ARTICLE NO. 78-814R

# Moving-Ground Simulation by Tangential Blowing

J. E. Hackett* and R. A. Boles†
*Lockheed-Georgia Company, Marietta, Ga.*

**Belt-type moving-ground equipment, used for ground-effect simulation in STOL and VTOL tests, can be inconvenient and costly, especially in large tunnels. In most cases, such difficulties may be avoided by employing tangential blowing from a single slot at the ground surface. The paper reviews several powered model tests using both moving-ground and tangential blowing and describes the slot configuration and test techniques which were developed. Ground skin friction is monitored to set blowing levels and no model-dependent calculations are needed. It is also shown that application to center-tunnel testing can delay tunnel flow breakdown considerably.**

## Nomenclature

$b$ = base model wing span
BLC = boundary-layer control
$c$ = nominal wing chord
$C_L$ = lift coefficient, based on $S$
$C_m$ = pitching moment coefficient, based on $S$, about wing quarter chord
$C_p$ = static pressure coefficient, $(p-p_0)/q$
$C_\mu$ = momentum coefficient, based on $S$
$H$ = total pressure
$H_0$ = mainstream total pressure
$h$ = model height above ground plane
$p$ = local static pressure
$p_0$ = effective static pressure at model station
$S$ = wing area
$U_\infty$ = freestream velocity
$X$ = distance measured axially downstream from model wing quarter chord
$y$ = distance measured laterally from tunnel centerline
$\alpha_T$ = angle of attack at tailplane, relative to fuselage axis
$\Delta\alpha$ = $\alpha_T$ increment between blown- and moving-ground conditions
$\delta^*$ = boundary-layer displacement thickness
$\eta$ = spanwise station $2y/b$

## I. Introduction

WHEN testing high-lift and especially powered-lift models over a fixed ground, model-induced pressure gradients may induce premature ground-surface, boundary-layer separation. Moving-model, fixed-ground tests are usually impractical so endless-belt, moving-ground techniques are used quite widely in conventional wind-tunnel tests. Campbell et al.[1] review results using both techniques and show that tests in a wind tunnel with a moving ground produce results quite similar to those for a moving model. However, even a moving ground can be inconvenient and costly, particularly at large scale. The present paper explores an alternative approach, employing tangential blowing along a fixed ground surface from ahead of a wind-tunnel model.

Presented as Paper 78-814 at the AIAA 10th Aerodynamic Testing Conference, San Diego, Calif., April 19-21, 1978; submitted May 26, 1978, revision received June 19, 1979. 

Index categories: Aerodynamics; Testing, Flight and Ground.

*Scientist. Member AIAA.
†Aerodynamics Engineer, Senior.

The choice of tangential blowing at the ground surface, rather than suction BLC, arose entirely from physical considerations. Results from experiments on a wing with a knee-blown flap[2] will be used to illustrate the principles involved. Figure 1a shows the chordwise distribution of undersurface pressures on the wing at moving-ground speeds ranging from 0 to 100% of mainstream speed. With the ground fixed (0%), there is suction over the entire undersurface and consequent lift loss. With the belt moving at mainstream speed (100%), the suction region is almost eliminated.

Figures 1b and 1c show, respectively, the "correct" moving-ground flow structure and the corresponding fixed ground case. The crucial difference between the two flows concerns the forward stagnation point location near the ground. In Fig. 1b, the moving belt carries air, next to its surface, at mainstream speed through the adverse wing/jet-induced static pressure gradient. In consequence, the total pressure of the air adjacent to the belt can substantially exceed the mainstream value: the belt adds energy to the fluid. Compared with fixed-ground flow, there are two significant consequences: the stagnation point becomes free, since it cannot attach to the surface, and it moves aft, thereby shortening the ground separation bubble.

The reason for employing ground blowing, rather than suction, BLC is now obvious—only by blowing can total pressures greater than mainstream be attained in the ground layer. With suction, ground layer total pressure cannot exceed the mainstream value and premature separation is inevitable in high-lift, near-ground cases.

It is obviously desirable for any ground-blowing scheme to be simple and independent of model measurements. The scheme should rest upon fundamental principles, rather than empiricism, in order to avoid the need to "calibrate" the system for every class of test. The present approach is aimed strongly in this direction.

The work described in Sec. II concerns the early, proof-of-concept stages of ground blowing development in which both theoretical and experimental studies were carried out (see also Refs. 2 and 3). These studies showed that relatively simple, single-slot ground blowing can produce correct or nearly correct underwing flows (Fig. 1b) under high-lift, near-ground conditions. Methods were developed for determining ground-blowing $C_\mu$, but these were somewhat configuration-dependent and there was an obvious need for a feedback system involving only ground surface measurements.

