Flight Performance of a Circulation Controlled STOL Aircraft

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Theoretical and wind tunnel studies have been performed on various high-lift airfoils using circulation control by blowing over a circular trailing edge. On the basis of these studies, a full scale Technology Demonstrator STOL aircraft was designed, constructed, and flight tested. Circulation control blowing air was provided by bleed air from a gas turbine. The first series of flight tests have recently been completed. Satisfactory STOL performance and handling characteristics were obtained. Advantages of this system are high lift to power ratio, and near level aircraft attitude at all speeds.

Nomenclature

C_1	= midspan wing chord in cruise configuration
C_2	= midspan wing chord in STOL configuration
$C_{L_{trim}}$	= aircraft overall lift coefficient based on cruise wing area
$C_{L_{wing}}$	= average wing lift coefficient
$C_{L_{flap}}$	= lift coefficient of the wing at the location of the 54 pressure taps
$\Delta C_{L_{flap}}$	= increase in $C_{L_{flap}}$ due blowing only maintaining propeller at idle
C_p	= wing pressure coefficient
$C\mu$	= blowing momentum per foot of flap, nondimensionalized by C_1 and dynamic head
Re	= Reynolds number based on C_1
R	= radius of curvature of Coanda surface
S_w	= wing area
S_T	= stabilator area
T	= airfoil maximum thickness
V_{ew}	= calibrated airspeed based on gross weight at sea level and corrected for position error
V_i	= aircraft indicated airspeed
α_c	= angle of attack corrected for downwash
α_g	= geometric angle of attack
β	= flap folding angle equal 170° in cruise configuration
δ_e	= stabilator angle
θ	= Coanda jet turning angle

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Index categories: Aircraft Configuration Design; Aircraft Performance; Aircraft Testing (including Component Wind Tunnel Testing).

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Introduction

IN December 1969, West Virginia University proposed to design and construct a Technology Demonstrator (TD) aircraft. The sole purpose of the TD is to provide a vehicle for full scale flight testing of high-lift powered airfoils with circulation control by blowing over a blunt trailing edge. This project was part of an on-going contract with the Office of Naval Research on the theoretical and experimental aspects of circulation control by blowing with possible applications to helicopter rotors.

The originator of this method of lift control was Davison.[1] Additional work on this problem has been done by Kind.[2,3§] Extensive experimental testing on cambered elliptical airfoils with circulation control was done at West Virginia University by Walters.[4] Concurrent to the experimental work, Ambrosiani and Ness[5] developed a self-contained computer program which calculates the obtainable lift coefficient as a function of airfoil geometry and blowing rate. The analysis combines potential flow analysis and boundary-layer theory. The iteration is ended when both upper and lower boundary layers separate at the same static pressure in the wake region at the trailing edge.

The results of the theoretical and experimental research on cambered elliptical airfoils were very encouraging and showed that for blowing rates in the range $0.02 < C\mu < 0.4$ the obtainable increase in lift coefficient ΔC_L ranges from 20 to 40 times the blowing coefficient. The obtainable augmentation ratio depends on the configuration, the blowing rate $C\mu$, the angle of attack and Reynolds numbers of both the airfoil and the Coanda jet. The strong Reynolds numbers dependency makes it difficult to predict the full scale performance from model tests. As the tunnel speed is increased to simulate high Reynolds number, the blowing jet velocity must be increased proportionally, resulting in supersonic jets and poor Coanda turning. The high-lift coefficients also create high induced downwash angles and the wind tunnel test data require large wind tunnel wall interference corrections.

The application of this high-lift principle to a full scale STOL aircraft is attractive because of the direct lift control (DLC) option and the good pilot visibility at low angles of attack while operating at high-lift coefficients. It is also of in-

§Kind, R.J., Visiting Professor, West Virginia University, Summer, 1968.

terest to obtain high Reynolds number data on the obtainable lift augmentation ratio and determine scaling and wind tunnel wall interference effects. The inherent disadvantages are the large aft shift in the center of pressure when blowing and the need for an inflight geometry change from a rounded trailing edge in the STOL mode to a sharp low drag trailing edge in the cruise configuration. It is for these reasons that in 1969 the Department of Aerospace Engineering at West Virginia University started to design and model-test several two dimensional airfoil configurations. One of these was selected and test flown recently on the TD STOL aircraft.

