Ground Effects on Lift for Turbofan Powered-Lift STOL Aircraft

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Early studies of turbofan powered-lift STOL concepts indicated that a basic problem of aircraft which incorporate such concepts would be a serious adverse ground effect on lift. Experience to date with actual powered-lift STOL aircraft, however, has not borne out this concern. This apparent disagreement is examined and recent research data are used to help explain some of the differences observed. Analysis indicates that most of the disagreement can be attributed to the use of wind tunnel data that were not directly applicable to the airplane because the model did not properly represent some of the design features and operating conditions of the airplane.

Nomenclature

Æ	= wing aspect ratio
C_L	= lift coefficient
C_{L_∞}	= lift coefficient out of ground effect
C_μ	= thrust coefficient
h/c	= wing height above ground in mean chords
V_B/V_∞	= ratio of ground belt linear speed to tunnel test velocity
α	= angle of attack, deg
δ_f	= flap deflection, deg
i_t	= horizontal tail incidence, deg
$\Lambda_{c/4}$	= sweepback of wing quarter chord, deg

Introduction

EARLY wind tunnel research on the jet flap in the 1950's gave promise of operational aircraft which would take advantage of the very high lift attainable with this new powered-lift system. It was very disturbing, of course, when early tests showed that ground effects on lift at these high lift conditions were highly adverse. Concern for this problem led designers to rule out low-wing arrangements for powered-lift STOL aircraft because their ground effects would be worse than for high-wing configurations. And at that time, there was serious doubt that even the high-wing configurations would have acceptable ground effects. Simulator studies based on wind tunnel research seemed to bear out this concern.

Despite all of these indications of potential ground effects problems, the three powered-lift STOL aircraft flown to date – the augmentor wing C-8A, the YC-15, and the YC-14 – have all exhibited favorable rather than adverse ground effects in flight. It is the purpose of this paper to explore the reasons for this apparent discrepancy in results. We shall examine more closely some of the early wind tunnel data to ascertain whether the results presented really justified the pessimism regarding ground effects at that time. In addition, results of recent wind tunnel research will be presented, some of which was carried out to obtain a more direct indication of the influence of such key parameters as wing sweep and flap span on powered-lift ground effects.

Only ground effects on lift are to be considered in this paper, since the primary purpose here is to explore the apparent discrepancies between the lift-in-ground-effect measurements made in the wind tunnel and those made in flight. It was considered beyond the scope of this study to treat the substantial ground effects on drag and pitching moment which have been well documented in previous investigations. A number of such investigations are covered in the references to this paper.

The presentation of data is arranged on the basis of the specific type of powered-lift concept involved: internally blown jet flap, augmentor wing, externally blown flap (EBF), and upper surface blown flap (USB).

Some of the pertinent dimensional characteristics of the C-8A augmentor wing, YC-14 USB, and YC-15 EBF airplanes are presented in Table 1 to assist in determining how well some of the wind tunnel research models represent the airplanes. All three of the airplanes have unswept wings mounted in the high-wing position on the fuselage. These high-wing arrangements, which are of course desirable for minimizing adverse ground effects, give values of h/c (height of wing above ground in mean chords) of 1.0, 1.38, and 1.22, respectively, with the wheels on the ground. Corresponding values of h/c for low-wing airplanes would probably range from about 0.6 to 0.8. The terms h/c and h/b have both been used extensively in the ground-effect literature for nondimensionalizing ground height. For consistency, only h/c will be used in this paper.

It is recognized that some differences in the ground effects measured with wind tunnel models and in flight could be attributed to time-dependent effects and to dynamic effects in the flare which are not taken into account in wind tunnel testing. This paper will not include consideration of such effects, and will be concerned only with steady-state flight conditions.

Internally Blown Jet Flap

Early Two-Dimensional Research

The first information on powered-lift ground effects was obtained by Dimmock on a two-dimensional jet flap model having a 30 deg jet flap.[1] A sample of his data is presented in Fig. 1 (left side). Dimmock's comment on these results was

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Table 1 Aircraft dimensional characteristics

	Augmentor wing C-8A	YC-14	YC-15[a]
Powered-lift system	Augmented jet flap	Upper surface blown flap (USB)	Externally blown flap (EBF)
Flap deflection (δ_f)			
Landing, deg	65	70	45
Takeoff, deg	40	0	23
Powered-lift flap-span/wingspan	0.71	0.40	0.75
Wing sweep ($\Lambda_{c/4}$), deg	0	5	6
Wing aspect ratio (Æ)	7.2	9.4	7.0
Wing taper ratio (tip-chord/root-chord)	0.70	0.35	0.32
h/c with wheels on ground	1.0	1.38	1.22

[a] Original wing.