Section III describes the development of "sensitive ground" techniques in which ground skin-friction measurements are used to determine ground-blowing $C\mu$ (see also Ref. 4). These techniques were then tested using a swept-wing, knee-blowing-flap model (see Sec. IV). Recognizing the danger of a too-thick ground layer engulfing the tailplane at angle of attack, careful flow measurements made in this

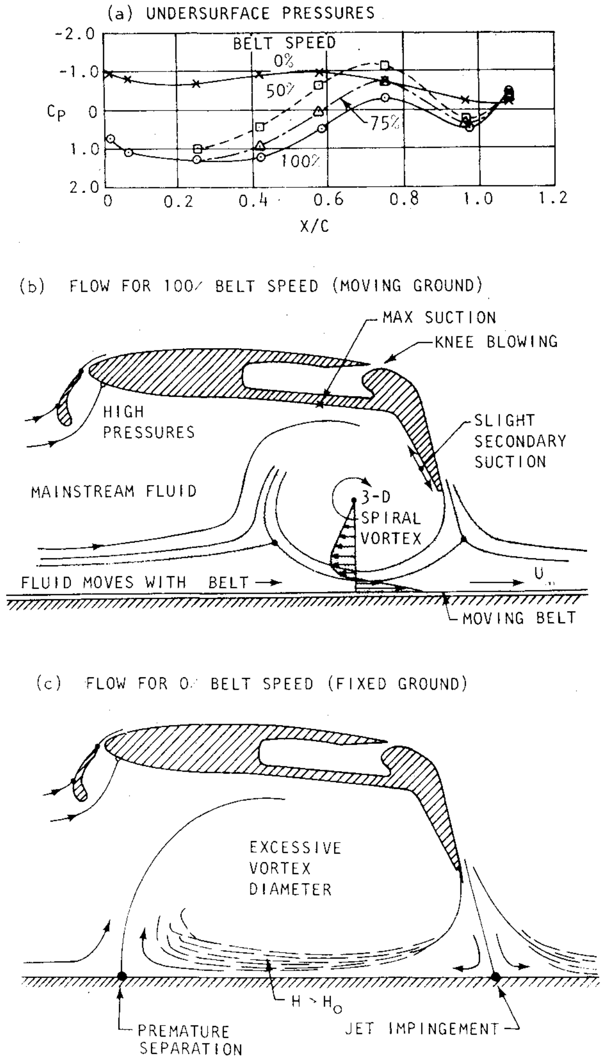


**Fig. 1 Effect of ground motion.**

region are also described. Being at an aft location, such measurements are a severe test of the ground blowing technique.

## II. Review of Straight Wing and Jet in Fuselage Tests

### A. Pressure Distributions (First Test Series)

Prior to the first test series, an extensive theoretical study was made involving fixed, moving- and blown-ground boundary-layer calculations (see Refs. 2 and 5). The calculations show that the shapes of moving- and blown-ground displacement surfaces are comparable. In both cases, the induced angle of attack at the model is quite small, but there is some negative flow cambering. For the blown ground, however, a substantial but constant $\delta^*$ component was also present. Nonetheless, the theoretical results were encouraging.

A high-lift wing model (Fig. 2) and a VTOL, jet-in-fuselage model (Fig. 3) were made. A moving ground (Fig. 4) was constructed for measuring datum results, and this could be replaced by a multislotted blown ground. A location 7.5 in. (i.e., approximately 2 chords) ahead of the model quarter chord was found to be optimum for the continuous slot, which was 30.0 in. wide and 0.067 in. high. Twenty, 1/4-in. diam nozzles set at 1.5 in. pitch comprised the multinozzle configuration, located 13.75 in. ahead of the model reference line (see also Fig. 7).

In the interest of understanding the underwing flows, heavy emphasis was placed on pressure measurements in the first

