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Application of Circulation Control to Advanced Subsonic Transport Aircraft, Part II: Transport Application

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An experimental/analytical research program was undertaken to develop advanced versions of circulation control wing (CCW) airfoils and to address specific issues related to the application of these blown high-lift devices to subsonic transport aircraft. The primary goal was to determine the feasibility and potential of these pneumatic configurations to increase high-lift system performance in the terminal area while reducing system complexity and aircraft noise. A four-phase program was completed, including 1) experimental development and evaluation of advanced CCW high-lift configurations; 2) development of effective pneumatic leading-edge devices; 3) computational evaluation of CCW airfoil designs plus high-lift and cruise capabilities; and 4) the investigation of the terminal-area performance of transport aircraft employing these airfoils. The first three phases were presented in Part I of this article. This segment, Part II, describes the fourth phase of the program. Experimental lift coefficient values approaching 8.0 at zero incidence were demonstrated by two-dimensional CCW configurations and were reported in Part I. These were used to predict 70–80% reductions in takeoff and landing distances for a three-dimensional advanced subsonic transport configuration employing a simplified pneumatic high-lift system. These results and the methodology used to obtain them will be presented in greater detail in the following discussions.

Nomenclature

a_x = longitudinal acceleration
C_D = wing or aircraft drag coefficient
C_d = airfoil drag coefficient
C_L = wing or aircraft lift coefficient;
$C_{L\,\mathrm{app}}$ = approach lift coefficient
C_l = airfoil lift coefficient
C_μ = jet momentum (blowing) coefficient
c = airfoil chord length
c_f = flap chord length
EKv = kinetic energy, vertical component
h = height above ground
$\dot{m}$ = blowing jet mass flow rate
q = freestream dynamic pressure
r = CCW flap radius
S = wing planform area
S_{eff} = effective blown planform area
S_g = ground roll distance
S_{50} = distance over 50-ft obstacle
T = ambient temperature
T = engine installed thrust
V = freestream velocity
V_{app} = approach velocity
V_j = isentropic jet velocity
V_{LO} = liftoff velocity
W_A = engine airflow
$W_{A\,\mathrm{core}}$ = engine core airflow
W_F = engine fan airflow
x = horizontal distance over ground
α = angle of attack
α_{stall} = stall angle of attack
Δ = delta, change in
δ_f = flap deflection angle
γ = climb angle

Subscripts
2-D = two dimensional
3-D = three dimensional

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Introduction

BASED on existing data,[1] pneumatic high-lift airfoils appear to offer significant payoffs in the design and development of next-generation subsonic transport aircraft. Both ground and flight experimental investigations have previously shown that a specific type of blown airfoil known as the circulation control wing (CCW) can greatly augment the high-lift capabilities provided by conventional mechanical flaps. References 1–12 provide summaries of some of these developments and include verification of CCW airfoil sections generating very high lift at low blowing rates. They also discuss successful CCW applications to and flight tests on fixed-wing short takeoff and landing (STOL) and rotary-wing vertical takeoff and landing (VTOL) aircraft. The CCW concept employs tangential blowing over round or near-round trailing edges to pneumatically replace multielement mechanical flaps. Here, the lack of a sharp trailing edge avoids the Kutta condition requirement that the stagnation streamline depart the airfoil at the trailing edge. The jet turning action does, in fact, produce a pneumatic cambering device. The result is very high-lift generation, with two-dimensional lift coefficients greater than 7.0 being generated at 0-deg angle of attack.[2] Lift augmentation ($\Delta C_l/C_\mu$) as high as 80 or more has been reported in Refs. 1 and 6. The driving parameter is the momentum coefficient, defined for three-dimensional wings as

$$C_\mu = \dot{m}V_j/qS \tag{1}$$

In addition, high-lift system complexity can be reduced by substituting simplified pneumatic components for mechanical flaps, tracks, and actuators. Figure 1 (from Part I of this article) shows a no-moving-parts CCW trailing edge applied to a NASA supercritical airfoil section.[7,8] Not only are the

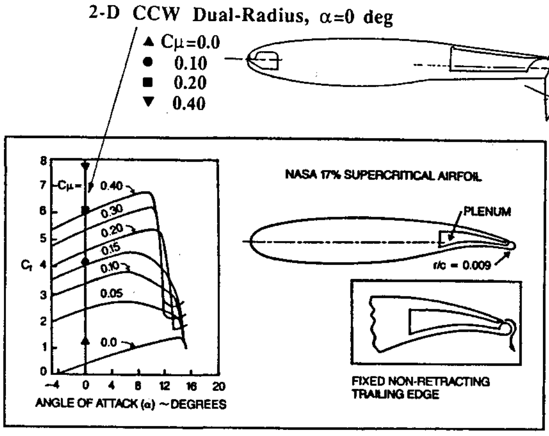

Fig. 1 Comparison of two-dimensional dual-radius CCW/supercritical airfoil with monoelement round CCW/supercritical high-lift system.

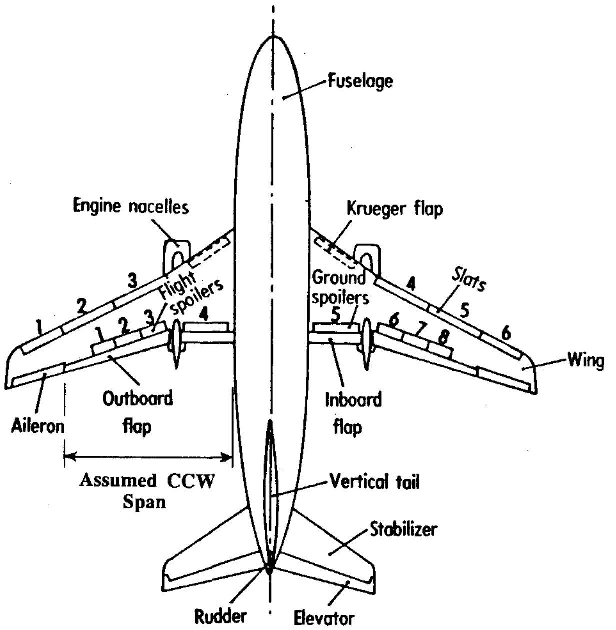

Fig. 2 High-lift and control surfaces for conventional B737 (from Ref. 13) and flap span for B737/CCW aircraft.

conventional leading-edge and trailing-edge components eliminated, but the resulting lift values (at zero incidence and up through maximum C_l) are quite significant. As this figure shows, CCW airfoils applicable to transports typically generated C_l values of 6 to 7, equal to or exceeding the high-lift potential of even the most complex multielement mechanical flap airfoils. Pneumatic concepts can further simplify transport aircraft wings by eliminating the need for mechanical leading-edge devices as well as mechanical-roll-control or direct-lift-control surfaces.[9] In Part I of this article, an advanced dual-radius CCW with a pneumatic leading edge was developed that generated lift coefficients approaching 8 at 0-deg incidence, which represents as much as 30–35% increase in lift over the prior CCW results. This airfoil is also shown in Fig. 1, where the resulting improvement in lift performance is seen as the solid symbols. Since blowing behaves as a pneumatic flap, lift curves through these α = 0-deg points will be parallel to curves at constant flap angles δ_f, with $C_{L\max}$ a function of the leading-edge device effectiveness.