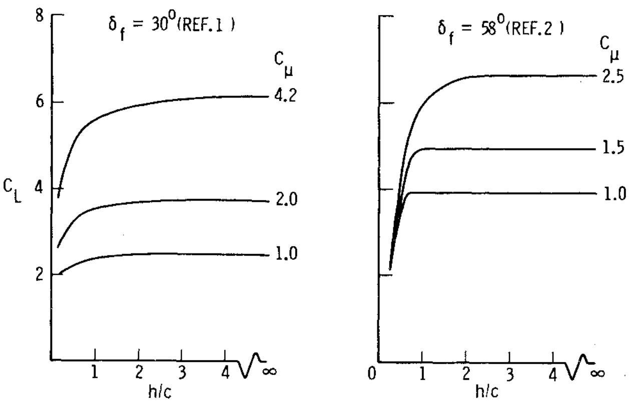

Fig. 1 Early two-dimensional jet flap data, $\alpha = 0$ deg.

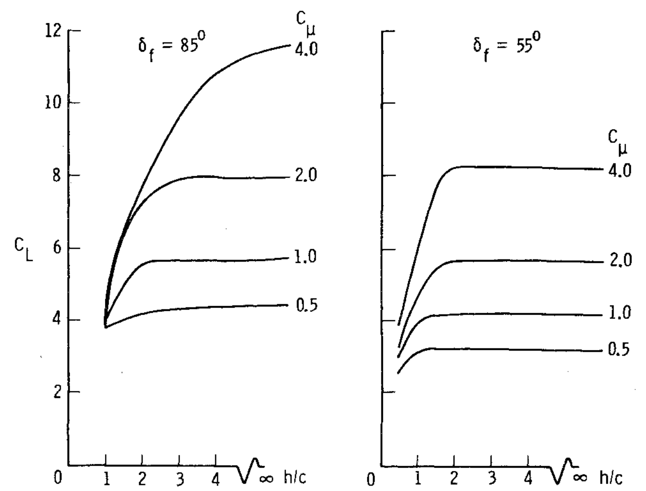

Fig. 2 Early three-dimensional jet flap data: Æ = 8.3, $\Lambda_{c/4} = 0$ deg, $\alpha = 0$ deg (Ref. 3).

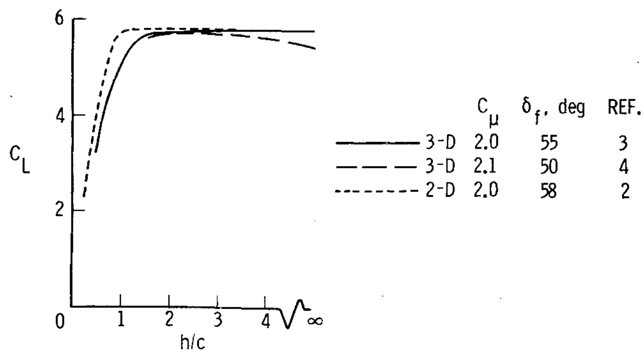

Fig. 3 Comparison of two- and three-dimensional jet flap data, $\alpha = 0$ deg.

that for C_μ values up to 2.0 and h/c values down to 0.3 "the effect is far from intolerable." Apparently he had been expecting very large lift losses and was pleasantly surprised to find only a 22% loss for the conditions he cited. Actually, he exaggerated the loss by referring to an h/c value of 0.3, which is unrealistically low even for a low-wing airplane. With a more reasonable value of h/c, the lift loss would be only 5 or 10% for the $C_\mu = 2.0$ case.

A much more comprehensive study of ground effects on a two-dimensional 58 deg jet flap model, including some excellent flow visualization work, was carried out later by Huggett.[2] Some of his results are presented on the right side of Fig. 1. Huggett's research indicated that the rapid dropoff in lift as the wing neared the ground started at about the same wing height at which the jet sheet struck the ground and produced a stagnation point, with flow going both forward and rearward along the ground from the point of impact. He used his data to show that an airplane having a thrust/weight ratio of 0.50 could have a lift coefficient of about 10 out of ground effect, but this would drop to about 4 at an h/c of 0.5. Perhaps he was setting his sights a bit too high with the C_L of 10 and was assuming an unrealistically low value of h/c. The data of Fig. 1 show that lift coefficients of 4 or 5 could be obtained, without any ground effect, down to h/c values of 1.0.