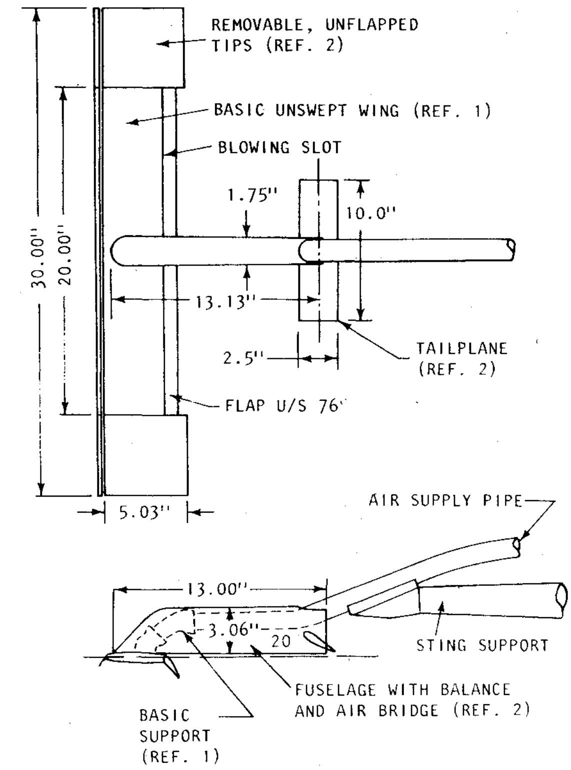


**Fig. 2 Straight-winged, knee-blown-flap model.**

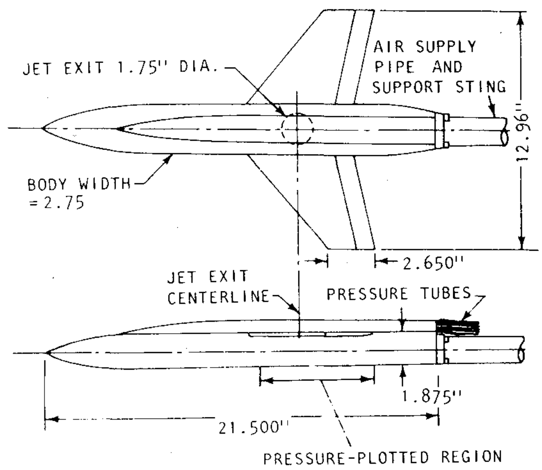


**Fig. 3 Jet-in-fuselage model.**

test series. The wing was pressure plotted at three stations and the jet model lower surface was also extensively instrumented. It was demonstrated[2,6] that the underwing separation bubble, present even with the ground moving (see Fig. 1), could be correctly simulated using ground blowing. Flow around the exit of the round VTOL jet was much less affected by the presence of the ground and was sensitive to the type of ground treatment only under extreme conditions.

On the basis of integrated pressure measurements and jet exit plane pressure distributions, ground blowing requirement charts were prepared in which ground $C_\mu$ was plotted as a function of $C_L\ c/h$ and of model height.[6] However, only zero angle-of-attack data were employed. These charts were used in the second tests series.

### B. Forces and Moments (Second Test Series)

Having established via pressure measurements the general feasibility of ground blowing, it was appropriate to extend the range of configurations and to measure forces and moments

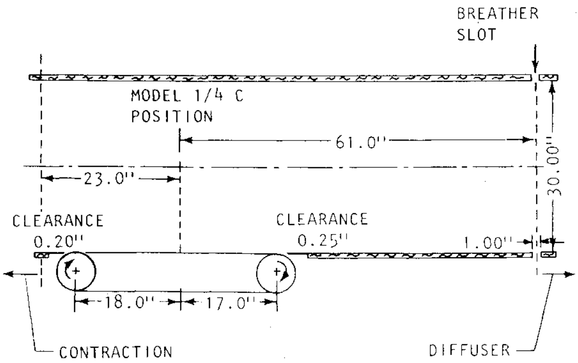


**Fig. 4 Moving ground installation in the 30 × 43 in. wind tunnel.**

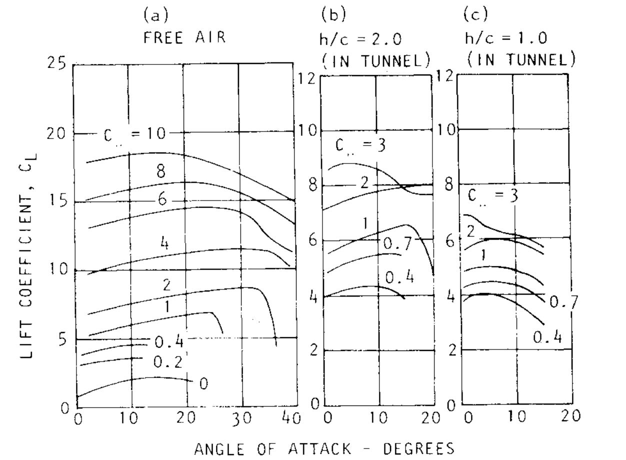


**Fig. 5 Lift performance for the straight-winged knee-blown-flap model.**

over an angle-of-attack range. Removable, unflapped tips, and a tailplane were built for the straight-wing model and a three-component balance and an airbridge were installed in a fuselage.

Figure 5 shows the lift curves taken from center-tunnel measurements (corrected to free-air conditions) and at one- and two-chords altitude above a moving ground. $C_L$ levels extend deeply into the floor separation, or flow breakdown range, indicating that a prime experimental objective—subjecting the ground boundary layer to the worst possible conditions—has been met.

In all but the high $C_\mu$, high $\alpha$ cases, application of ground blowing [as determined by the $C_L(c/h)$ parameter] reproduced the Fig. 5 data to within measurement accuracy. An after-the-fact review of ground skin-friction data showed that ground blowing had been inadequate under the most extreme conditions.