While the high-lift and simplifying capabilities of these CCW devices have been confirmed in experimental programs and in actual flight demonstrations,[10,11] specific application-related issues need to be addressed to take maximum advantage of these pneumatic benefits. The two-dimensional research discussed in Part I developed new versions of the CCW pneumatic airfoil. The present research project, Part II, was undertaken to resolve these application issues in order to make pneumatic airfoil technology available for use in next generation transports or on retrofits of existing aircraft. Specific issues to be addressed in Part II include analytically applying

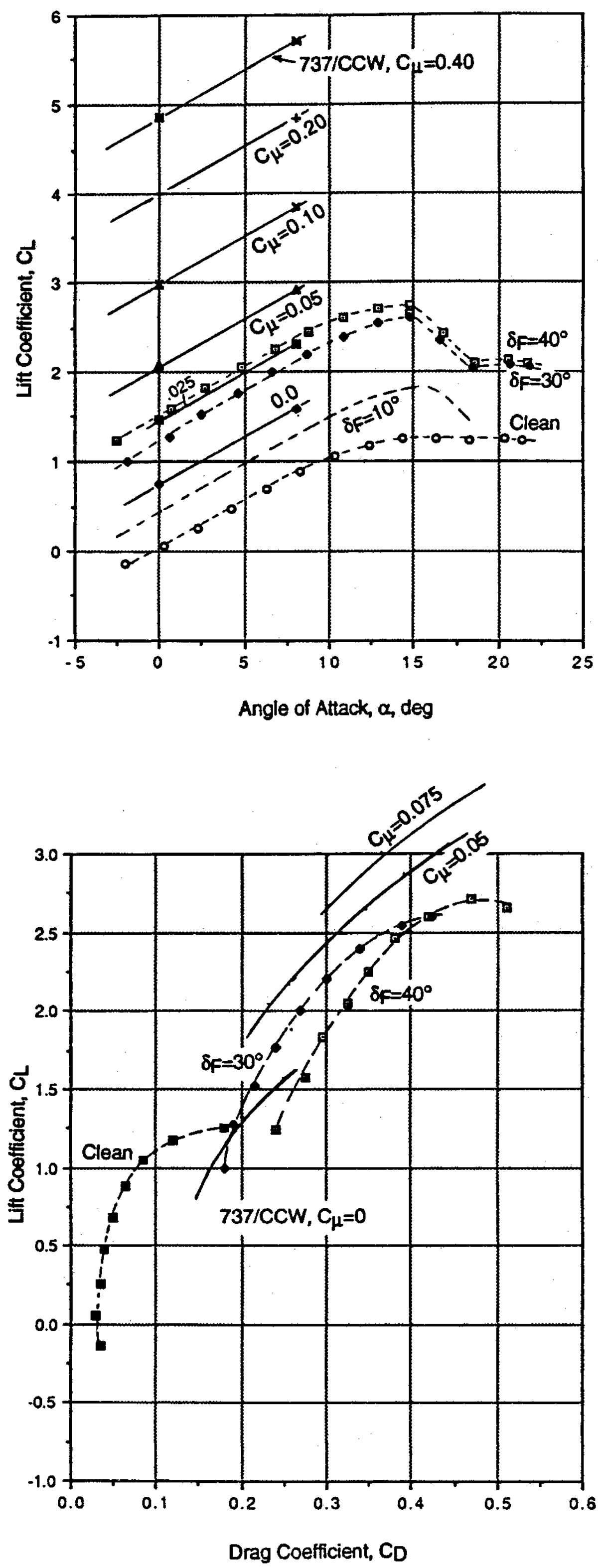

Fig. 3 One-eighth-scale wind-tunnel lift and drag data for B737 aircraft (from Ref. 13), and predicted B737/CCW data (90-deg CCW flap, 60-deg Krueger flap).

Table 1 Aerodynamic characteristics of the conventional B737 aircraft

Condition	Flap	α	C_L	C_D
Takeoff ground roll	30 deg	1.0 deg	1.320	0.196
Liftoff	30 deg	8.0 deg	2.130	0.288
Landing ground roll	40 deg	1.0 deg	1.640	0.275
Approach	40 deg	6.0 deg	2.175	0.342

Table 2 B737-100 terminal area operating parameters

Empty weight	62,000 lb
Typical gross weight	111,000 lb
Maximum landing weight	101,000 lb
Typical landing speed	144 mph
FAA takeoff field length	4,300 ft
FAA landing field length	4,000 ft

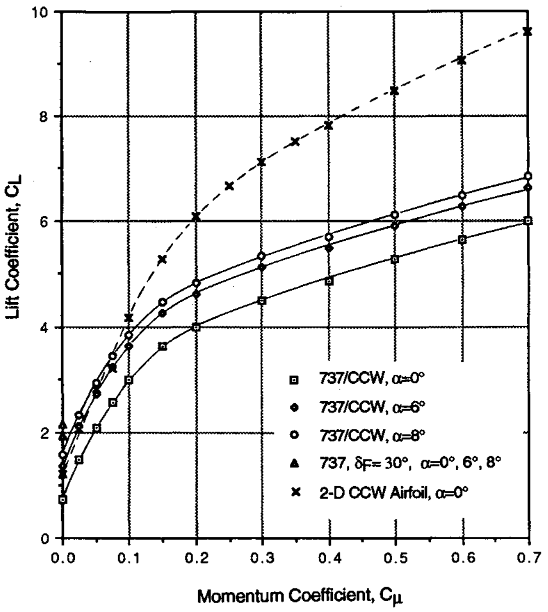

Fig. 4 B737/CCW aircraft lift due to blowing (90-deg CCW flap, 60-deg Krueger flap).

