Ground Effects in STOL Operation

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The effects of operation near the ground are of primary importance in determining the takeoff and landing characteristics of STOL aircraft. A study is presented which compares the results of theoretical analysis with those of wind-tunnel tests using a fixed ground plane with blowing boundary-layer control as well as the moving belt ground plane. These results are used to define the characteristics of STOL lifting systems near the ground to serve as a basis for an examination of limitations imposed on STOL operation. Variations in aircraft design parameters and operating techniques are explored to indicate ways of reducing the adverse effects of ground proximity.

Introduction

CURRENT interest in the development of Short Takeoff and Landing (i.e. STOL) aircraft for commercial application has refocused attention on the various aspects of STOL technology. This is particularly true in those areas which are critical to STOL operation and where advances and new concepts enhance the potential for really economic STOL systems.

Although an objective look at the recent development of high-lift technology, which is fundamental to STOL, will show substantial gains, the limitations imposed by ground effects remain essentially unchanged. It has long been recognized that the phenomena associated with ground proximity which have a significant influence on the aerodynamic characteristics and operation of conventional aircraft, can be severely limiting to STOL aircraft operation. In fact, they can dictate certain aspects of configuration selection and design. Perhaps less appreciated is that these phenomena have two fundamental aspects, one related to the potential flow about the lifting system and the other associated with limitations due to air viscosity and flow separation. Both play important and sometimes independent roles in determining the flight characteristics of the airplane near the ground.

It is the aim of this paper to discuss these fundamental aspects for STOL airplanes having lift systems for which the primary dependence is on circulation lift. The correlation between theory and experiment has been used to provide a satisfactory level of confidence in both areas as well as the test techniques necessary to obtain definitive data. With this as a basis, the characteristics of most STOL aircraft near the ground can be broadly defined to study the basic limitations imposed on STOL operation due to ground effects. Furthermore the influence of the more important airplane design parameters and operating techniques can be explored to indicate design directions required to achieve near-optimum STOL performance.

STOL Configuration Considerations

Since the present aim is to discuss the fundamental aspects of ground effect phenomena for STOL aircraft, it is important to define the range of STOL concepts and operating conditions for which the discussion is generally valid. For present purposes, the emphasis will be on those systems which can provide a landing field length approaching 2000 ft with a wing loading of 90 psf. This corresponds to a landing speed near 80 knots with an approach C_L of 4.0. Shorter field performance generally requires increasingly large amounts of direct powered lift resulting in configuration concepts and operational problems more closely associated with the V/STOL regime. These are considered beyond the scope of this discussion.

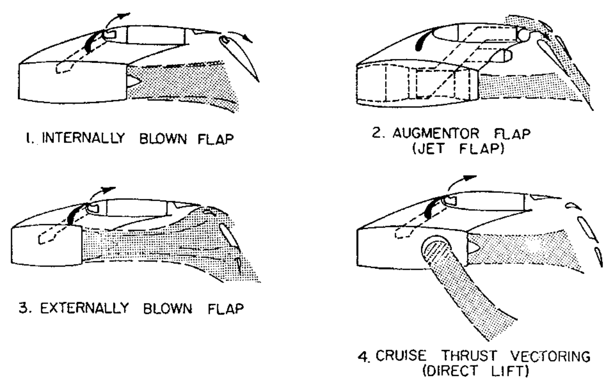

Fig. 1 STOL configuration concepts.

Over a period of time, a substantial number of STOL configurations have emerged which incorporate various techniques, including the use of engine power, for achieving very high lift. Figure 1 shows schematic representations of most of the basic concepts which are active candidates for future STOL airplanes. The internally blown flap configuration, Concept 1, is shown with a turbofan engine arranged to avoid significant impingement on the trailing edge flap. This concept may incorporate both leading edge and trailing edge blowing through internal ducts to provide high circulation lift. Such an arrangement, for which the trailing edge is blown to attachment, most nearly matches the analytical model used herein. The jet flap is closely related to Concept 1 except that a jet sheet is formed at the trailing edge with substantial excess momentum.

The augmentor flap, which is the essential element of Concept 2, may have special advantages (e.g. low noise) and can be considered a particular case of the jet flap concept. The conclusions drawn for systems with circulation lift may be considered generally valid for the augmentor wing or the jet flap at comparable lift levels, provided that the excess momentum in the jet sheet is relatively small. For situations where the jet sheet carries substantial lift ($C_\mu \sin\delta_f / C_L > .3$) the ground effect analysis given herein cannot be considered valid without further extension.