Because of its aft location, tail force and, hence, pitching moment is a good indicator of the correctness of ground simulation by blowing, particularly at high angle of attack. Figure 6 shows the variation of pitching moment about wing quarter chord (horizontal scales) with wing angle of attack (vertical scales). Open symbols represent (datum) moving-ground data, filled symbols are for the blown-ground cases and tagged symbols represent the fixed-ground cases. Letters F and T represent the onset of floor separation and tail stall, respectively, as angle of attack is increased. The model $C_{L_{max}}$ condition and passage of the tailplane through the wing wake are also indicated. The trailing edge of the tail touches the ground at 15½ deg angle of attack, indicated by the hatched regions on the plots.

With the tail off (upper plots, Fig. 6) fixed- and blown-ground trends were similar but, on a point-by-point basis, the blown-ground agreement was better below $C_{L_{max}}$. With increased $C_\mu$, fixed ground data failed to reproduce even the moving-ground trends and there was substantial data scatter due to unsteadiness. Blown-ground results reproduced trends well up to $C_\mu = 3$, but indicated some pitch up at the high blowing rates. Later results (see Sec. IV.B.) suggest that this is attributable to the inadequate ground-blowing $C_\mu$ mentioned previously. On adding the tailplane (lower plots, Fig. 6), similar tendencies are observed and it is remarkable that the blown ground continued to perform well, even when the tailplane almost touched the ground.

Drag results for both the preceding straight wing and for the swept wing (see Sec. IV) must be regarded as inconclusive.