Early Three-Dimensional Research

The earliest three-dimensional ground effect data on a powered-lift configuration were obtained by Vogler and Turner[3] on an unswept jet flap model having jet deflections of 55 deg and 85 deg. The data, some of which are presented in Fig. 2, were generally quite similar to Huggett's two-dimensional data for comparable flap deflections. And, like Huggett, the authors of Ref. 3 emphasized the very large lift losses obtained at high values of C_μ and low values of h/c. The comparison plot in Fig. 3 shows the same trends for the two- and three-dimensional data, but somewhat more adverse ground effect for the three-dimensional case. Some three-dimensional data obtained by Butler, Guyett, and Moy[4] are also shown in Fig. 3, but the dropoff in lift does not appear because the model was not tested at values of h/c below 1.5.

The effects of angle of attack on ground effect were first shown in Ref. 4. Samples of data for jet deflections of 50 deg and 20 deg, presented in Fig. 4, show substantial effects of angle of attack. At 0 deg angle of attack, the ground effect was slightly favorable, but as angle of attack was increased, this favorable effect disappeared. Wing stall occurred at a much lower angle of attack in ground effect, particularly for the higher values of C_μ and lower value of h/c. The ground effects were generally more severe with the higher jet flap deflection. Although these data do show pronounced adverse ground effects at high values of C_μ and angle of attack, it should be noted that the ground effects at 0 deg angle of attack do remain favorable even at very high values of C_μ and

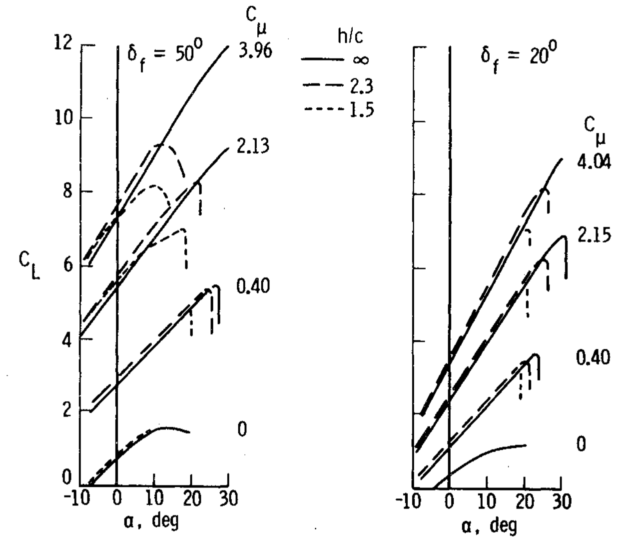

Fig. 4 Effect of angle of attack on three-dimensional jet flap data: $A\!\!\!R = 9.0$, $\Lambda_{c/4} = 0$ deg (Ref. 4).

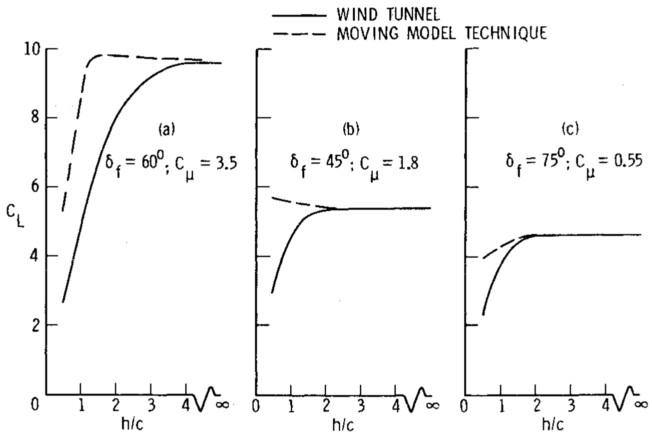

Fig. 5 Comparison of test techniques: jet flap, $A\!\!\!R = 6.0$, $\Lambda_{c/4} = 0$ deg, $\alpha = 0$ deg (Ref. 7).

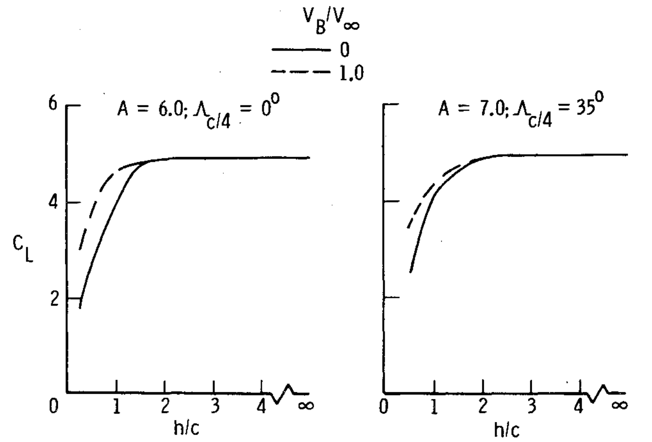

Fig. 6 Effect of moving belt ground plane: jet flap, $\delta_f = 60$ deg, $\alpha = 0$ deg (Ref. 9).