Another arrangement which continues to show good promise is the externally blown flap indicated as Concept 3. The effectiveness of this scheme derives from the spreading and turning of the engine exhaust directed at the trailing edge flap. Emergence of a portion of the high-energy flow through the flap slots maintains attachment of the external flow over the

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flap. Increased effectiveness may be realized by including boundary-layer control at the wing leading edge. Since the basic physical processes involved are related to those of the jet flap, the ground interaction problem for the externally blown flap is quite similar to that of the jet flap at comparable values of C_μ and lift. However, in this case the results of ground effect theory may be considered valid somewhat beyond the limits of validity for the jet flap. This is because the jet leaving the wing or flap trailing edge is more concentrated and thus carries relatively less circulation lift than in the case of the jet flap. Thus for both Concepts 2 and 3 the effect of ground proximity can be based on the wing circulation lift; i.e., the total lift minus the vertical component of the force corresponding to the jet momentum.

An arrangement which incorporates provisions for independent deflection of the engine thrust with a high lift wing is shown as Concept 4. This is one example of the many possible approaches using direct powered lift to achieve short field capability. Many such schemes produce concentrated jets which do not interact significantly with the high lift system at values of C_μ typical of normal flight conditions. Thus in this case also, the ground effect problem can be analyzed using the theory derived for systems with circulation lift. The direct lift is accounted for separately as in the manner outlined above for the externally blown flap.

It will be noted that no representation is given of systems using a turboprop-wing combination. Even though the volume occupied by the high-energy flow is very large in this case, the flow processes involved can be considered similar to those of the externally blown flap. Thus, on a more approximate basis, it is possible to relate the characteristics of the externally blown flap to those of the propeller-wing combination at the appropriate levels of C_μ and lift.

In summary, then, the ground proximity effects to be discussed in this paper will be based primarily on theory and experiment which apply in a strict sense only to systems with circulation lift. The results will nevertheless be appropriate to a good approximation to the configurations shown in Fig. 1 when appropriate corrections are made to account for that portion of the lift carried directly by jet momentum.

Ground Effects in Potential and Real Flow

The basic nature of the changes which are induced in the potential flowfield has been well known for some time and analyzed through simple mathematical models, using the Lanchester-Prandtl lifting-line theory. The digital computer has made possible the use of more sophisticated mathematical models with which the details of the potential flowfield can be determined in and out of ground proximity. In such models, the real wing is simulated by distributed singularities (vortices and/or sources) and the ground influence is represented by image singularities which are the reflection of the real wing in the ground plane.

Airfoils near the Ground

It is instructive to study two-dimensional airfoil characteristics since a large portion of a finite wing behaves very much like a two-dimensional wing when appropriate flow-angularity and velocity corrections are introduced.

In two-dimensional analyses the singularities representing the image induce velocities at the airfoil which oppose the stream velocity and effectively increase the camber and incidence of the airfoil. Such models are able to adequately predict the general effects of ground proximity for a wide range of conditions (angle of attack, camber, flap deflection, etc.). Variations in lift and pitching moment as a function of wing height and angle of attack for a 50° flapped airfoil are shown in Fig. 2, as calculated by a distributed-vorticity scheme.[1]

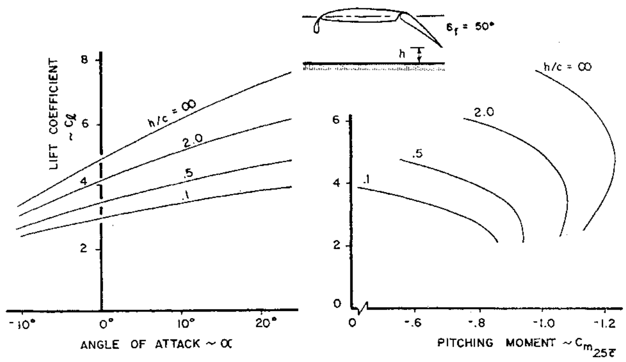

Fig. 2 Theoretical section characteristics.