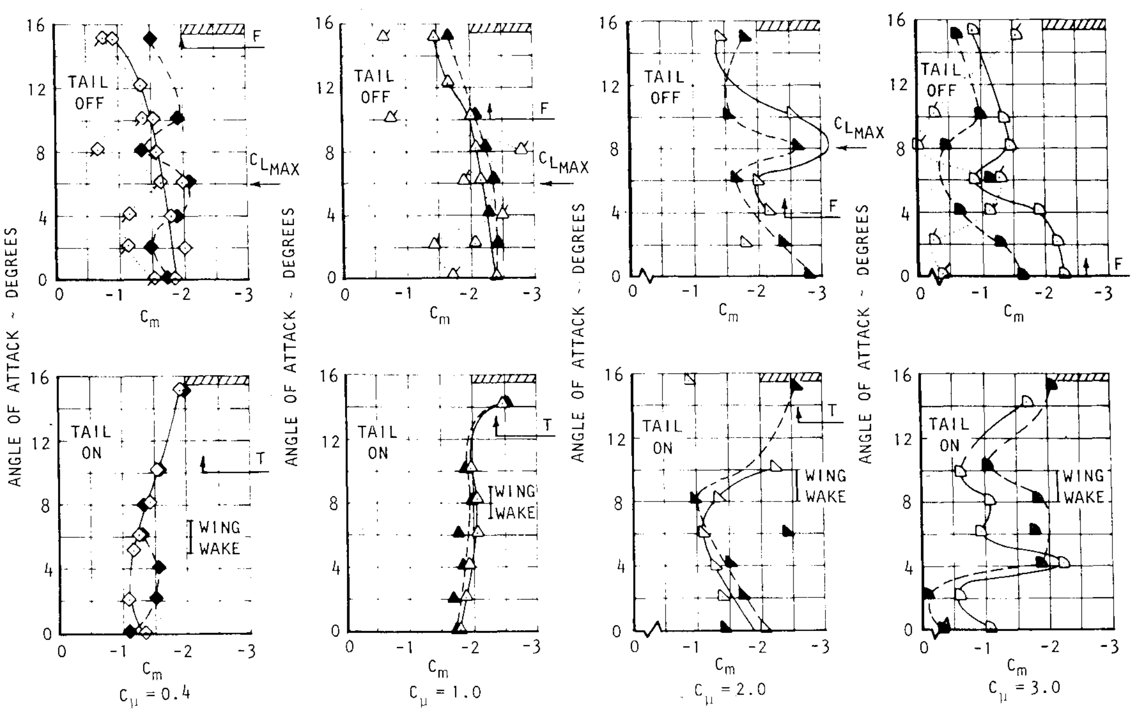


**Fig. 6 Pitching moments for the straight-winged knee-blown-flap model at $h/c = 1.0$.**

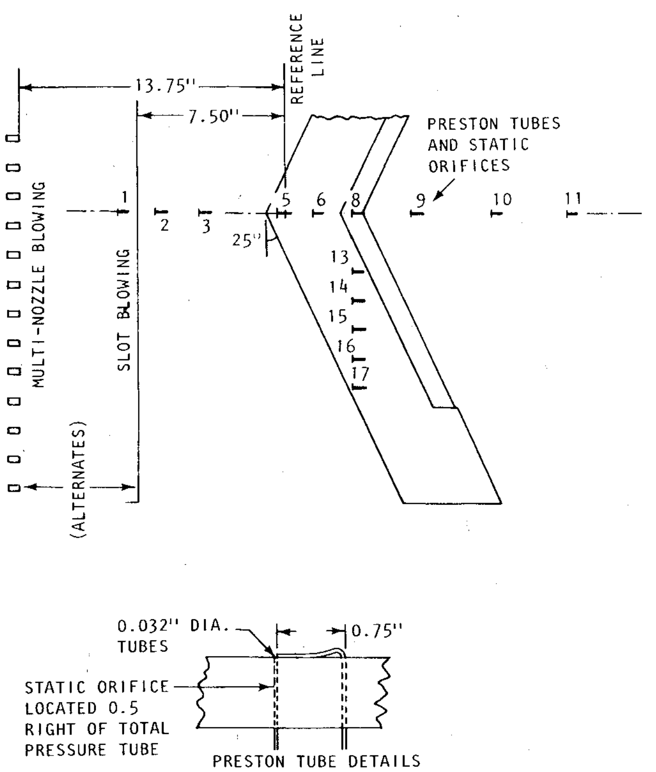


**Fig. 7 Test layout for ground blowing, showing swept wing with tips fitted.**

There was some tendency for drag to be higher in blown-ground cases[3] when parts of the models dipped into the ground layer. However, wind-axis, rather than body-axis balance data are needed to define the trends properly.

Operational shortcomings of $C_L(c/h)$-based prediction methods became apparent during the phase two tests and an attempt was made to use ground skin-friction feedback. However, the existing scanivalve/pressure transducer instrumentation was both insufficiently sensitive and generally unsuitable for multichannel, on-line feedback. Thus, there was a major incentive for the third test series to improve the ground monitoring methods in order that the $C_L(c/h)$ approach could be replaced by on-line feedback from the ground skin-friction indicators.

## III. Development of "Sensitive Ground" Techniques (Third Test Series)

An "ideal" blown-ground system might include multiple slots with spanwise divisions, each with its own sensor and a feedback system which sets the wall-layer velocity maximum to equal mainstream speed. However, both theoretical studies[5] and later underwing pressure measurements[6,2] showed that simpler schemes may be adequate. Since the entire ground layer moves streamwise with a moving belt and is unseparated, one requirement for the blown ground is that the blown layer shall be unseparated. Whether this necessary condition is also sufficient must be determined experimentally.

To place feedback for the no-separation condition on a quantitative basis, the floor was instrumented using Preston-type skin-friction gages as shown in Fig. 7. Each was connected across a heavily-damped center-zero dial-type pressure gage that could be observed continuously. Further details of the instrumentation are given in the conference version of this paper.

It was found that the analog display provided an excellent physical "feel" for ground-flow conditions. The damping in the system was especially useful, since the flow in the jet impingement region was very unsteady and wool tufts on the floor, for example, were of very limited use. In a typical test with no ground blowing, gages 1-6 ahead of the flap position (see Fig. 7), read positively indicating attached flow. Gage 8, just ahead of impingement, reads negatively indicating the anticipated reversed flow bubble. Gages 13-17 showed a strong reversed flow trend, probably due to forward moving jet fluid ahead of impingement.

As ground boundary-layer control was applied, gages for upstream positions tended to swing positively and gage 17 was the last to center. This sequence varied with model attitude and blowing rate. In all cases, however, the "correct" blowing rate was provisionally defined as the minimum to insure zero or positive skin-friction reading at all gage positions. Most readings through 13 were typically strongly positive under this "most critical gage zero" strategy and gages 14-17 read almost zero. Quantitative details are given in Ref. 4.

Recognizing that the transverse gage row (Fig. 7) was less than ideal for the swept wing, blowing was increased 20% beyond the "most critical gage zero" value in case separation had occurred aft of gage 17. A reduced blowing strategy was also tried, relying only on the centerline gages. However, the original procedure gave the best overall results and was adopted as the standard method for ongoing tests.

Figure 8 shows the ground-blowing settings, determined via the "most crticial gage" procedure, as a function of the test parameters for the model with no tips fitted. There was little change on adding tips. At one-chord model altitude, the required blowing level increased monotonically with $\alpha$ and $C_\mu$, and the most critical gage shifted outboard with increases in both variables. At two chords altitude, the jet impingement point moved aft into a region where the instrumentation was more sparse. At $C_\mu = 2$, the impingement point was evidently just aft of gage 10 up to 4 deg angle of attack, but the separation bubble was then "lost" by the system because of the large spread between gages 9 and 10. As a result, inadequate blowing rates were set at the larger angles of attack at this $C_\mu$. This was reflected by measurements at the model (see below).

Present experience suggests that closer gage spacings should be used aft of the model location, to accommodate tests with the model at higher altitudes. It also appears preferable to use a second chordwise row, situated just outboard of the middle of the powered semispan, rather than the spanwise row shown in Fig. 7. Though further tests with more comprehensive floor instrumentation appear desirable, the force, moment, and tailflow results reviewed later suggest that blowing levels set using the existing instrumentation reproduce moving-ground conditions fairly closely.

