flight cards and the envelope expansion tests were evaluated to determine milestone points for the flight test phase of the program. Unannounced typical failures were introduced and pilot reaction and recovery procedures were monitored. The Coanda flow switch on the throttle was evaluated and its sense of direction was changed as a result of pilot procedure during emergency.

The value of the above activities and modifications were readily evident during the flight test phase. The SAS functioned properly and provided the necessary control over aircraft dynamics to allow the pilots to successfully investigate high angle of attack conditions, approaches, landings, and takeoffs. No SAS-dedicated flights needed to be expended to improve controlability. The SAS was on-line for the entire duration of the test program and the reaction control tip jets were found to be desirable even though their "bang-bang" operation was not optimal and pitch changes due to duct pressure perturbations were disturbing. The estimated aerodynamic characteristics from tunnel tests appear to be in a favorable direction; however, to resolve certain anomalies would require increased flight testing. Ground effect was expected to be a control problem during landings due to limited stabilizer throw. The difficulty did not occur in flight because of favorable thrust interference effects on required tail incidence and because pitch-down due to ground effect appeared to be only half of that simulated. Pitch damping was deadbeat throughout the entire envelope and pitch maneuverability was more than adequate. The lateral directional behavior of the aircraft at low speed was sensitive to gusts. Overall handling qualities were made sensitive by flow separation aft of the flaperons, deflection of which resulted from asymmetric roll trim requirements of the wing.

STOL Performance Predictions and Test Results

The previous investigations confirmed the potential for significant high lift capability of the concept, and the data were supplied to Grumman Aerospace Corporation under contract to predict full-scale STOL performance of the flight demonstrator. This involved conversion of the wind tunnel data to full-scale, addition of the lift component due to the associated upward inclination of engine thrust, analysis of aircraft flight envelopes, takeoffs, and landings, and dynamic analyses. While the engine data of Fig. 9 indicated that as much as 16% of the airflow could be bled from existing ports, a portion of this is needed on the aircraft for electrical power generation and the environmental control system; the

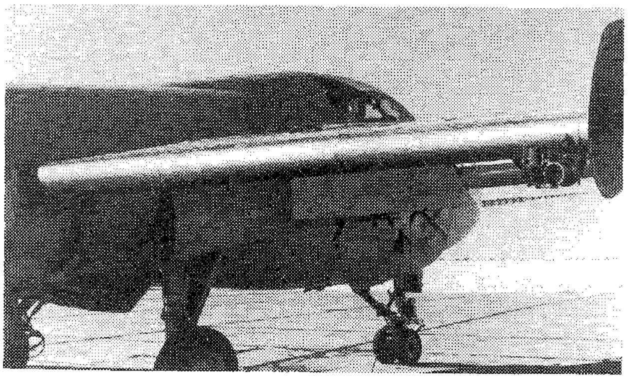

Fig. 10 Ground test, showing tip jets and Coanda turning.

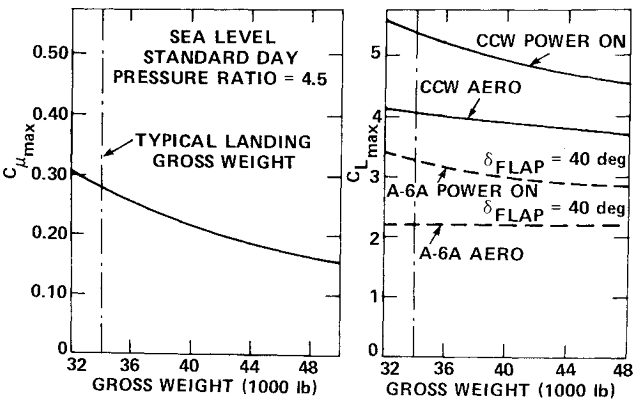

Fig. 11 Predicted maximum available C_L and C_μ with 10% bleed.