At low wing heights and high lift coefficients the induced horizontal velocity effect is dominant, causing a decrease in airfoil lift from its freestream value. Although not shown here, the induced camber and incidence effects are dominant at high wing heights and low lift coefficients, causing some increase in airfoil lift. At high lift coefficients the pitching moment varies drastically as the wing approaches the ground. The changes are caused primarily by large forward shifts in the center of pressure which reduce pitching moment near the ground. This effect is shown by Fig. 3a which displays the surface pressures at constant flap angle ($\delta_F = 50°$) and lift coefficient ($C_l = 4.0$). Of further importance is a large increase in adverse gradient at the leading edge which is known to result in earlier flow separation as the ground is approached. Figure 3*b* shows the surface pressure distributions for $\delta_F = 50°$, $\alpha = 8°$, and various ground heights. The prominent effect of reduced local velocity induced by the image system is evident.

Finite Wings near the Ground

The effect of ground proximity on finite aspect ratio wings carrying circulation lift can be determined by potential flow theory in much the same way as for airfoils. Accurate flowfield predictions require sophisticated mathematical models with iterative schemes to determine the correct trailing vortex trajectories. However, for most purposes the over-all aerodynamic characteristics of finite wings can be satisfactorily determined using less complicated schemes such as vortex-lattice methods,[2] and ignoring some of the complexities of the flow such as the vortex roll-up. The wing and its image can be modeled with a system of multihorseshoe vortex singularities. Bound vortex segments represent the chordwise lift distribution and trailing vortex elements emanating from the wing trailing edge correspond to the spanwise variation of lift.

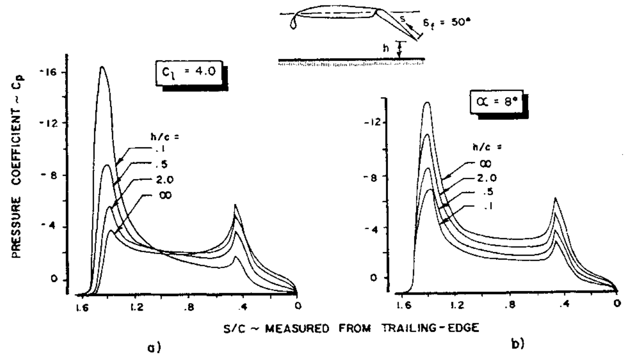

Fig. 3 Theoretical section pressure distributions.

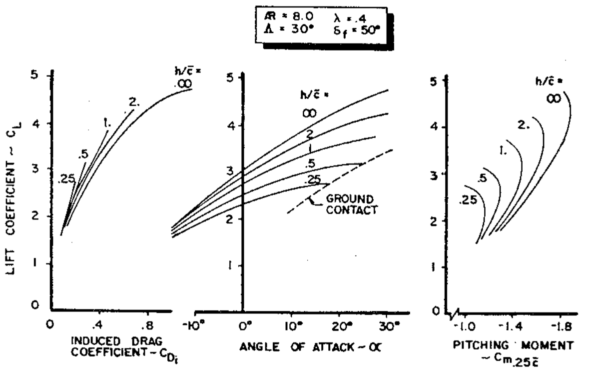

Fig. 4 Theoretical wing characteristics.

Such a model was used to calculate the lift, drag and pitching moment characteristics of a flapped wing at several ground heights. Data are given in Fig. 4 for a straight-tapered wing having aspect ratio, $AR = 8$, taper ratio, $\lambda = 0.4$, quarter chord sweep angle, $\Lambda = 30°$, flap deflection $\delta_F = 50°$ with a flap extension ratio of 0.35. It should be noted that when the wing height is measured in chord length, $h/\bar{c}$ the changes in lift and pitching moment for finite wings are similar but less severe than in the two-dimensional case. Two relieving effects contribute to this phenomenon. For a finite wing at a given attitude, the downwash induced at the wing by its trailing vortex system is reduced as the ground is approached. Also, because of the finite span of the bound vorticity, the image-induced velocity opposing the freestream at a given sectional C_l is always less than in the two-dimensional case. The percentage loss in aerodynamic force level due to ground effect increases rapidly with lift level. For example, when the lift coefficient away from the ground, $C_{L\infty} = 2$, lift decreases 4% at $h/\bar{c} = 1.0$; when $C_{L\infty} = 5$, the lift loss is 21% at the same $h/\bar{c}$. Induced drag and pitching moment changes follow similar trends but are substantially greater.