## IV. Swept-Wing Test (Third Test Series)

### A. Force and Moment Tests

The swept-wing model, which is shown in plan view in Fig. 7, was derived from the straight-wing, knee-blown flap model by adding 25 deg of sweep while maintaining the streamwise airfoil shape. However, the flap upper surface angle was reduced to 60 deg to make the model more representative of practical configurations. In the swept-wing tests, the tailplane was replaced (for particular runs) by a pitch-yaw rake aligned with the fuselage axis. This permitted local flow effects at the tail and in the vicinity of the wing tip to be discriminated and also avoided some tail stall difficulties experienced previously.

The swept-wing model was tested at $C_\mu$ values of 0.2, 0.4, 1.0, 2.0, and 4.0 over angle-of-attack ranges of 0-12 deg and 0-16 deg at one- and two-chords altitude, respectively. The ground boundary-layer control monitoring and setting procedures were the same as described earlier. Reference 4 contains comprehensive lift, drag, and pitching moment data for both the continuous slot and the multiple-nozzle ground configurations (see Fig. 7). These data are voluminous and only illustrative samples will be quoted here. Conclusions are based on the whole data set.

The lifting performance of the swept wing was generally similar to that shown in Fig. 5. However, sweep and reduced flap angle reduced the lift levels somewhat and $C_L \sim C_\mu$ curves at constant $\alpha$ peaked earlier. At one- and two-chords altitude, the lift curves for the swept wing were approximately one $C_L$ unit lower than the Fig. 5 values.

Figure 9 shows measured lift results as a function of $C_\mu$, $\alpha$, and ground treatment. At $C_\mu = 1$ and 2, the fixed ground data reflect a serious lift loss in relation to the "correct" moving-ground values. This loss is restored with ground blowing applied with some overshoot. In the case of the continuous slot, which is closer to the model and requires less momentum input, this overshoot is not serious. However, the multiple-nozzle ground BLC configuration, which required almost-doubled momentum input, gave excessive lift overshoot at high angles of attack. This suggests that the wing and/or the flap tip dipped into the thicker, multiple-nozzle, ground surface layer.

The "overshoot" described previously is apparently caused by overblowing. This was largely avoided by using the continuous blowing slot located closer to the model. Analysis of detailed skin-friction readings[3] shows some overblowing still occurred at the model centerline. Locally reduced blowing, in this region, might further improve the agreement between blown- and moving-ground results.

Examination of pitching moments (Fig. 10) seems to confirm that parts of the model dipped into the thicker, multiple-nozzle ground layer. With tips fitted (Fig. 10, upper curves), there is increasing nose-down pitch at the higher angles of attack, which indicates that the Fig. 9 lift increase is aft-located. The fact that removing the wing tips (Fig. 10, lower curves) removes much of the previous pitch-down provides further confirmation of direct interference between the ground layer and the wing tip.

As indicated in Fig. 5, the span over which ground blowing was applied equalled the with-tips wing span. Blowing rate was uniform across the span. Since the tip was unflapped and was much more lightly loaded than the remainder of the wing, it seems likely that a reduced blowing rate would have been appropriate ahead of the tip. This suggests that the spanwise extent of blowing should be reduced and blowing requirements should be fed back to individually controlled spanwise segments.

### B. Flow at the Tailplane Location

The pitch/yaw rake was fitted at a tail location situated in the wing quarter-chord plane with the model at zero angle of attack. This position is uncharacteristic of STOL configurations, which usually have high tails, but was chosen deliberately as a "worst case." The back of the rake almost touched the ground at high angles of attack. With the model at one-chord altitude, $C_\mu$ of 0.4 and 10 deg angle of attack, flow vector plots showed that the rake intersected an inboard vortex about 0.8 in. from the fuselage side.[3] With increasing model altitude or $C_\mu$, the vortex center moved down below the measurement region. Another major observation was that at one-chord altitude, the presence of the floor largely suppressed any increase in jet-induced downwash as $C_\mu$ was increased.

Figure 11 shows pitch-angle distributions at various angles of attack for blown- and moving-ground configurations with model $C_\mu = 4.0$. The angles shown are direct rake readings and thus indicate the angle of attack which would be experienced by a fixed tailplane. The left part of Fig. 11, which is for one-chord altitude, shows significant differences between blown and moving grounds. These arose because ground blowing was inadequate (see Fig. 8). Nonetheless, the distributional details are well reproduced. At $h/c = 2$, ground