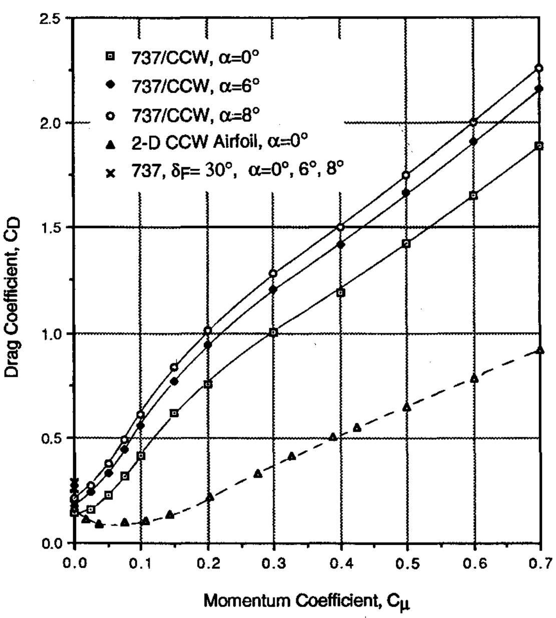

Fig. 5 B737/CCW aircraft drag due to blowing (90-deg CCW flap, 60-deg Krueger flap).

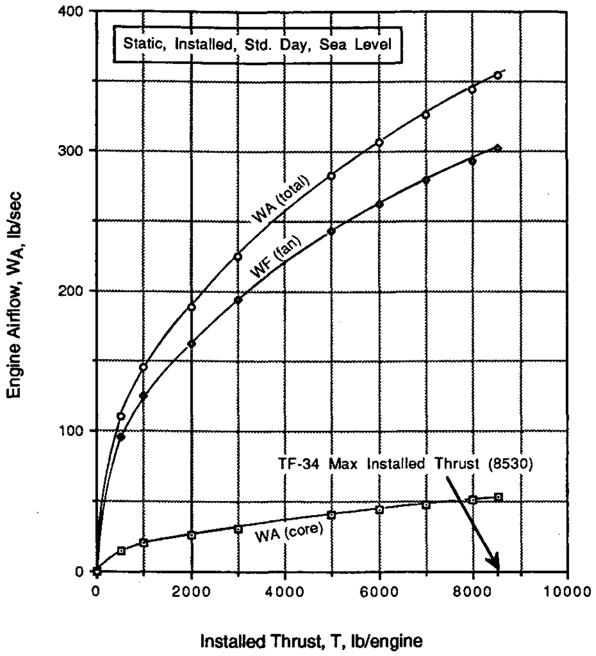

Fig. 6 TF-34 thrust and airflow characteristics.

the two-dimensional results of Part I to a postulated advanced subsonic transport, and investigating system performance for that aircraft employing a CCW high-lift system. Results of these investigations will be presented in the following sections.

Investigation of CCW System Performance

Results of the two-dimensional evaluations presented in Part I of this study were incorporated into the design of an advanced CCW high-lift system for a subsonic commercial transport aircraft. This required prediction of the blown aircraft's high-lift capabilities with available or postulated air sources powering the system, and employing appropriate analytical routines to predict the takeoff and landing performance. These analyses had to take into account any new restrictions placed on blown high-lift aircraft if these deviated from conventional mechanical systems. The following sections discuss generation of the aircraft high-lift characteristics, prediction of the associated terminal area performance of the modified commercial transport, and discussion of resulting issues relevant to blowing system integration into the CCW aircraft.

Transport Aerodynamic Characteristics

The Boeing 737-100, a twin-engined commercial transport (hereafter referred to as B737) was chosen as a comparative sample case to investigate potential gains to be realized from the CCW application. This aircraft was especially convenient as NASA Langley Research Center currently operates that configuration (Research Aircraft NASA 515) in its ongoing Subsonic Transport High-Lift Flight Research program. In its production version, it employs a triple-slotted mechanical flap with leading-edge slats and Krueger flaps, thus placing it near the best of the mechanical systems shown in Fig. 1 of the Part I article. Figure 2 shows the arrangement of these mechanical components on the B737 wing, and the comparable CCW system proposed for the same span. (In actual application, the authors would propose full-span blowing all the way to the outboard aileron edge, with roll control by means of differential blowing, but that would have been an unfair comparison to the actual mechanical flaps in this case.)

In the absence of actual full-scale flight test data for this aircraft, NASA Langley personnel supplied Ref. 13, which provided B737 baseline geometry and aerodynamic characteristics from $\frac{1}{8}$-scale wind-tunnel results. These model data,

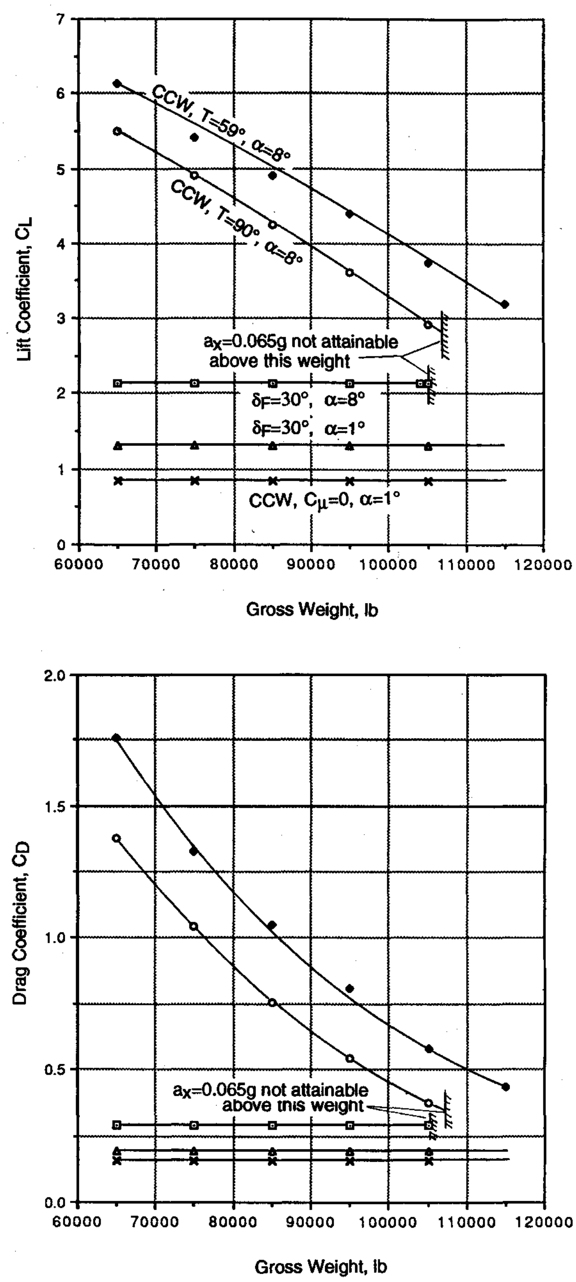

Fig. 7 Lift available at takeoff for B737 and B737/CCW aircraft (90-deg CCW, 60-deg Krueger), sea level.