WVU STOL Wing Development

The first design was a modification of a NACA 64_2-415 airfoil called WVU Type "A" STOL wing (see Fig. 1). The circular hinged end of the sharp trailing-edge flap was used to form a Coanda surface by allowing the flap to rotate 166° to a retracted position inside a cavity of the wing. Above this cavity was a low pressure air supply duct to allow uniform spanwise blowing. The drooped and blown leading-edge STOL nose was designed by Inumaru¶ based on a statistical analysis of wind tunnel test results. The design aspects and the 1971 wind tunnel model test results are given in Ref. 6. Shortcomings of the Type "A" STOL wing were: a) the reduction in wing chord when operating in the high lift mode; b) the inefficiency of ducting low pressure blowing air; c) leading edge blowing was only effective for angles of attack beyond 15°.

Based on the experience gained with Type A, a new model Type B wing was designed (see Fig.2). For its performance improvement over Type A, see Ref. 7. In Type B wing the leading-edge blowing was eliminated. The leading-edge nose radius was reduced and the Coanda wall radius was increased. This wing was designed for high-pressure hot air blowing using a new flap design. This flap retracts by folding forward in flight and increases the wing chord by 20% in the STOL mode. An internal ejector was developed which provides boundary-layer control by suction at the flap hinge and optimizes the blowing jet Reynolds number. The blowing jet slot and Reynolds number were varied and the optimum jet slot to wall radius ratio was found to be 0.03 for best Coanda turning and maximum lift. High-pressure jet engine compressor bleed air was used to obtain small ducting, however this results in supersonic nozzle velocities. This high-temperature, high-velocity jet does not produce the optimum slot Reynolds number for Coanda turning, but the Reynolds number can be optimized without loss in momentum by incorporating a high-mass ratio ejector. The ejector is designed to exhaust into the circulation control wall jet blowing slot. For optimum Reynolds number, the slot is designed to equal 0.03 times the wall radius. The ejector makes the slot larger for easy maintenance and the exit jet cooler. The air entrained by the ejector is drawn through the hollow corrugated flap and provides the necessary cooling. The flap hinge suction reduces the boundary-layer thickness upstream of the blowing slot, which greatly improves the Coanda turning angle. A 1/6-scale wind tunnel model showed a 10% increase in lift due to the effect of flap hinge suction (see Fig. 3). The effective angle of attack on the two dimensional wind tunnel model differs from the geometric angle of attack due to the model end effects and the wind tunnel wall interference. The effective angle can be computed by matching the theoretical pressure distribution with the one found experimentally as shown in Fig. 4. Note also the high suction peak near the trailing edge, which causes a high nose-down pitching moment.

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Other interesting configurations and recent model tests have been reported by Englar.[8] At very high values of the lift coefficient, other methods such as the augmentor wing or externally blown flap should be used.

STOL Aircraft Design Considerations

The Technology Demonstrator was designed by the first two authors (see Fig. 5) and was test flown by the third author. The Type B wing selected for this test satisfied the following design objectives: a) low drag, high wing-loading cruise configuration, desirable for economic high-speed cruise and good ride qualities; b) variable drag and low wing-loading STOL configuration desirable for low controllable approach speeds, obtained through the use of a folding flap (see Figs. 6 and 7); c) high-lift coefficient at low blowing coefficient by uniformly blowing over a rounded trailing edge along most of the wing span for maximum blowing effectiveness; d) good pilot visibility, because high lift can be generated in a near level flight attitude at full blowing; e) low duct volume and low losses through the use of high-pressure jet engine bleed air with up to three atmospheres pressure in a 3" diam duct and using an internal ejector to optimize the Coanda jet Reynolds number, and reducing the jet noise; f) prevention of flap stall by boundary-layer suction at the flap hinge. The removal of the boundary layer upstream of the trailing edge blowing slot enhances the Coanda turning around the blunt trailing edge; g) prevention of leading-edge stall through the use of a specially designed drooped leading edge; h) the option of quickly varying the blowing pressure and thus the lift coefficient for DLC (direct lift control) or for flare-out during landing; i) the option of roll control by varying the blowing rate over either the left or the right wing flap; j) blown and drooped ailerons for good roll control at low speeds; k) blowing air pressure regulation by using a variable opening electric dump valve while maintaining constant jet engine compressor mass flow bleed; l) very rapid forward folding capability of the flap in order to return to a conventional configuration for flight-test safety; and 2) ease of construction and light weight.