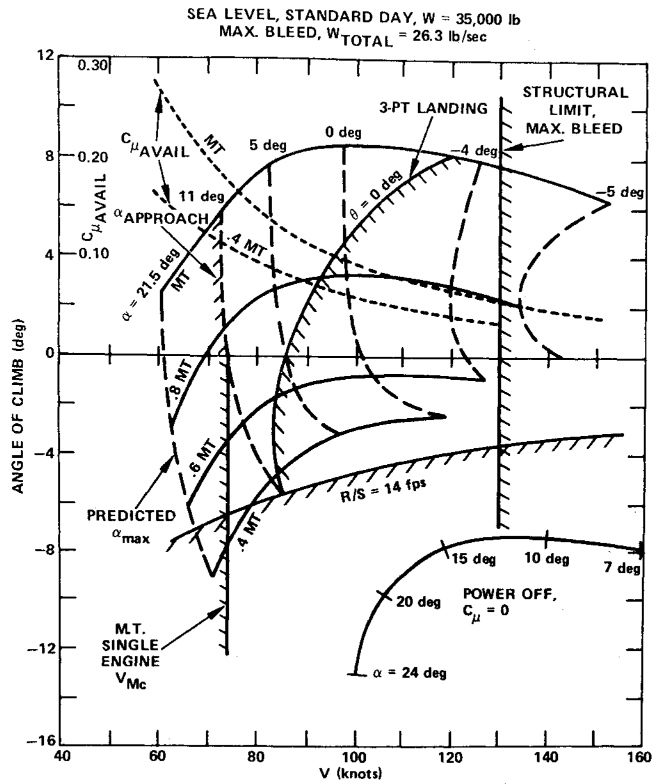

Fig. 12 A-6/CCW typical STOL flight envelope.

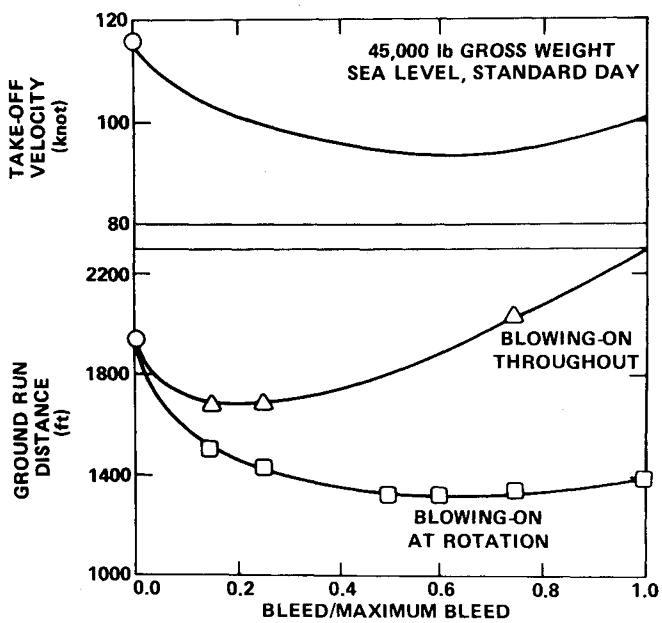

Fig. 13 A-6/CCW takeoff ground run and velocity.

powered wing was thus designed to operate on a maximum bleed flow of 10%. Figure 11 shows the predicted available momentum and lift coefficients as functions of aircraft gross weight. For the blown wing operating at a constant bleed rate, these coefficients vary with weight due to the associated velocity and dynamic pressure required for level flight at a given weight. The difference between available lift coefficient, "power on" (total) and "aero" (power off) is the vertical component of engine thrust coefficient, which can be greater than 1.0 at light aircraft weight and low speeds. For a characteristic 34,000 lb flight demonstrator, the 10% available bleed yields $C_\mu = 0.28$ and power-on $C_{L_{max}} = 5.4$, as compared to 3.3 for the conventional A-6A. The approach