C_L. Moreover, the 50 deg jet deflection data show that the ground effect for the lower value of C_μ remains favorable up to an angle of attack of almost 20 deg where the lift coefficient is about 4.8.

Two summary papers on jet flaps[5,6] looked at these early two- and three-dimensional jet flap ground effects and tried to put them in the proper perspective. The effects of angle of attack, flap deflection, and value of C_μ were all recognized as important, and it was indicated that the takeoff condition should not be of too much concern since a low flap deflection would be used. The landing condition, however, was expected to require serious attention to the adverse ground effects obtained under very high lift conditions.

Moving Model and Moving Ground-Plane Techniques

One concern that arose during the early jet flap ground effect studies was that the conventional wind tunnel ground-board technique was not correctly simulating airplane flight conditions because the boundary layer on the ground board was modifying the flowfield about the model.[7] It was felt that the adverse ground effects would generally be alleviated if the ground-board boundary layer could be eliminated. Two new testing techniques were therefore developed to study this problem: the moving model technique and the moving ground-plane technique.

In the moving model technique,[7] the test model was mounted on the tow carriage of a hydrodynamic testing facility and moved over a stationary ground plane installed over the water. For comparison, the same model was tested in a wind tunnel with a conventional fixed ground plane. Results of the two sets of tests, presented in Fig. 5 for flap deflections of 45 deg, 60 deg, and 75 deg, show a pronounced difference between the results with the two techniques. The ground effects measured with the moving model technique are much smaller, and there is even a favorable ground effect for the $\delta_f = 45$ deg case. Obviously, the boundary layer over the wind tunnel ground board was contributing greatly to the adverse ground effects being measured.

The favorable results with the moving model technique led to the development of the moving-belt ground plane, which eliminated the ground-board boundary-layer problem while still making use of conventional wind tunnel testing.[8-14] In this technique, the fixed ground plane is replaced by a wide endless belt which moves at the same velocity as the airstream to prevent the boundary-layer development under the test model. Results obtained with this technique were quite similar to those obtained with the moving model.[8] Typical data from Ref. 9 are presented in Fig. 6 for the moving ground plane ($V_B/V_\infty = 1$) and fixed ground plane ($V_B/V_\infty = 0$). Data are shown for an unswept wing and a 35 deg swept wing for a flap deflection of 60 deg. The unswept wing data of Fig. 6 show less effect of test technique than the unswept wing $\delta_f = 60$ deg data of Fig. 5, apparently because it is for a much lower lift coefficient out of ground effect. The data of Fig. 6 also indicate a smaller beneficial effect of the moving-belt ground plane for the swept wing than for the unswept wing.

In Ref. 9 Turner analyzed the available moving ground-plane data to determine under what conditions it is necessary to use a moving ground plane to avoid inaccuracies in ground effect data. He concluded that for test conditions in which the lift coefficient is less than 20 times the wing height above the ground (measured in spans), a conventional ground plane can be used. Converting this relationship to ground height in chords gives the following requirement: C_L must be less than (20/aspect ratio) (h/c) to use a conventional fixed ground plane. For an airplane with an aspect ratio of 7 and an h/c of 1.2 with the wheels on the ground, testing could therefore be done at lift coefficients up to 3.4 without requiring a moving ground plane.

Augmentor Wing

Prior to the flight tests of the C-8A augmentor wing research airplane, force tests of large scale augmentor wing models were conducted in the NASA Ames Research Center 40- × 80-ft tunnel. One of the models had an unswept wing (similar to the C-8A airplane) while the other had a 27 deg swept wing. Data obtained with these models, taken from Refs. 15 and 16 and unpublished data, are presented in Fig. 7. Data for both the swept and unswept wings show a slight

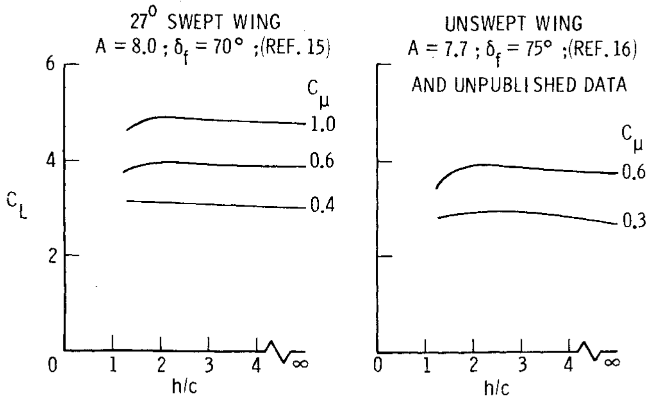

Fig. 7 Augmentor wing wind tunnel data: fixed ground plane, $\alpha = 0$ deg.