It was decided to use the basic BD-4 fuselage as a base for the design. The fuselage was highly modified structurally in order to incorporate the various hardware installations required. The major modification was the installation of a large compressed air supply in the fuselage in order to obtain reasonable values of the flap blowing coefficient $C\mu$. Circulation control blowing air with a pressure up to 28 psig is furnished by an Airesearch GTC 72 jet engine which provides up to 2 lb/sec of compressed air, permitting a wide range of test conditions as well as being of reasonable weight.

For takeoff and landings, this flap is rotated to any arbitrary set position desired by the pilot. The mechanical arrangement is such that the flap folding mechanism serves the dual purpose of an air delivery system to the flaps from the air supply mounted in the fuselage and the mechanical actuator for both flaps.

The 3-in. diam trailing edge hot compressed air delivery duct has a sliding connection to the hinged portion of the flap in order to allow for a ¾ in. thermal expansion in the spanwise direction. This design has proven to be satisfactory and the critical slot gaps have remained essentially constant with and without blowing (see Fig. 8) Roll control at low speeds was maintained by blowing over the ailerons which can be drooped up to 20°. The blowing air for the ailerons is derived from the compressor bleed air; however, a separate ejector is incorporated at the wing fuselage junction in order to entrain ambient air. This procedure increases the mass flow available for aileron blowing and simultaneously cools the air prior to its delivery through the wing to the aileron plenum.

To avoid the excessive losses due to spillover between the flap and aileron sections of the wing, large fences were installed at each end of the flaps and ailerons. These fences have been designed to serve also as mounting supports for possible

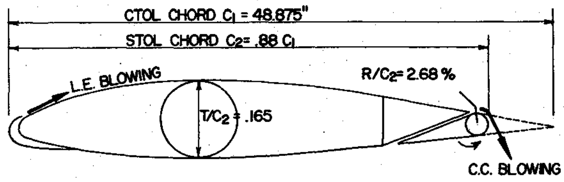

Fig. 1 Type A STOL wing with blowing over both leading edge and round trailing edge, but reduced wing chord in the STOL mode.

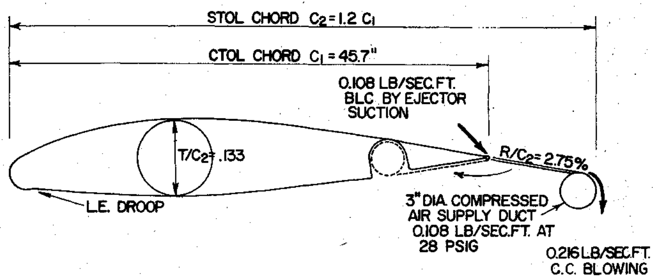

Fig. 2 WVU type B STOL wing with blowing over a round trailing edge and increased wing chord in the STOL mode.