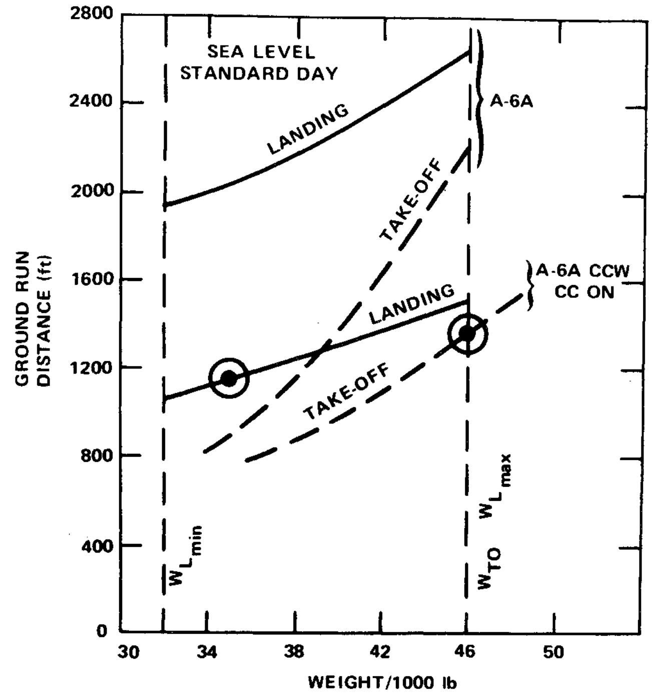

Fig. 14 Predicted CCW and A-6 ground run distances.

condition associated with these maximum C_L values is defined as an angle of attack 10 deg less than stall. The flight envelopes, a sample of which is presented in Fig. 12, have been developed for the anticipated range of parameters such as weight, altitude, amount of bleed, etc. This type of information is customary in STOL analysis and indicates the aircraft performance potential in the STOL regime. The flight envelopes consist of plots of angle-of-climb vs speed for different thrust settings. The plots give an idea of power setting required to climb or to glide at a predetermined angle, and indicate if the available power excess is marginal. In addition, the angle of attack α, the flight path angle, the ground angle θ, the rate of sink, and the approach angle of attack are marked. The relationship between these parameters and the speed can be read from the plot and serves as the flight guideline. It is evident that, on a standard day, the approach speed on a 3 deg glide slope would be 76 knots at a 0.6 MT (Military Thrust) setting and at a weight of 35,000 lb. The predicted stalling speed at sea level would be 61 knots. The $\theta = 0$ line indicates a condition where the aircraft makes a 3-point touchdown, and 14 ft/s rate of sink is the structural limit of the landing gear. Figure 12 is based on wind-tunnel data; flight test revealed a higher drag level and the actual curves are thus slightly lower.

The optimum procedure for takeoff, blowing-on, was derived analytically and verified during the flight test. The results are presented in Fig. 13 showing the effect of reduced amounts of blowing used throughout the entire ground run, and of turning on a given amount of blowing only when the speed for aircraft rotation to takeoff incidence is reached. This latter technique shows the optimum at 60% of the maximum bleed. Figure 14 shows that, using this procedure for takeoff, the takeoff and landing curves of ground run vs weight are more closely spaced with CCW, producing a more balanced field length. The CCW aircraft requires a 45% shorter field for operation in the range of specified weights.

An alternative to STOL takeoff is to lift off at the conventional velocity and distance and use the increased lift to provide a valuable overload capability. Using the same 2100 ft ground run required by the standard A-6 at 45,000 lb, the CCW version can lift a gross weight of 52,000 lb, an increase of 16%, as shown in Fig. 15. If a nominal CCW production installation weight of 1100 lb is subtracted, the payload is