shown in Fig. 3, were used to represent the B737-100 in the following analyses. Also shown are predicted characteristics of the CCW version of this aircraft (to be discussed below). The following should be noted: 1) the Fig. 3 wind-tunnel data are untrimmed and out of ground effect, and 2) Reynolds number corresponds to q = 30 psf on the $\frac{1}{8}$-scale model, not full-scale.

Critical to takeoff and landing performance is the operational angle of attack. Using FAA guidelines for commercial transports (FAR Part 25, Ref. 14), the takeoff velocity should be $1.10 \times V_{\text{stall}}$, and the touchdown velocity $1.15 \times V_{\text{stall}}$. If the takeoff flap setting is assumed as 30 deg, and the landing flap as 40 deg on the B737 aircraft, takeoff will occur at α = 8 deg, and landing at α = 6 deg. This corresponds to the aerodynamic characteristics for the conventional aircraft (from Fig. 3), shown in Table 1.

It is realized that actual B737 takeoff is probably at a lesser flap setting angle than 30 deg (possibly 10 deg or so), but wind-tunnel data for that flap setting was not available. The 10-deg lift curve is approximated in Fig. 3, but drag was not

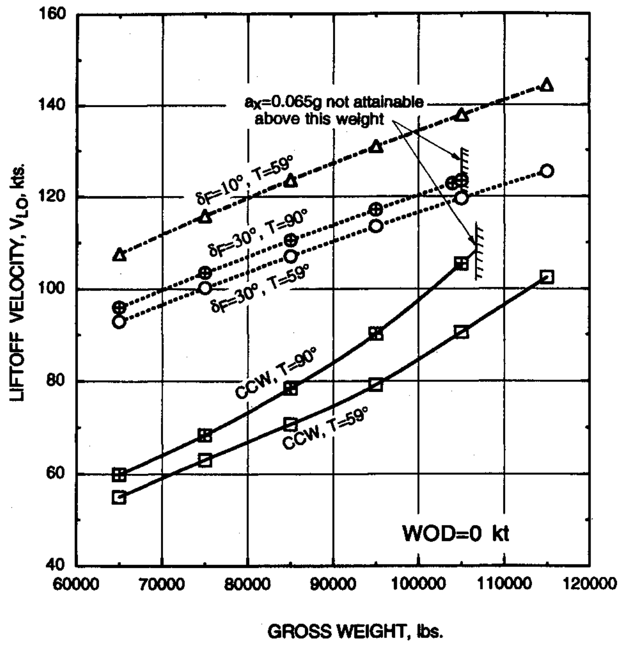

Fig. 8 Predicted liftoff velocities for B737 and B737/CCW.

easily interpolated. For the takeoff and the climbout calculations, the shortened ground roll due to increased lift at 30 deg rather than 10 deg will be offset somewhat by the increased drag. The main intent here is to compare the takeoff trends from a conventional flap to those for the CCW configuration. Pertinent B737-100 operational data obtained from Ref. 15 are shown in Table 2.

B737/CCW Aerodynamic Characteristics

In the absence of wind-tunnel evaluations of a three-dimensional B737/CCW model, an existing semiempirical method[10,16,17] was used to convert data for the two-dimensional dual-radius CCW airfoil with the Krueger leading-edge flap (Figs. 3, 11, and 14 from Part I) into three-dimensional finite-wing data for the B737, spanning the same portion of the wing as the existing mechanical flaps and leading-edge devices, Fig. 3. This method adjusts the two-dimensional data for sweep, taper ratio, aspect ratio, partial-span flaps, and three-dimensional lift curve slope, and provides an increment in lift at α = 0 deg, which is then added to the clean aircraft lift at zero incidence:

$$C_{L_{\text{blown}}} = C_{L_{\text{clean}}} + \Delta C_{L_{\text{CCW}}} = 0.04 + 0.5804\Delta C_{l_{\text{CCW}}} \quad (2)$$

Here, all input two-dimensional values ($C_{l_{\text{CCW}}}$) are the α = 0-deg value at a given C_μ for the flap at 90 deg (see Fig. 1), and the clean B737 value (C_L = 0.04) came from Fig. 3. An entire family of these values will exist, as both blowing and incidence are variable. The blowing-dependent values of $\Delta C_{l_{\text{CCW}}}$ came from the two-dimensional data (such as Fig. 6 of Part I) corresponding to the appropriate two-dimensional C_μ, based on only the blown wing area S_{eff}:

$$C_{\mu_{\text{2-D}}} = C_{\mu_{\text{3-D}}} S/S_{\text{eff}} \quad (3)$$

The lift due to incidence is derived by assuming (based on much past experience) that the blown lift curves will parallel the mechanical-flap curves for the same affected wing area. Using this procedure, the lift data of the B737/CCW configuration at α = 0, 6, and 8 deg were generated and plotted in Fig. 4. The original two-dimensional data at α = 0 deg are shown for comparison. These B737/CCW lift curves are also plotted in Fig. 3 for comparison to the baseline B737. The 6-