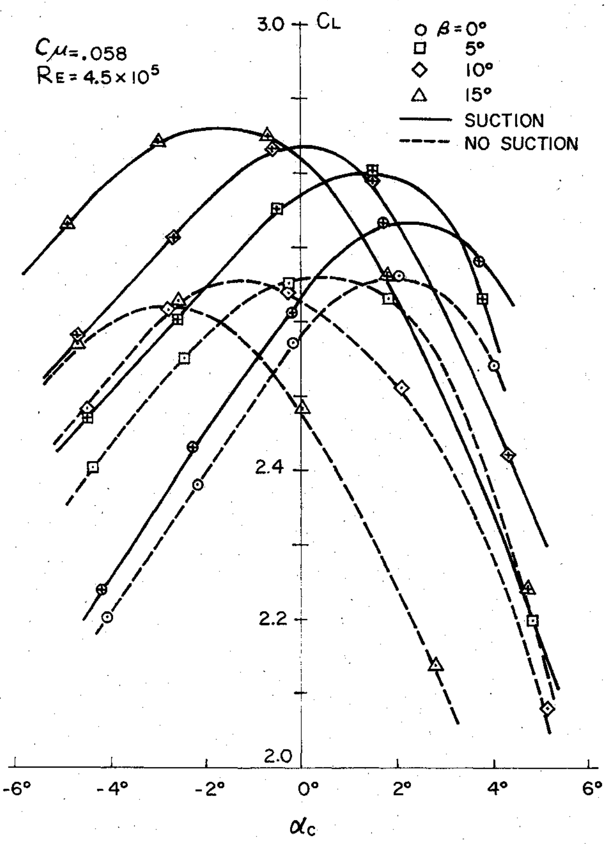

Fig. 3 Type B wing wind tunnel performance at low Reynolds number and, blowing coefficient with and without flap hinge suction. Note effect of flap deflection angle and angle of attack.

future addition of fixed slats. Notice also, that the flap itself has a rather large fence which "rides" with the flap. Due to the large nose-down pitching moments associated with all powered airfoils, the horizontal tail surface area is large. Since a large tail downwash was anticipated, both the leading-edge radius and the up travel of this all-moving tail were increased.

Many safety devices have been built into the aircraft. A spin chute is mounted near the tail. A door ejection system is provided for rapid egress from the plane. A fire retardant system for the gas turbine mounted behind the pilot is

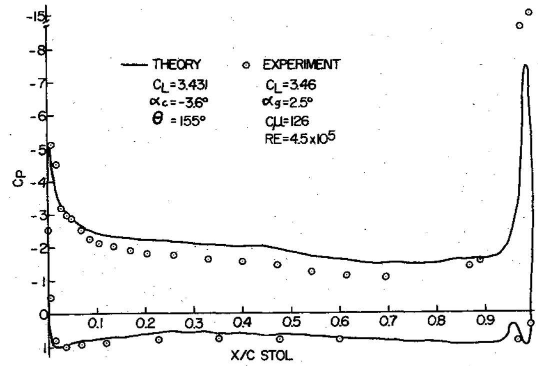

Fig. 4 Typical wind tunnel model theoretical and experimental pressure distribution on type B STOL wing at low Reynolds number.

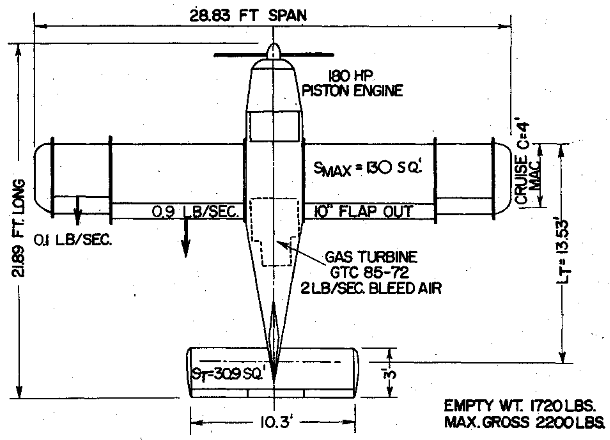

Fig. 5 WVU technology demonstrator STOL aircraft plan view and dimensions.

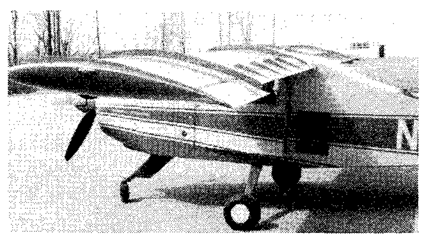

Fig. 6 TD STOL aircraft with flap folded in cruise configuration.

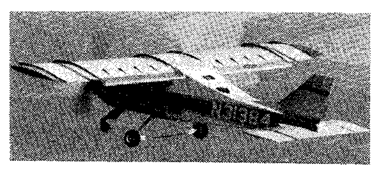

Fig. 7 TD STOL aircraft with flap out in STOL configuration.