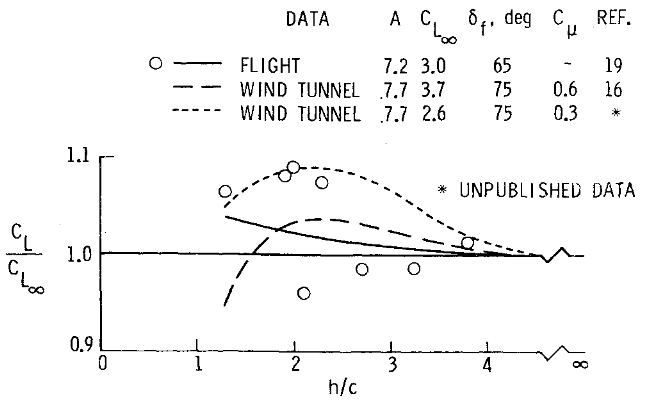

Fig. 8 Comparison of augmentor wing wind tunnel and flight data, $\Lambda_{c/4} = 0$ deg.

increase in lift as h/c is reduced to about 2. Then, except for the swept wing at a C_μ of 0.4, there is a dropoff in lift as h/c is further reduced to 1.3. The initial papers presenting these data[15-17] emphasized the lift loss at the lower ground heights, and one of them[16] made use of the unswept wing data at the C_μ of 0.6 ($C_{L\infty} = 3.7$) in a flight simulator to predict the landing flare characteristics of the C-8A augmentor wing airplane. The simulator results indicated that the adverse ground effect would cause difficulty in performing landing flares with the airplane.

Because of these anticipated difficulties, the initial STOL landings with the C-8A airplane were approached very cautiously, but the pilot was pleasantly surprised to find no adverse ground effects for the conditions tested.[18] In fact, he had some difficulty with excessive floating after a flare, indicating some small positive ground effect. Reference 18 suggested that the discrepancy could have been caused by erroneous data being programmed into the simulator or by the test conditions not being identical in the simulator and in flight.

A comparison of the ground effect data obtained in flight tests of the C-8A[19] at a C_L of 3.0, with wind tunnel data for the unswept model, is shown in Fig. 8. It was necessary to bracket the flight C_L of 3.0 with model C_L's of 2.6 and 3.7, since directly comparable wind tunnel data were not available. The symbols represent measured flight data points which have considerable scatter. The solid line faired curve for the flight data was therefore based on a parameter identification technique using data collected in four approaches at a C_L of 2.65.[20] The wind tunnel and flight results appear to be at least in qualitative agreement in that they both indicate a positive ground effect.

In Ref. 21, quantitative differences between the model and flight data are attributed to differences in the configuration of

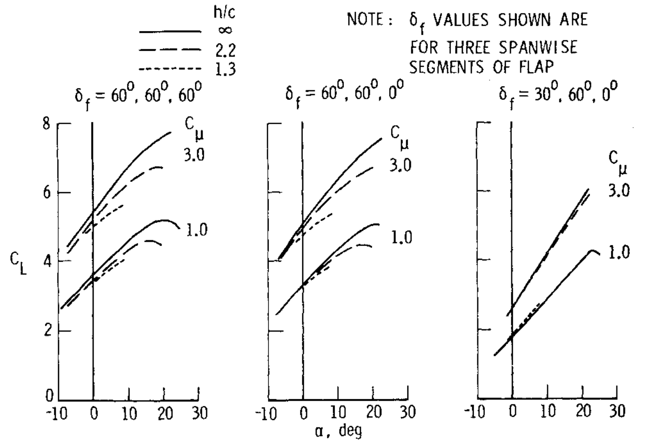

Fig. 9 EBF wind tunnel data: $\text{Æ} = 7.0$, high wing, $\Lambda_{c/4} = 25$ deg, tail off, $V_B/V_\infty = 1.0$ (Ref. 22).