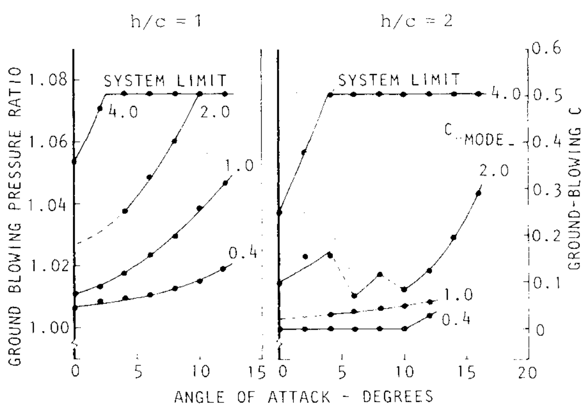


**Fig. 8 Settings for ground blowing using continuous slot.**

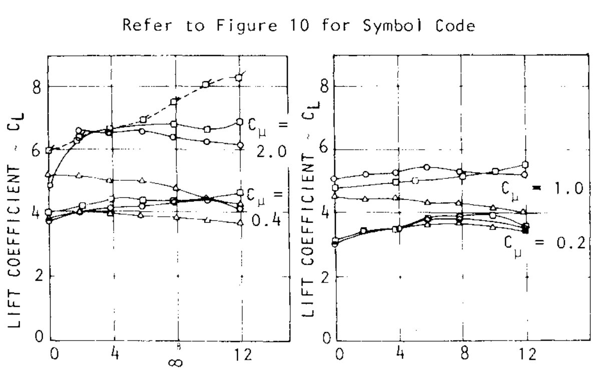


**Fig. 9 Lift data for swept wing with tips fitted, $h/c = 1.0$.**

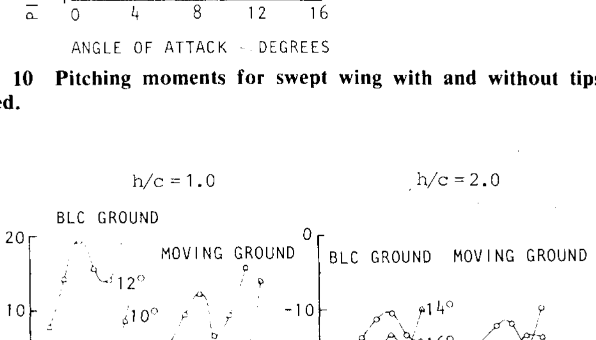


**Fig. 10 Pitching moments for swept wing with and without tips fitted.**

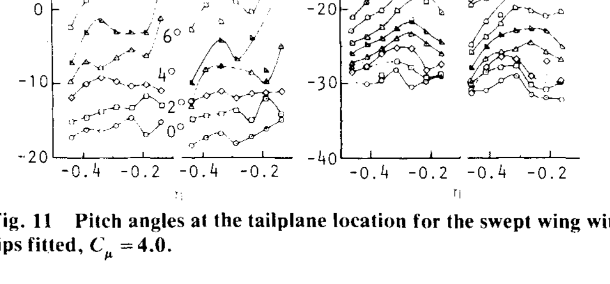


**Fig. 11 Pitch angles at the tailplane location for the swept wing with tips fitted, $C_\mu = 4.0$.**

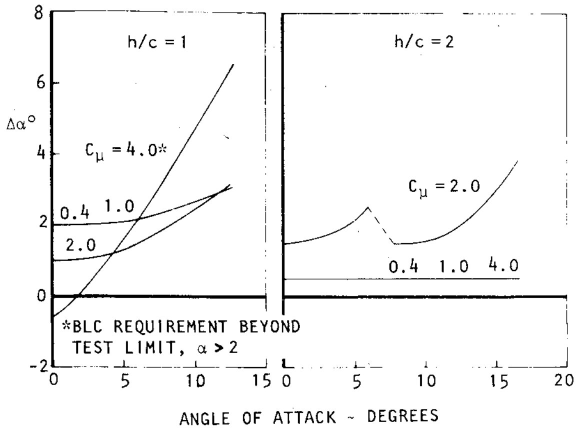


**Fig. 12 Tailplane upwash increment due to ground blowing.**

blowing was adequate and it may be seen from Fig. 11 that ground blowing reproduces the moving-ground conditions very well.

Plots similar to Fig. 11 were prepared for other $C_\mu$'s and mean flow angle differences, between blown- and moving-ground cases, were determined graphically. Figure 12 shows that, at one-chord altitude, flow downwash at the tail position is generally 2-3 deg less for the blown-ground configuration. The only exception is the $C_\mu = 4$ case mentioned previously. At $h/c = 2$, there is a similar exception, but for $C_\mu = 2$ where ground blowing was again known to be inadequate (Fig. 8). Otherwise, ground blowing reproduced the moving-ground results very well at this altitude.

The possibility of flow distortion at the tailplane is perhaps the most serious potential hazard in connection with the ground-blowing technique. However, the preceding flow measurements show that with ground-blowing settings determined by the ground skin-friction feedback technique, this is not a serious problem, even for a low-mounted tailplane. This confirms the conclusions of Ref. 3 (see also Fig. 6), which are based on tail-on/tail-off pitching moment comparisons.