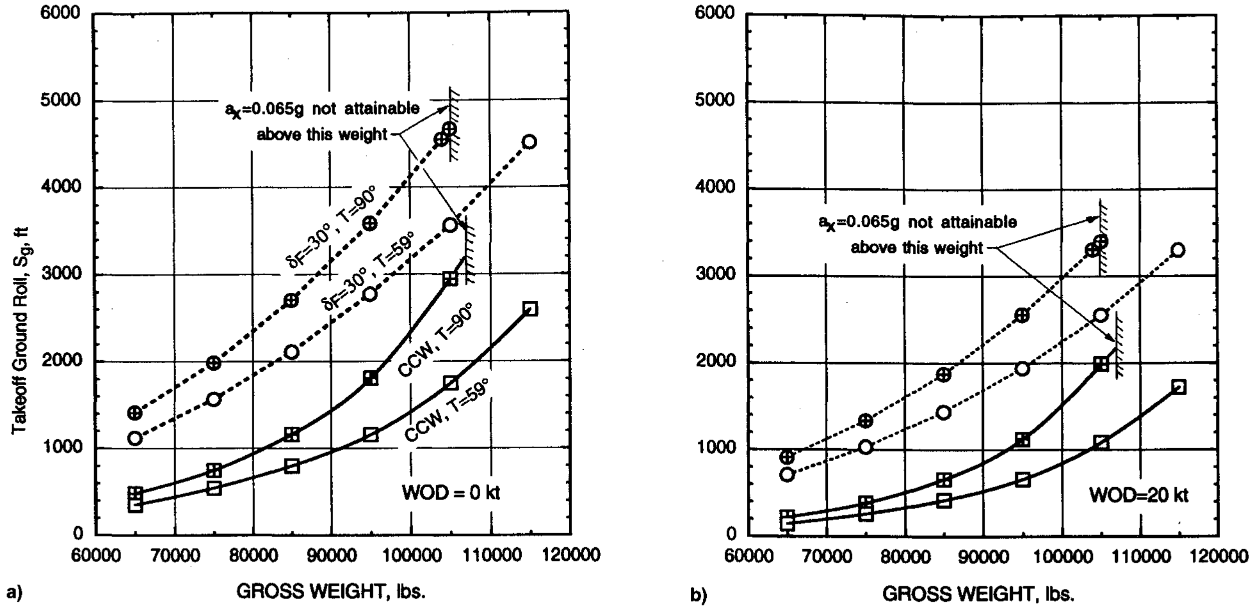

Fig. 9 Predicted ground rolls for B737 and B737/CCW aircraft, sea level: a) no head wind (WOD = 0 kt) and b) 20-kt head wind.

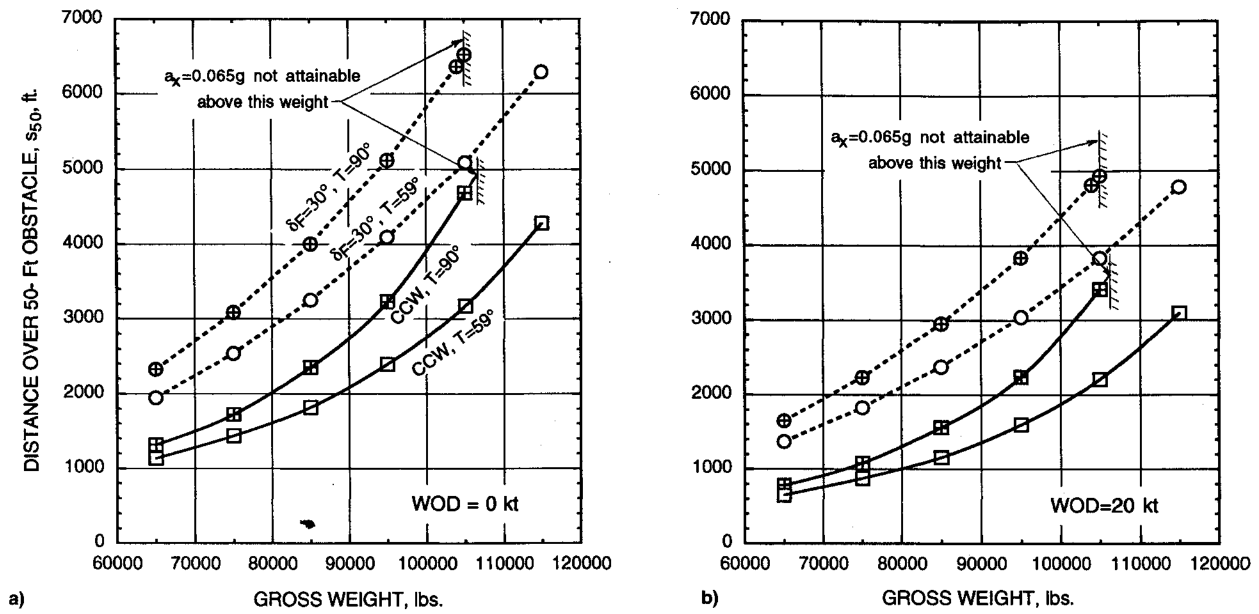

Fig. 10 Predicted distance over a 50-ft obstacle for B737 and B737/CCW: a) no head wind (WOD = 0 kt) and b) 20-kt head wind.

and 8-deg angle-of-attack values are retained as the landing and takeoff values of the B737/CCW aircraft to make results directly comparable to the conventional B737.

The blown drag was determined using the same semiempirical method,[10,16,17] and is described in more detail in Ref. 18:

$$C_D = C_{D_{\text{clean}}} + C_{D_{\text{profile}}} + C_{D_{\text{blowing}}} + C_{D_{\text{incidence}}} \tag{4}$$

where $C_{D_{\text{clean}}}$ is the zero-incidence cruise drag of the baseline B737, and $C_{D_{\text{profile}}}$ is derived from the two-dimensional measured drag at $\alpha = 0$ deg corrected for area S/S_{eff} and three-dimensional planform effects, just as $C_{L_{\text{blown}}}$ was. Figure 5 shows the resulting drag for the two-dimensional airfoil at $\alpha = 0$ deg, and for the three-dimensional B737 and B737/CCW aircraft at $\alpha = 0$, 6, and 8 deg. Representative drag polars for the CCW aircraft with 90-deg flap deflection, both with and without blowing, have been added to those of the conventional aircraft in Fig. 3. These data are sufficient to predict takeoff and landing performance once the aircraft engine characteristics are known.