Among the configuration parameters which influence the magnitude of the ground effect on a finite wing are aspect ratio, sweep, taper ratio, flap deflection, and flap span b_f. The effects of these parameters on aerodynamic characteristics near the ground are displayed beginning with Fig. 5. For the same $C_{L\infty}$, the percentage lift loss increases with aspect ratio (Fig. 5a) but the differences are not significant over the practical range of aspect ratios ($6 < AR < 10$). Figure 5b illustrates the lift loss characteristics associated with wing sweep. These are significant even for relatively modest sweep angles. For example increasing sweep from 0° to 30° results in a lift loss increment of about 4% of $C_{L\infty}$ at $h/\bar{c} = 1.0$. Figure 5c shows the effect of part-span flaps for typical values of b_f/b. In this case, the swept, tapered planform with $b_f/b = 0.7$ exhibits a lift loss increment at $h/\bar{c} = 1.0$ of about 2% of $C_{L\infty}$ relative to the wing with full-span flap.

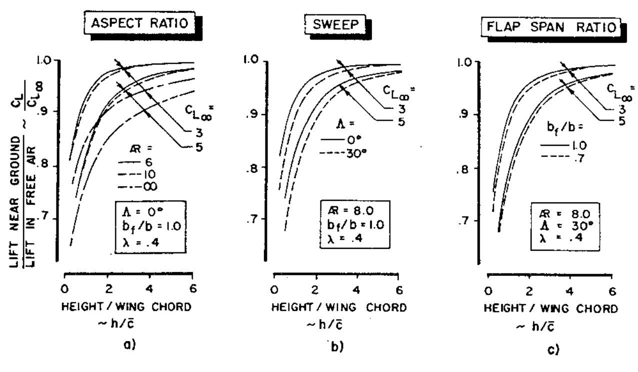

Fig. 5 Wing planform effects.

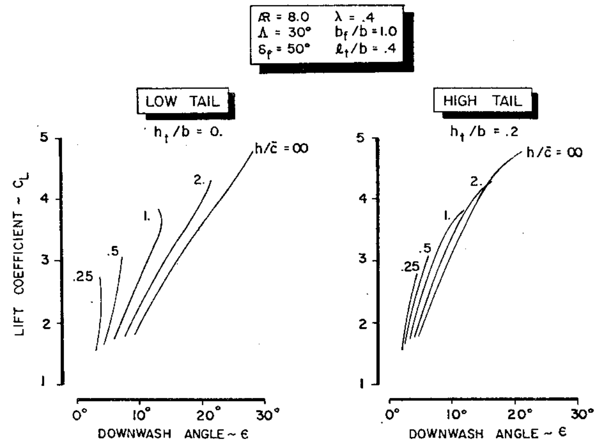

Fig. 6 Downwash at the tail for full-span flaps.

We turn now to the downwash characteristics at the tail which are most important in relation to the total pitch characteristics of the airplane. The ground effect on the flowfield in the region of the tail surfaces is presented in Fig. 6 for the swept, tapered configuration with full-span flaps. For the low tail position a rapid reduction in downwash angle, ε, is experienced as the ground is approached at constant C_L, and the reduction increases with C_L. Relatively small reductions in downwash occur at the high tail position as the wing height decreases. Some tendency toward trend reversal appears at high C_L.

Similar trends are shown in Fig. 7 which illustrate the effect of part span flaps ($b_f/b = 0.7$) at both low and high tail positions. However, at the same lift level the effects are much larger.

Comparison with Experiment

The recent interest in STOL configurations has prompted numerous wind-tunnel tests of STOL models to investigate ground effects. The reliability of such tests has improved markedly as a result of advances in testing techniques, such as the use of a ground plane either with blowing boundary-layer control or with a moving-belt design. Data from two such tests (Refs. 3 and 4) on externally blown flap STOL configurations have been compared with the predictions of the simplified vortex-lattice model. Figure 8 shows this correlation for a range of lift coefficients extending well into the STOL regime and indicates remarkably good agreement. In making this comparison, it is important that jet reaction forces be removed from the test data since the theoretical model does

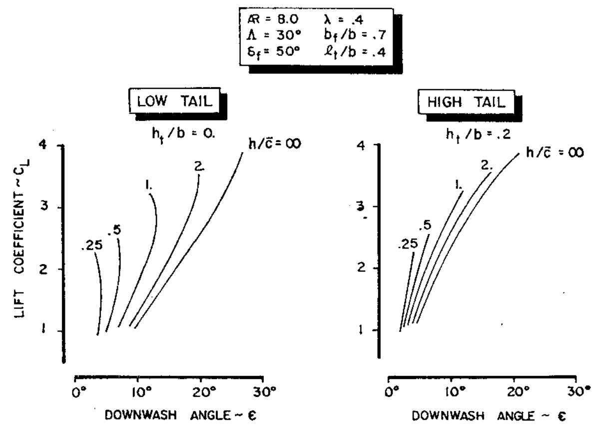

Fig. 7 Downwash at the tail for part-span flaps.