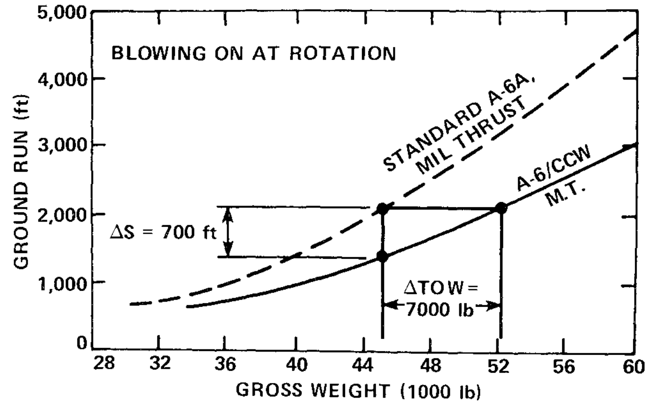

Fig. 15 Effect of CCW on A-6A short takeoff or overload capability.

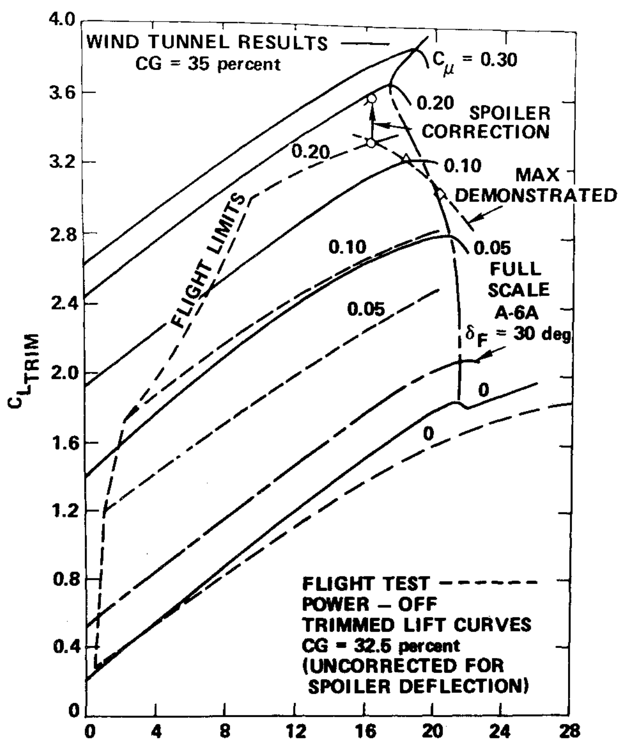

Fig. 16 A-6/CCW trimmed lift curves.

increased by 5900 lb or 36%. This percentage increases at larger gross weight.

A 22.2-h flight test program was conducted from Jan. 29, to March 1, 1979 to verify the predicted STOL performance of the CCW aircraft. Details and results of this flight program are presented in Ref. 8, but several highlights are presented here to show comparison to predicted results.

1) The highest demonstrated aerodynamic trimmed lift coefficient (corrected by addition of lift loss due to spoiler input) was 3.60 at $C_\mu = 0.20$ and $\alpha = 16$ deg, as compared to 1.79 for the conventional flapped A-6A at the same angle of attack. As Fig. 16 shows, the corrected flight-test data agree quite well with the wind-tunnel data, thus indicating trimmed $C_{L_{\max}} = 3.90$ at $C_\mu = 0.30$ is obtainable. Flight speed corresponding to $C_L = 3.60$ was 67 knots for a gross weight of 32,400 lb at 5000 ft altitude.

2) Approach speed for a typical 34,000 lb A-6 was reduced from 120 knots for the standard aircraft (labeled optimum) to 82 knots for the CCW with 8% bleed (power reduced to provide equilibrium approach), Fig. 17.