## V. Conclusions

A scheme is described for applying tangential blowing at the ground surface to replace belt-type moving-ground equipment used in STOL and other high-lift testing. Early tests (Sec. II and Ref. 2) demonstrated the general feasibility of the scheme and indicated that the desired results might be achieved using a single, continuous blowing slot situated just ahead of the model.

Emphasis in the present paper centers on the control of blowing level using feedback from skin-friction gages distributed over the ground surface (see Fig. 7). Physical considerations suggest that ground blowing should be increased until no skin-friction indications are negative, i.e., the entire ground layer moves in the mainstream direction as does the corresponding layer next to a moving belt.

To determine the practicality of skin-friction feedback, a slotted ground was suitably instrumented and tests were made on a swept wing with a 60 deg flap, at altitudes of one and two chords. Three-component balance measurements and low-mounted tail-rake flow measurements were made. Datum tests were carried out in all cases using a moving ground. Major aims were to check the validity of the "no-negative skin-friction" hypothesis and to investigate potentially adverse effects when the wing tip or the tailplane entered the ground layer at angle of attack. The following conclusions were reached:

1) Ground BLC is essential for center-tunnel and for ground-effects testing if $C_L$ $(c/h)$ exceeds two. Under most circumstances, ground blowing, applied as described herein, eliminates the majority of the difference between fixed- and moving-ground results.

2) Lift, pitching moment, and tailplane flow measurements in ground effect generally confirmed that the "no-negative skin-friction" hypothesis is correct. Inferior results were obtained using alternative blowing strategies and when either blowing capability or skin-friction feedback were inadequate. These observations suggest that spanwise segmentation of blowing, with individual feedback, would reduce an observed tendency to overblow the ground layer at the model centerline (see also conclusion 4).

3) With the "no-negative skin-friction" scheme in operation, force and moment results at $h/c = 2$ indicated that ground blowing removes almost all of the differences between fixed- and moving-ground results. This was also true at $h/c = 1$ up to $C_L = 6$.

4) Above $C_L = 6$ at $h/c = 1$, lift- and pitching-moment measurements suggested that extra tip lift occurred which increased with angle of attack. The magnitude of the effect increased with tips added, indicating that the span of the blowing slot, which equalled the with-tips span, was excessive. It appears that individual control of a number of spanwise segments would be an advantage in this region as well as at the model centerline (conclusion 2). This would improve the agreement with moving-ground data at high-$C_L$ levels.

5) The continuous slot, used routinely, was replaced by a multiple-nozzle array for some tests. This produced a thicker layer which increased the swept-wing pitch/lift problem. In the form used, the multiple-nozzle arrangement is only suitable for tests at $h/c = 2$ and above.

6) Drag in blown-ground cases was generally higher than for the moving ground and trends were frequently inconsistent with those in lift and pitching moment. The use of a body-axis balance lead to considerable data scatter and drag results must be regarded as inconclusive.

7) The present results suggest that, with the combined use of spanwise-segmented blowing and more extensive skin-friction sensors, the present ground-blowing technique will produce results which remove a substantial proportion of the differences between fixed- and moving-ground results under the conditions described previously.

## Acknowledgment

The work described in this paper was supported by NASA-Ames under contracts NAS2-6690, NAS2-8745, and NAS2-9155. The help and encouragement of K. Mort and B. Page, who monitored these contracts, is gratefully acknowledged. The authors also wish to acknowledge helpful discussions with J. P. Campbell, formerly of NASA-Langley, who reviewed this paper.

## References

[1] Campbell, J.P., Hassel Jr., J.L., and Thomas, J.L., "Ground Effects on Lift for Turbofan Powered-Lift STOL Aircraft," *Journal of Aircraft*, Vol. 15, Feb. 1978, p. 78.

[2] Hackett, J.E. and Boles, R.A., "Wake Blockage Correlations and Ground Effect Testing in Closed Wing Tunnels," *Journal of Aircraft*, Vol. 13, Aug. 1976, pp. 597-604.

[3] Hackett, J.E., Boles, R.A., and Lilley, D.E., "Ground Simulation and Tunnel Blockage for a Jet-Flapped, Basic STOL Model Tested to Very High Lift Coefficients," NASA CR 137,857, March 1976.

[4] Hackett, J.E. and Boles, R.A., "Ground Simulation and Tunnel Blockage for a Swept, Jet-Flapped Wing Tested to Very High Lift Coefficients," NASA CR 152,032, June 1977.

[5] Hackett, J.E. and Praytor, E.B., "Ground Effect for V/STOL Aircraft Configurations and Its Simulation in the Wind Tunnel: Part I—Introduction and Theoretical Studies," NASA CR 114,495, Nov. 1972.

[6] Hackett, J.E., Boles, R.A., and Praytor, E.B., "Ground Effect for V/STOL Aircraft Configurations and Its Simulation in the Wind Tunnel: Part II—Experimental Studies," NASA CR 114,496, Nov. 1972.