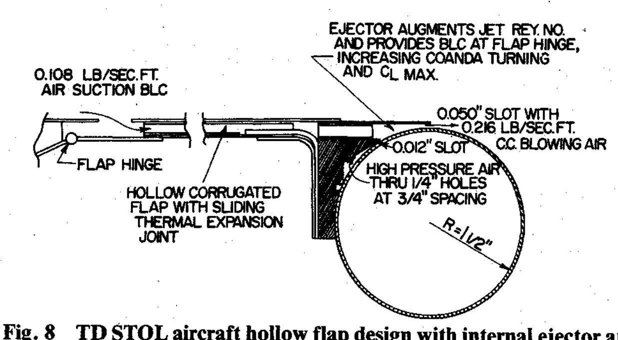

Fig. 8 TD STOL aircraft hollow flap design with internal ejector and thermal expansion joint.

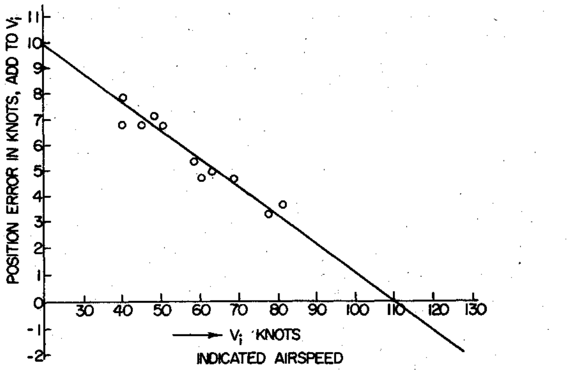

Fig.9 TD position error correction obtained by formation flying with a calibrated chase plane.

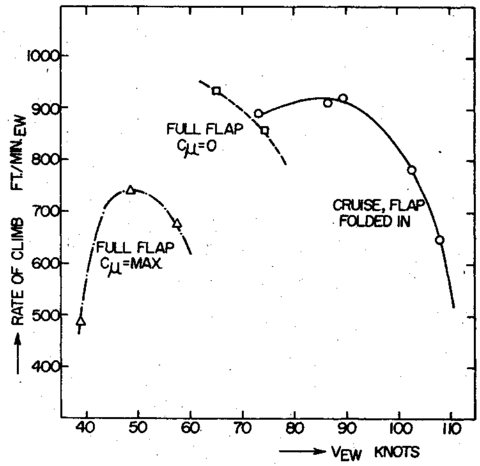

Fig. 10 Rate of climb data reduced to sea level and gross weight.

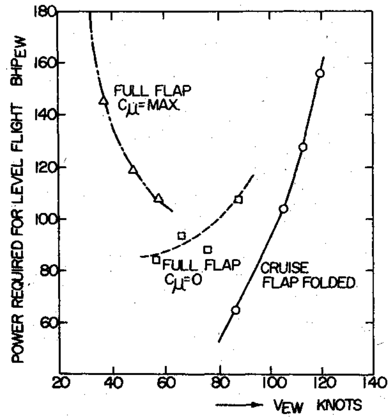

Fig. 11 Power required for level flight reduced to sea level and gross weight.

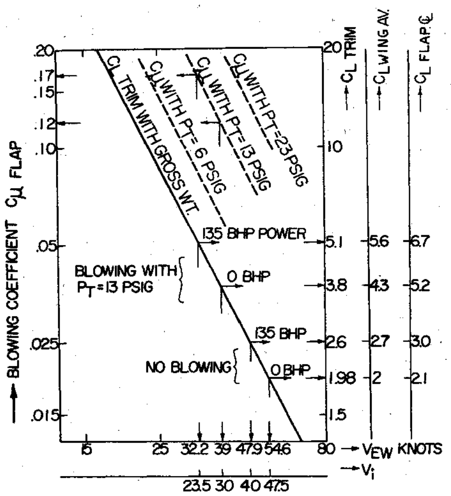

Fig. 12 Full flap power on and power off stall performance.