Engine Characteristics with Blowing

Detailed engine characteristics for the B737-100's JT8D-15 turbofan engines with blowing were not available at the time of these initial predictions. It was thus decided to scale the characteristics of an existing similar engine, the TF-34 turbofan, for which satisfactory performance data was known.[17,19] At this point, it was assumed that bleed would be taken directly from the engine to avoid requiring a separate auxiliary power unit (APU). The JT8D-15 engine characteristics were scaled from the TF-34, using a 1.67116-scale factor based on rated thrust and an 8% installation thrust loss, which were applied to the data of Fig. 6. To avoid larger thrust loss due to core bleed, it was further assumed that only airflow from the fan would be used to power the CCW on takeoff and landing, and that the maximum pressure ratio available was

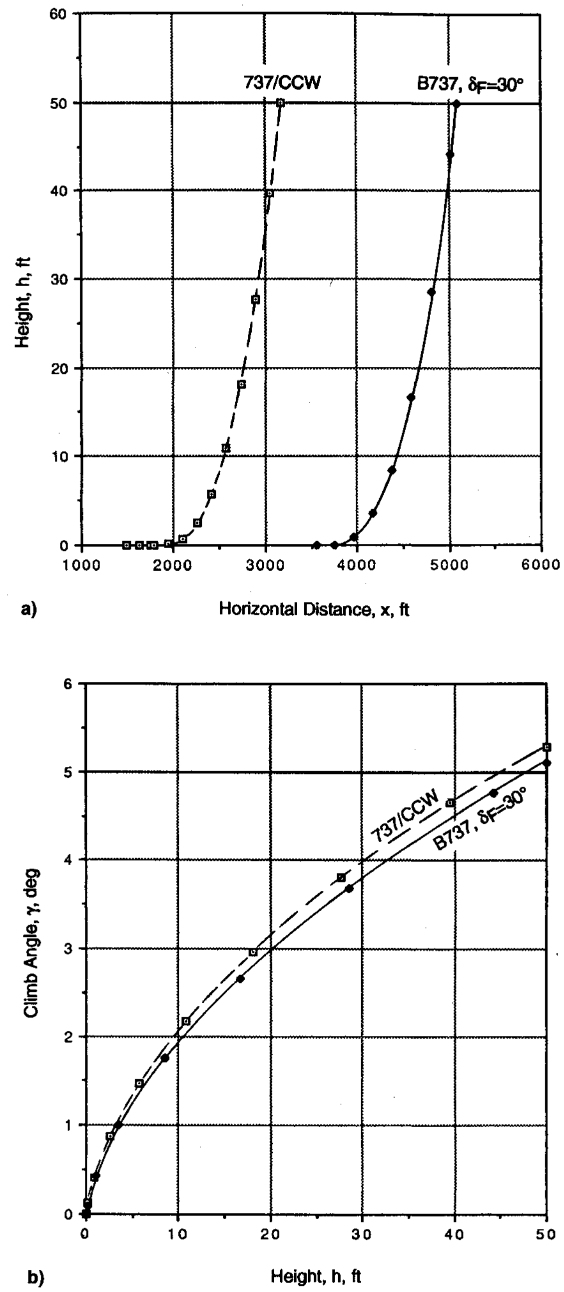

Fig. 11 Predicted takeoff flight paths for B737 and B737/CCW aircraft: a) flight path and b) climb angle. Gross weight = 105,000 lb, T = 59°F , WOD = 0 kt.

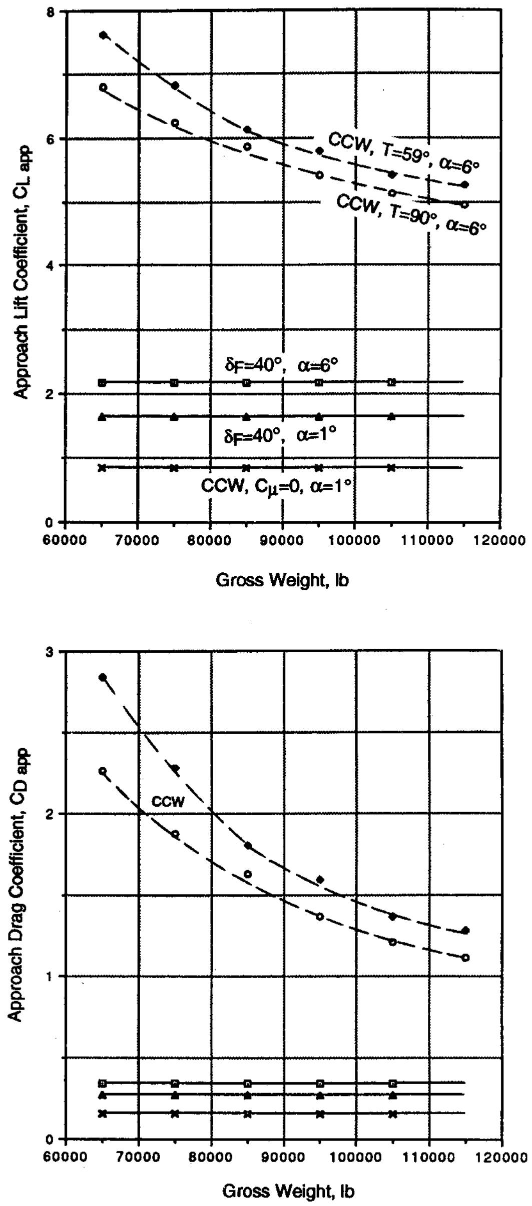

Fig. 12 Available lift for B737 (40-deg flap) and B737/CCW (90-deg CCW flap, 60-deg Krueger flap) at approach incidence down a 4-deg glide slope and during ground roll.

1.5. Thrust loss due to fan bleed was assumed to be equal to the percent of airflow removed from the fan (i.e., 5% fan airflow removal resulted in 5% thrust loss). Further details of engine bleed, ram drag accounting, etc., are provided in Ref. 18.

B737 and B737/CCW Takeoff Performance

To analyze the effects of pneumatic high-lift systems on the takeoff performance of advanced transport aircraft, an existing STOL takeoff performance routine developed during the A-6/CCW STOL Demonstrator program[10,16,17] was revised and updated. Since takeoff and landing conditions are not known a priori for blown aircraft (i.e., C_L and C_D are dependent on C_μ, which is dependent on attainable liftoff dynamic pressure, which is dependent on weight, blowing momentum, and available C_L and C_D, which are dependent on C_μ, etc.), an iterative routine is required. This is further complicated by additional requirements such as one-engine-out on takeoff, takeoff acceleration required, climbout gradients, etc. The existing numerical routine was verified for a Navy A-6 aircraft using existing Navy operational data sets and charts.[16,17]