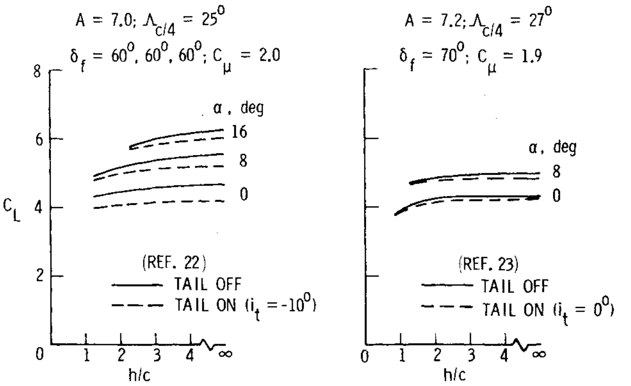

Fig. 10 Comparison of EBF landing flap data: high wing, $V_B/V_\infty = 1.0$.

the engine nozzle arrangement on the model and airplane, and to the fact that the tunnel tests were made with a fixed ground plane.

Externally Blown Flap

Early Data

Although research was initiated on the externally blown flap in 1956, the first ground effect data on an EBF configuration was not obtained until 1970.[22] Data from this investigation, presented in Fig. 9, show the effects of h/c, flap deflection, C_μ, and angle of attack. The δ_f values refer to the deflection of the three spanwise flap segments, starting with the inboard segment. The $\delta_f = 60$ deg, 60 deg, 60 deg is thus a full-span landing flap configuration, and $\delta_f = 60$ deg, 60 deg, 0 deg is a partial-span landing flap configuration. The $\delta_f = 30$ deg, 60 deg, 0 deg is intended to represent a takeoff flap setting.

The results of Fig. 9 are somewhat similar to the jet flap results of Fig. 4 in that they show that ground effect generally gets worse with increases in α, δ_f, and C_μ. The EBF data, however, do not show the increase in lift in ground effect at $\alpha = 0$ deg shown by the jet flap data, except for the takeoff flap deflection at a C_μ of 1.0. The dropoff in lift with increasing α is also somewhat more gradual with the EBF model. It is interesting to note that the EBF model with the takeoff flap configuration shows essentially no ground effect over the α and C_μ range tested.

Crossplots of the full-span landing flap data from Fig. 9 are presented in Fig. 10, together with similar data from Ref. 23. Both sets of data show a gradual loss in lift with decreasing h/c with the horizontal tail off or on. Note that the landing flap deflections for the model data in Fig. 10 are (60 deg, 60

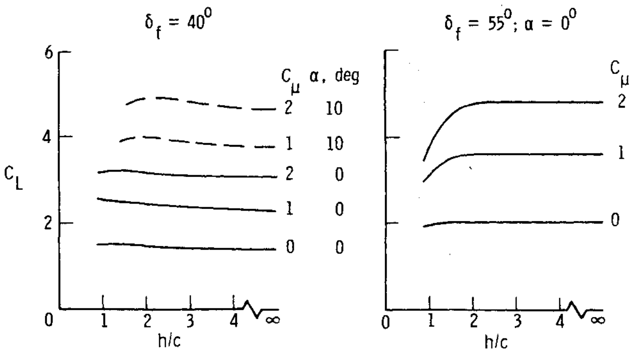

Fig. 11 Recent swept-wing EBF data: $AR = 7.3$, $\Lambda_{c/4} = 25$ deg, $V_B/V_\infty = 1.0$, model of Ref. 26.

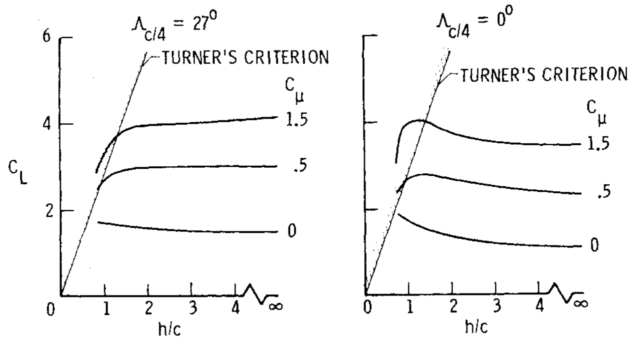

Fig. 13 Effect of sweep on EBF data: $AR = 7.0$, $\delta_f = 60$ deg, $V_B/V_\infty = 0$ (unpublished data).