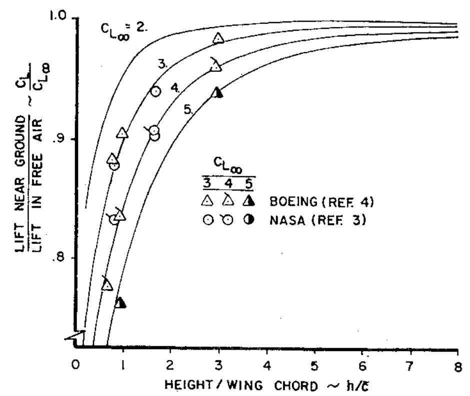

Fig. 8 Test/theory comparison.

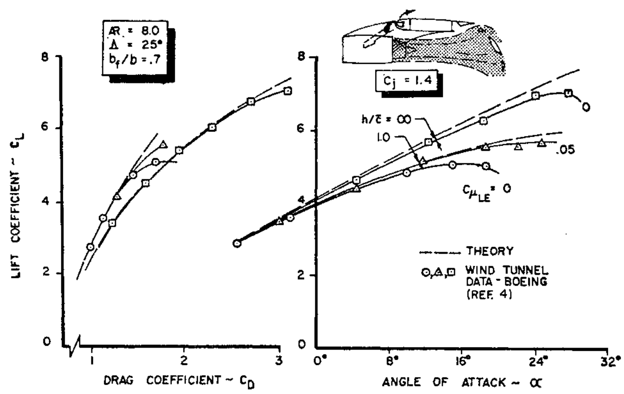

Fig. 9 Flow separation effects.

not simulate the jet. Thus, only circulation lifts are compared.

The theoretical method described above is highly satisfactory in determining many important effects of ground proximity on high lift configurations, in spite of the simplicity of the model. Effects of aspect ratio, sweep, taper ratio, flap deflection, flap extension, and flap span can be treated adequately when viscous flow or separation effects are small. When substantial areas of the wing or flaps experience partial (or full) flow separation large effects on drag and pitching moment can occur which generally invalidate comparisons with potential flow theory.

Viscous Effects

In many instances, especially at higher lift levels, the losses in lift are increased due to flow separation as the airplane approaches the ground. This phenomenon is a result of changes in the pressure distribution as shown in Fig. 3, where leading-edge pressure gradient is seen to increase as the wing section approaches the ground. Extensive two-dimensional testing has indicated close correlation between high-pressure gradients and early section stall. Wind-tunnel evidence of this phenomenon on a finite-span wing is demonstrated in Fig. 9, where an externally blown flap STOL configuration having $AR = 8$ suffers early flow separation near the ground, limiting the $C_{L\max}$ to a relatively low value. The drag polar also exhibits a tendency to early breakaway from the theoretical trends. However, as long as the leading edge is provided with adequate boundary-layer control, the experimental data follows the calculated potential flow trends quite closely. This approach can be extended to higher lift levels as required.

Performance Effects

The previous discussion has aimed at establishing a valid basis for the analysis of STOL performance and design trades in areas where ground proximity effects are of primary importance. Since the objective is to show performance limits, the effects of wing height will generally be based on the use of a potential flow model. This approach is justified by assuming that for a specific configuration and flight condition, sufficient boundary layer control or other high lift techniques are used to prevent separation on the wing. Obviously this has practical limits beyond which the major conclusions will not be valid. These will be pointed out as appropriate.

Figure 10 illustrates a typical takeoff profile over a 35 ft obstacle. The shaded area indicates generally the portions of the takeoff operation for which ground proximity has important effects. The primary areas of interest are: 1) drag experienced during the ground run, 2) liftoff speed V_{LO}, and 3) the effect of drag and V_{LO} on the air distance. Although more precise calculations can be made, it is easy to show that the ground run distance is given quite accurately by the following relation:

$$S_{\mathrm{GROUND}} = (V^2_{LO}/2g)/(\langle a\rangle/g) \tag{1}$$

where the average acceleration, $\langle a\rangle$, is expressed by

$$\langle a\rangle/g = T_o/W - \mu - .5(C_{DT} - \mu C_{LT})/C_{LLO} - .7(T_o/W)(V_{LO}/V_{\mathrm{JET}}) \tag{2}$$

and T_o = engine static thrust, V_{Jet} = engine exhaust velocity, W = airplane weight, μ = ground friction coefficient.