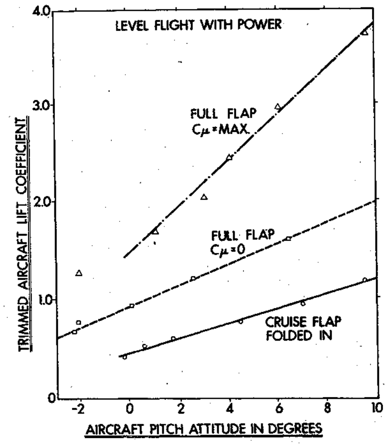

Fig. 13 Effect of flap and circulation control on the aircraft pitch attitude as measured from the aircraft waterline.

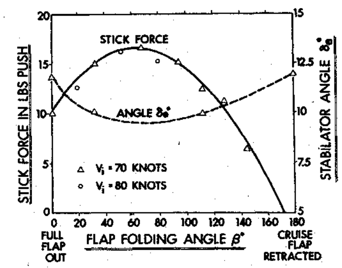

Fig. 14 Effect of flap transient on stick force and stabilator angle.

provided as well as an insulated fire wall between the pilot cabin and rear engine compartment. For operational safety the blowing air can be either shut off or dumped instantly through a bypass valve. The flap retraction time from the fully extended to retracted position is only four sec so that the plane may be returned to a completely conventional cruise configuration in a reasonably short time. In the event of flap actuator failure, a pilot hand-operated override actuator is provided.

Flight-Test Program

The main objective of the preliminary flight-test program was to determine the obtainable lift coefficients of the wing and to define the operating envelope of the vehicle with circulation control, and to qualitatively determine the handling qualities of the aircraft with the unique flap and the circulation control system. Flight tests were limited to high-lift performance at altitude with one flight series in ground effect but no attempt was made to demonstrate STOL performance with this research aircraft.

Discussion of Results

Determination of the position error correction for the airspeed and altimeter system was attempted using a trailing static cone as the static reference and a Kiel Tube as a reference total head. The results were uncertain due to the interaction of the gas turbine exhaust and the trailing cone, and the P.E.C. data was therefore obtained by formation flying with a calibrated chase plane, a Cessna 150. The data shown in Fig. 9 is reasonably consistent and shows large airspeed corrections in the STOL mode with circulation control operating.

The rate of climb data, Fig. 10 shows that the best sea level rate of climb is approximately 925 ft/min at 85 knots. Rate of climb with full flap and full blowing is lower than the cruise flap configuration and is very speed-limited in that the rate of climb falls off very considerably with ± 10 knots of the best climb speed. However, the climb performance of the aircraft is adequate for the research aircraft mission. Additional excess thrust horsepower is required for the demonstration of STOL performance. As was stated previously, the TD was not intended to be a viable STOL aircraft but rather to serve as a platform for testing the high-lift STOL wing. It is anticipated that a larger engine will be installed in the future.

The power required for level flight data, Fig. 11, showed that the effect of the deployed, round trailing-edge flap considerably increased the power required for level flight from the cruise-flight condition. The effect of circulation control was to increase the power required in level flight in the STOL mode such that below sixty knots the aircraft was operating on the back-side of the power curve and the minimum zero-sink flying speed at sea level is 32 knots.

Stalls were performed in the cruise flap, fully extended flap, no blowing and extended flap with full blowing with the front engine at idle, power for level flight, and full throttle. The minimum indicated airspeed for full circulation control and full power was 23.5 knots, which is equivalent to a calibrated airspeed of 33.2 knots and corresponds to a maximum trimmed aircraft lift coefficient of 5.1 and a lift coefficient at the middle of the flap of 6.7 with a blowing coefficient $C\mu = .17$. A summary of the results of the stall tests is shown in Fig. 12. The power-off stall with blowing results in $V_i = 30$ knots, $V_{ew} = 39$ knots, and lift coefficients $C_{L_{\mathrm{trim}}} = 3.8$ and $C_{L_{\mathrm{flap}}} = 5.2$, with $C_{\mu_{\mathrm{flap}}} = .12$.

The power-off and blowing-off stall gives $C_{L_{\mathrm{flap}}} = 2.2$. Note all lift coefficients are based on cruise chord length. The power-off lift augmentation ratio due to blowing along is: $\Delta C_{L_{\mathrm{flap}}} / C\mu = 25.8$.