Figures 7–11 show typical results of the effects of blowing on B737/CCW available lift, liftoff speeds, and ground rolls. In Fig. 7, the takeoff lift and drag coefficients do not vary with weight for the conventional B737 during ground roll (α = 1 deg), or at liftoff (α = 8 deg), nor for the B737/CCW during unblown ground roll. However, available C_μ, and thus the blown C_L and C_D, do vary with weight and available airflow momentum, which thus affects liftoff speed. Notice that at lighter weight, the available C_L from blowing is as much as three times that of the baseline B737, and 75% greater at the heavier weights. Figure 8 presents the corresponding reductions in liftoff speed due to CCW, ranging between 15–40% (depending on weight) of the speeds of the B737 with 30-deg flap deflection. Also shown is the approximate curve for the 10-deg flap setting. These significant reductions in liftoff speed were produced by using only engine fan bleed on an otherwise standard B737 to power a CCW high-lift system. Figures 9 and 10 depict the resulting reductions in takeoff ground roll distance and distance over a 50-ft obstacle,

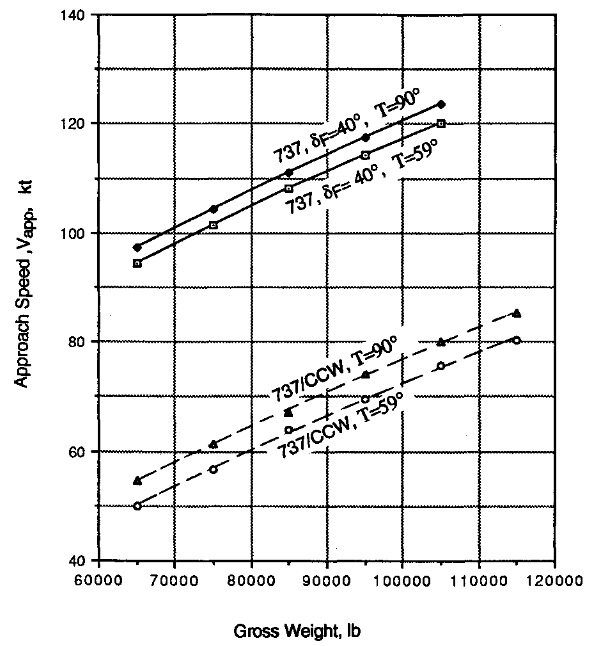

Fig. 13 Predicted reduction in equilibrium approach speeds down at 4-deg glide slope for B737 and B737/CCW aircraft at sea level (90-deg CCW flap, 60-deg Krueger flap).

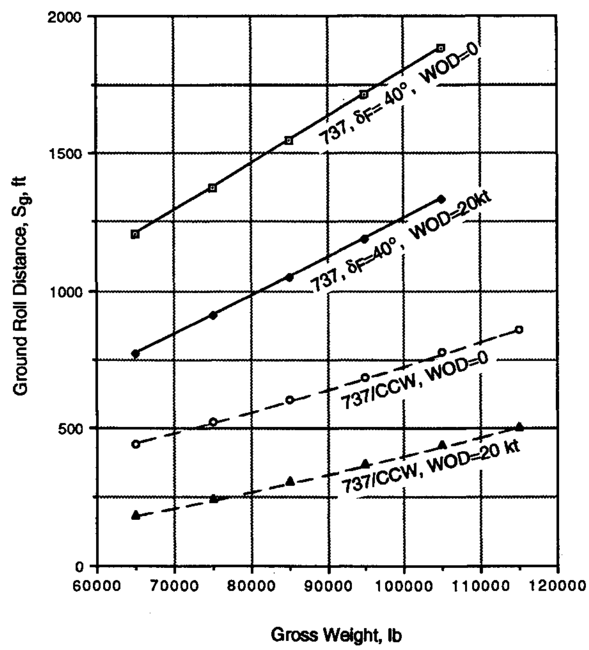

Fig. 14 Predicted landing ground roll for B737 and B737/CCW aircraft at sea level, T = 59°F.

and how those parameters are affected by temperature and head wind [labeled wind-over-deck (WOD)]. Relative to the conventional B737, the CCW version reduced ground roll distances from 37 to 80% (with light weight, 20-kt head wind, and T = 59°F being the best conditions), and reduced distance over the 50-ft obstacle by 27–74%. While a flap angle of less than 30 deg might be expected to increase the conventional aircraft's performance by reducing the drag, the same would be expected for a takeoff version of the B737/CCW with a flap deflection less than 90 deg.

Note the limitations placed on performance by the requirement that available blowing be reduced (to reduce drag and increase thrust) until the available horizontal acceleration at liftoff is at least 0.065 g. This results from a Navy operational limitation to account for the possibility of one-engine-out at liftoff, and is retained here as a conservative measure. It should eventually be replaced by the commercial aviation equivalent limitation. Figure 11 shows the climb angle and flight path after liftoff for a typical 105,000-lb B737 and B737/CCW, both with no head wind. Blowing was not reduced after the CCW aircraft's liftoff, and its flap deflection remained at 90 deg; thus that aircraft still experienced high-induced drag during climbout. The B737's flap remained at 30 deg. Nevertheless, the CCW climb angle at 50 ft is virtually the same as the B737, whereas the CCW aircraft traversed only 60% of the ground distance. This performance could be improved if the bleed rate were reduced as the aircraft was climbing, i.e., to maintain a constant rate of climb.

B737 and B737/CCW Landing Performance

To continue analysis of the effects of pneumatic high-lift systems on the terminal area performance of advanced transport aircraft, an existing STOL landing performance routine developed during the A-6/CCW STOL Demonstrator program[10,16] was also revised and updated. This existing landing program had also been verified for a Navy A-6 aircraft.[10,17] As was the case for takeoff, landing conditions for blown aircraft were also not known a priori. An iterative routine was again required. This landing analysis was further complicated by additional requirements imposed, such as no acceleration down the glide slope, maximum allowable rate of sink at touchdown, etc. Figures 12–16 show typical results of the effects of blowing, head wind, and temperature on available aerodynamic coefficients, approach speed, and landing ground roll. There is a significant impact on landing performance produced by using only enough engine bleed to maintain equilibrium flight along the glide slope. Even so, increases in available lift for the CCW range from 2.5 to 3.5 times the conventional aircraft in Fig. 12. The generation of high induced drag on approach is of great benefit, as it offsets thrust and allows equilibrium flight down steeper glide slopes onto smaller runways. Figure 13 shows that approach speed reductions of 36–47% are possible when blowing is applied to the 737/CCW. The positive effect of head winds on reducing landing ground roll is seen in Fig. 14, where the full weight range of 737/CCW aircraft experience less than 500-ft ground rolls on a standard day with a 20-kt head wind. Figure 15 depicts the resulting 54–76% reductions in landing ground roll due to CCW, even with no head wind. In these data, either spoilers or shutdown of CCW blowing were applied during the ground rolls to unload the wing and add weight to the gear for better braking. Note that an alternate advantage of blowing is that a much greater aircraft gross weight can be landed by the blown aircraft in the same ground roll distance as the conventional aircraft. For instance, on a 90-deg day (Fig. 15), a 145,000-lb B737/CCW aircraft can land in the same 1270-ft ground roll required for a 65,000-lb basic B737, resulting in a 123% gross weight overload capability produced by CCW.