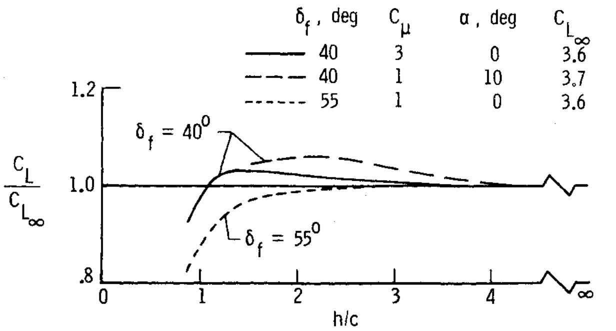

Fig. 12 Effect of flap deflection on swept-wing EBF: $AR = 7.3$, $\Lambda_{c/4} = 25$ deg, $V_B/V_\infty = 1.0$, model of Ref. 26.

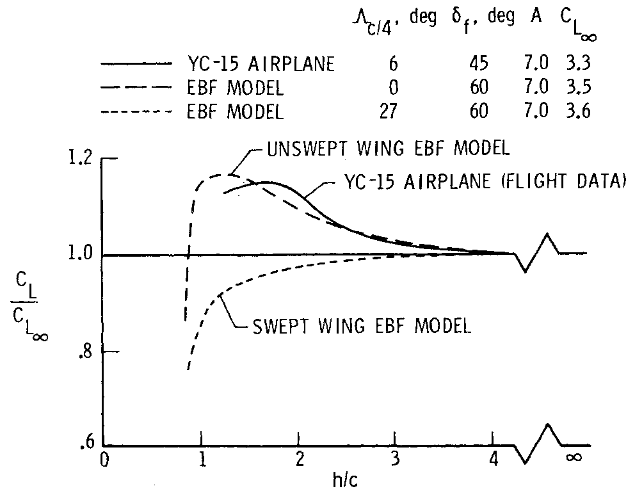

Fig. 14 Comparison of EBF flight and wind tunnel data.

deg, 60 deg) and 70 deg, which are considerably higher than the 45 deg deflection for the YC-15. The takeoff flap data may take on added significance here for the EBF since the lift coefficients obtained at 8 deg or 10 deg angle of attack are not greatly different from the flight lift coefficients obtained to date with the YC-15 EBF airplane. Moreover, the takeoff flap deflections, (30 deg, 60 deg, 0 deg) and 35 deg, are not greatly different from the YC-15 airplane landing flap deflection of 45 deg.

The early EBF ground effect data of Ref. 22 were used in two generalized studies of powered lift ground effect by Gratzer and Mahal[24] and Hassell and Judd.[25] Gratzer and Mahal compared theory and experiment and indicated the effects of various design and operating parameters. They concluded that powered lift ground effects will generally be adverse and will be a problem for STOL aircraft. Hassell and Judd used data from Ref. 22 to emphasize that the adverse ground effect is serious for approach lift coefficients of 4 to 5. They also presented results of an in-flight simulator study which indicated a definite increase in the difficulty of performing the landing flare when these adverse ground effects are present.

Recent Data

A recent investigation with an EBF model[26] has provided further results which may be more directly comparable with YC-15 flight data. Some data from this investigation, for flap deflections of 40 deg and 55 deg, are presented in Fig. 11. The data for $\delta_f = 55$ deg show a dropoff in lift at the lower values of h/c similar to that shown in Fig. 10 for the landing flap data from Refs. 22 and 23. The data for $\delta_f = 40$ deg, however, show a favorable ground effect over the range of angle of attack and C_μ covered in the figure. A direct comparison of the ground effect with the two flap deflections is shown in Fig. 12 for a lift coefficient out of ground effect of 3.6 or 3.7. One of the curves shown for $\delta_f = 40$ deg is for 10 deg angle of attack, since this condition is most nearly trimmed in drag for this flap deflection and is therefore more representative of an actual flight condition. The $\delta_f = 40$ deg data show a positive ground effect down to very low values of h/c.

All of the data on EBF ground effects in Figs. 9-12 were obtained with swept-wing models while the YC-15 EBF airplane has an unswept wing. Since theory[27] and some experimental work have indicated more favorable ground effects for an unswept wing, an investigation has recently been conducted at NASA Langley Research Center with simplified EBF wind tunnel models to obtain more information on the effect of wing sweep. One of the models was unswept with a rectangular planform and the other had 27 deg sweep with a taper ratio of 0.3. Both models were tested with a flap deflection of 60 deg. Data for the two models are presented in Fig. 13. Since these tests were run with a fixed ground board, boundaries are shown on the plots to indicate which combinations of C_L and h/c would satisfy Turner's criterion for requirement of a moving ground plane. These boundaries show that some of the data at the lowest values of h/c and highest lift coefficients are probably questionable. It appears, however, that the conditions of interest for correlation with YC-15 flight data ($h/c = 1.2$ and $C_L = 3.3$) are on the right side of the boundary and are therefore reliable data. The swept-wing data in the left plot of Fig. 13 show adverse ground effects generally similar to those in Figs. 10 and 11 for the EBF swept-wing models in the landing configuration. The unswept wing, however, has positive ground effects over the h/c and C_L range of interest.