The effect of flaps, blowing and drooped ailerons results in a $\Delta C_L = 1.82$ with the drooped aileron accounting for approximately 0.11 of the ΔC_L. The effects of front engine power on the trimmed aircraft lift coefficient in the cruise flap configuration is a $\Delta C_L = 0.42$, and a $\Delta C_L = 0.62$ with flaps out and no blowing, and a $\Delta C_L = 1.79$ with flaps out and full circulation control. Since the aircraft attitudes are flat in the circulation control mode it would appear that the large ΔC_L increment is due to propeller slipstream effects on the blown flap and not on the vertical component of thrust of the propeller.

All the flight tests involving flaps, with or without blowing, were for the fully extended position with flap deflection angle $\beta = 0°$ as shown in Fig. 7. The wind tunnel test shown in Fig. 3 indicates that $\beta = 15°$ produces higher lift coefficients. However, time did not permit flight tests on the effect of flap position.

The general stall characteristics show a sharp break accompanied by considerable wing drop, large aircraft pitch changes, and large excursions in yaw. The altitude lost on most stalls was less than 200 ft.

A simple pendulum attitude indicator was used to determine fuselage attitude in stabilized flight at various aircraft airspeeds in the cruise flap, full flap, no blowing, and full flap-full circulation control configurations. The results are plotted in Fig. 13 in the form of trimmed aircraft lift coefficients at very small values of aircraft pitch attitudes. For example, aircraft C_L of 4.0 with power for level flight can be obtained with a fuselage pitch attitude of approximately 10° nose up. This characteristic of this high-lift system is very advantageous for STOL operations in confined spaces and also for U.S. Navy carrier applications.

Flap transient data was obtained by a series of flap angle increments at trimmed flight conditions of 70 knots and 80 knots from flap angles of 0° to 173° deployment with stick forces and elevator angles being measured at each flap angle. The results are plotted in Fig. 14. Maximum elevator stick force excursions of 17 lb were recorded with a deployed flap out of trim condition of 10 lb. The elevator angle excursion during flap deployment resulted in a bump to the aircraft which is easily controllable.

The aircraft performance was just adequate for the research mission of the takeoff and landing demonstrations. The handling quality suffered from a lateral-directional control force gradient mismatch in that pedal forces were very light and aileron forces very heavy. This will be corrected before future flights. Since large roll rates could be induced by the rudders and the adverse yaw was large, coordinated flight with the basic aircraft was difficult; turbulence aggravated this problem.

The flap deployment and gas turbine engine operations were satisfactory. Circulation control operation was satisfactory and slow flight was accomplished at very small values of aircraft pitch attitude. Directional stability was degraded in the high-lift mode and the aircraft was speed unstable below sixty knots. Stick-free longitudinal stability was marginal in the high-lift mode but adequate longitudinal control authority was available down to the stall. High-lift operations very close to the ground did not disclose any radical changes in elevator effectiveness in and out of ground effect.

Conclusions

The Technology Demonstrator aircraft satisfactorily demonstrated the capability of generating large aircraft trimmed lift coefficients with circulation control by blowing over a rounded trailing edge at low blowing coefficients. The TD also demonstrated that the high-lift coefficients can be obtained at low aircraft attitude resulting in good pilot visibility. The large nose-down pitching moments increase the longitudinal stability but make the maximum trim lift coefficient about 10% less than the average wing lift coefficient.

The in-flight flap extension and retraction transients are acceptable. The large changes in aircraft lift coefficients did not seriously degrade the longitudinal handling qualities. High-lift operation in and out of ground effect did not show radical changes in elevator effectiveness. The leading edge droop design was adequate. The 1/6-scale wind tunnel model was tested at a Reynolds number of 4.5×10^5 and produced without flap hinge suction a lift coefficient of $C_{L_{\max}} = 3.5$ with a blowing coefficient $C\mu = .12$. For the same $C\mu$ value as above, the effect of Reynolds number and flap hinge suction causes a significant increase in $C_{L_{\max}}$ in the TD prototype which operates at a Reynolds number of 1.5×10^6 at 39 knots.

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