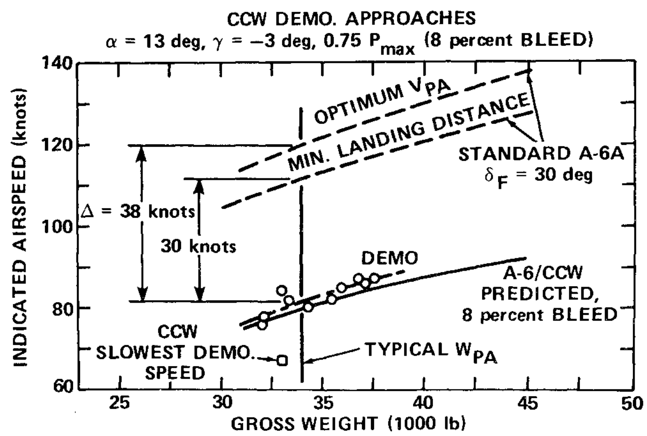

Fig. 17 Effect of CCW on A-6A power-on approach speeds.

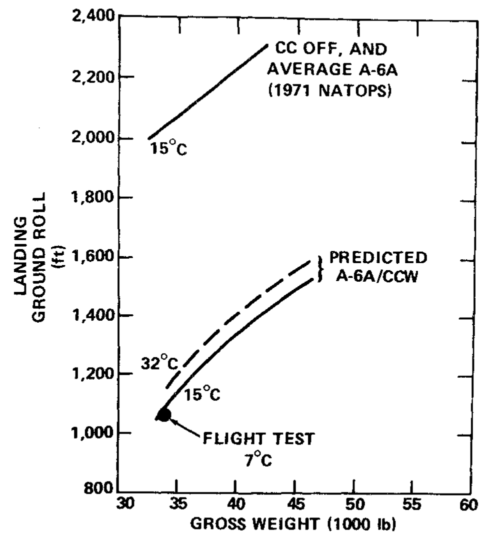

Fig. 18 A-6/CCW landing distance vs gross weight.

3) Landing ground roll at 34,000 lb was reduced from 2050 to 1080 ft as predicted, Fig. 18. Very little adverse ground effect was experienced.

4) A takeoff ground roll of 700 ft was demonstrated at 34,000 lb. Analytical study and Fig. 15 predict greater percentage reductions at higher gross weight.

5) The aircraft was fully controllable at $\alpha = 29$ deg, blowing off, and handling was better than that predicted by the flight simulator, blowing on and off.

6) All the failure modes flight tested were shown to be fully controllable, including blowing- and single-engine failures.

The test aircraft modification contract did not require redesigning the aircraft to provide operationally desired handling qualities. However, since the handling qualities turned out to be better than those predicted by the flight simulator, the pilots were able to penetrate the low speed envelope deeper than originally anticipated and thus pushed the aircraft's capability so that all program goals were accomplished or exceeded.

Summary and Conclusions

A testbed aircraft design and modification and a flight demonstration program have been conducted to confirm the short takeoff and landing characteristics of the circulation control wing concept on an A-6A flight demonstrator. Wind tunnel, engine bleed, and flight test investigations have verified that the test aircraft can double the lifting capabilities of the A-6A by use of existing bleed airflow. A trimmed lift coefficient of 3.60 produced a 67 knot airspeed for the demonstrator, and indicated that maximum lift coefficients predicted by tunnel results were obtainable by the manned aircraft. The program's proof-of-concept objectives were accomplished, and the following potential payoffs of a CCW-configured Navy high performance aircraft are evident: 1) significant reductions in takeoff and landing velocities and distances, and associated impact on reduced size of air-capable ships; 2) alternative of increasing the aircraft's gross overload capability by 36% (or larger) increases in payloads; 3) increased aircraft and equipment lifespan due to reduced kinetic energy and impact during ship-board landings; 4) reduced accident rates and increased pilot reaction times due to significantly lowered approach velocities; 5) increased pilot visibility at lower approach angle of attack and steeper glide slopes; and 6) provision of a simple and relatively lightweight STOL high lift system without major wing structural and engine modifications and with possible elimination of flap surfaces, tracks, and actuators.

The results of the proof-of-concept flights thus provide the Navy with a very effective design concept for use on sea-based aircraft in the fleet of tomorrow. Similar gains are expected for non-Naval aircraft and possibly commercial configurations.

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