A comparison of these swept- and unswept-wing EBF model data with YC-15 flight data obtained in steady flight at various values of h/c is shown in Fig. 14. The unswept-wing model data are in good agreement with the flight data, indicating that wing sweep may be an important factor determining the ground effects of powered-lift STOL aircraft.

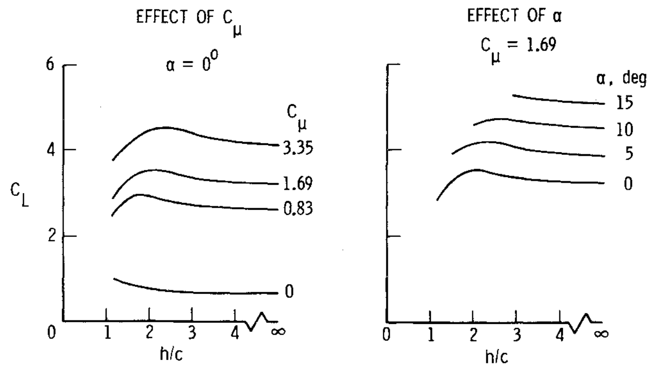

Fig. 15 USB wind tunnel data: $AR = 8.2$, $\Lambda_{c/4} = 0$ deg, $\delta_f = 60$ deg, $V_B/V_\infty = 1.0$, model of Ref. 26.

The close quantitative agreement between these model and airplane results is probably fortuitous since there are a number of differences between the two configurations, such as flap deflection and wing taper ratio.

The YC-15 airplane has an essentially unswept wing and a landing flap deflection of 45 deg. To date, no wind tunnel model incorporating both these features has been tested. However, both the swept-wing model with 40 deg flap deflection (Figs. 11 and 12) and the unswept-wing model with 60 deg flap deflection (Figs. 13 and 14) show definitely positive ground effects. It would certainly be expected, therefore, that wind tunnel tests of an exact model of the YC-15 airplane would produce positive ground effects generally similar to those observed on the airplane. The conclusion can then be drawn that the apparent discrepancy between YC-15 flight ground effects and the early EBF model ground effects can be explained by differences in configuration such as wing sweep and flap deflection and differences in the flight lift coefficient being considered.

Upper Surface Blown Flap

Only a limited amount of data have been obtained on the ground effects associated with upper surface blown flaps. Results are presented in Ref. 26 for an unswept USB model with flap deflections of 60 deg and 20 deg. Some of the data for 60 deg flap deflection are presented in Fig. 15. The model had generally favorable ground effects except at the very low values of h/c. If one disregards the h/c values below 1.38 (the value for the YC-14 airplane with its wheels on the ground), the ground effects are favorable in all cases. Boeing has obtained similar results in ground effect tests of a USB model representing the YC-14 airplane.

Although no quantitative data on the ground effects of the YC-14 airplane have been published, preliminary flight test results indicate a positive ground effect for the airplane. The model and airplane results thus appear to be in at least qualitative agreement.

Concluding Remarks

This review of powered-lift ground effect research was undertaken to explore the reasons for the apparent discrepancy between the pessimistic predictions of ground effect based on early wind tunnel research and the generally favorable ground effects exhibited by the three powered-lift STOL aircraft flown to date. The study revealed a number of specific reasons for disagreement between wind tunnel and flight results, and also indicated quite clearly that the fundamental problem involved was one of trying to predict flight characteristics from wind tunnel results that were not appropriate because of substantial differences in aircraft design features and/or operating conditions.

It thus appears that the favorable ground effects of all three airplanes can be readily explained by appropriate wind tunnel data. This should not be taken to mean, however, that adverse ground effects will never be experienced by these airplanes or similar follow-on airplanes. The same sets of wind tunnel data which indicate positive ground effects for the flight conditions flown to date also show that changes in aircraft design parameters and operating conditions could lead to adverse ground effects. For example, if very large improvements in landing performance (higher approach lift coefficients) are sought by going to much higher values of thrust coefficient, angle of attack, or flap deflection, the favorable ground effect now enjoyed by these airplanes could well become adverse.

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