A related concern, of course, is whether the existing landing gear can absorb the extra weight. Figure 16 shows the predicted vertical component of kinetic energy EK_V resulting from landing at the speeds shown in Fig. 13. If the maximum B737 gross weight of 101,000 lb is taken as an upper bound on weight for the conventional aircraft at 90°F, the landing limit on vertical kinetic energy that can be absorbed at this aircraft weight is approximately 0.32×10^6 ft-lb. This value is not experienced by the B737/CCW aircraft until the weight is approximately 150,000 lb at 90°F. Thus, these large overload capabilities appear entirely feasible when considering gear loads; wing structural loads or other constraints still need to be evaluated. These types of analyses will be essential to performance prediction for advanced transports fitted with CCW, even though commercial operational requirements may vary from those applied here. These takeoff and landing performance analysis routines show relative performance im-

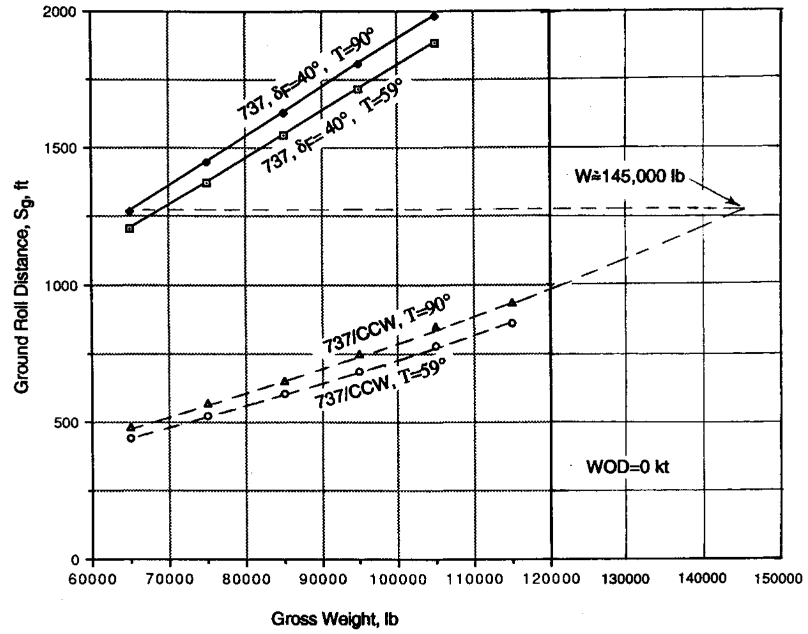

Fig. 15 Predicted landing ground roll for B737 and B737/CCW aircraft at sea level with no head wind.

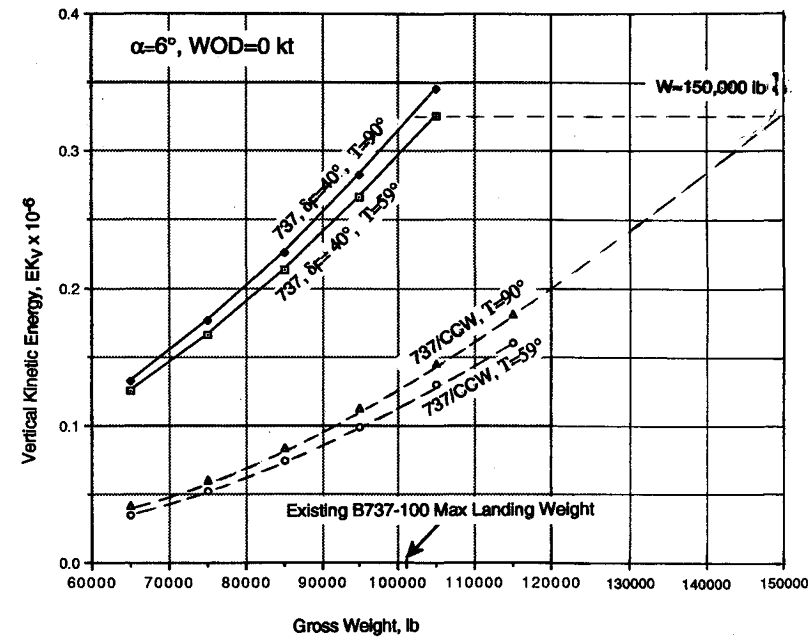

Fig. 16 Vertical kinetic energy resulting from B737 and B737/CCW landing at sea level with no head wind.

provements and should be used for further analysis once additional trimmed aerodynamic and propulsive data become available for the Boeing 737, or other representative current-day commercial subsonic transport aircraft, both with and without blowing.

Conclusions

The above three-dimensional analytical results confirm that the high-lift potential (two-dimensional C_l of 8 at $\alpha = 0$ deg) of advanced circulation control airfoils is a viable means for improving the takeoff and landing performance of representative subsonic transport aircraft. Control of overall wing characteristics (lift, drag, and moments) on these aircraft is available to the pilot through variations of blowing rates, angle of attack, leading-edge (LE) or trailing-edge (TE) flap deflections, and slot height. These results offer the potential for reduced complexity and lower terminal-area noise levels for subsonic transport aircraft equipped with CCW high-lift systems, and indicate similar payoffs for higher-speed transports. The results, together with those from Part I of this study, strongly suggest the potential of practical CCW transport configurations to provide the following capabilities:

1) CCW performance will greatly reduce takeoff and landing speeds, yielding reduced runway lengths, smaller noise footprints, and increased safety of flight in terminal areas.

2) Greatly increased liftoff gross weight and landing weight developed by smaller wing area will allow transport wings that are more optimized for cruise and greater cruise fuel efficiency.

3) Pneumatic CCW configurations will greatly reduce high-lift system complexity, as will the combination of high-lift, roll-control, and direct-lift-control surfaces into a single multipurpose pneumatic surface.

4) Steep climbout and approach flight paths due to STOL capability can yield reduced noise exposure to surrounding communities.

It is thus recommended that further development be pursued.

Acknowledgments

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