Subscripts T and LO indicate conditions during ground run and at liftoff, respectively. The air distance is given with good accuracy by a somewhat more complex relation which is applicable for the usual case where the airplane is still in transition over the obstacle. This relation is

$$S_{\mathrm{AIR}}/h = [1 + (V_2{}^2 - V_{LO}{}^2)/2gh + \{[1 + (V_2{}^2 - V_{LO}{}^2)/2gh]^2 + 16K_a(D/L)(V_{LO}{}^2/2gh)(T/W - D/L)\}^{1/2}]/2(T/W - D/L) \tag{3}$$

where h = obstacle height, V_2 = velocity over the obstacle, D/L = airplane drag to lift ratio (average), $K_a = \{1 - 1/3[(V_2{}^2/V_{LO}{}^2) - 1]\}^{-1}$. Equations (1) and (2) show that the ground run distance is primarily a function of airplane T_o/W, C_D, and $V_{LO}{}^2$ with a first-order dependence on the latter. It should be recognized at the outset that the permissible liftoff speed, V_{LO}, is tied directly to the minimum unstick speed, V_{MU}, as indicated in Fig. 10. For a given airplane wing loading, W/S, this can be shown to depend directly on the wing height since the presence of the ground substantially changes the drag polar and limits the achievable lift levels. While the liftoff speed is of primary importance, neglecting the effect of ground proximity on drag can result in a decrease in the calculated average acceleration and a corresponding increase in ground run distance of 10% or more. The air distance is a more involved function of drag and V_{LO} and depends to a certain extent on piloting technique during takeoff. If the airplane is kept near constant speed over the air segment, V_{LO} has only a second-order effect, while if a substantial acceleration is allowed (or required), the influence of V_{LO} quickly assumes first-order importance. On the other

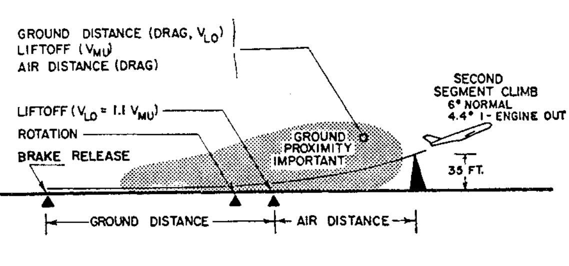

Fig. 10 STOL takeoff profile.

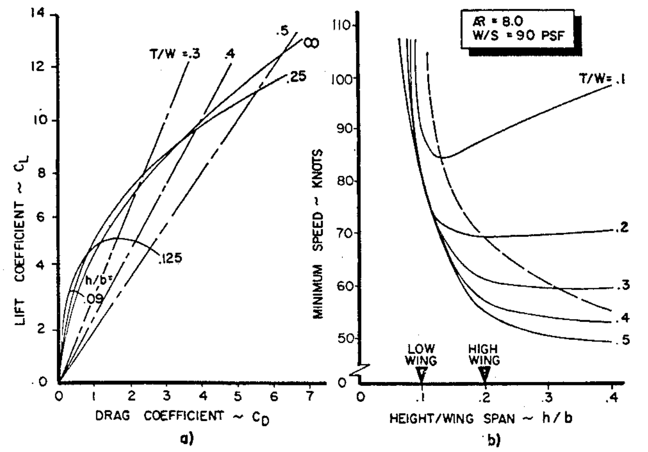

Fig. 11 Ground effects on takeoff.

hand for given values of V_{LO} and V_2, ignoring the effect of ground proximity on drag can produce errors of 25% or more in the calculated air distance.

We return now to the limiting effects of ground proximity on V_{LO} which under current and proposed methods of airplane certification depend on the value of V_{MU} actually demonstrated on takeoff. Figure 11a illustrates the effect of wing height on the envelope drag polar for a typical STOL airplane having the aerodynamic characteristics noted. These parameters correspond to the envelope polar for a range of flap deflections from the takeoff to the landing configuration for a system in which no flow separation effects occur. The plot includes lines of constant thrust-to-weight ratio, T/W, covering a range of values from the CTOL to the STOL regimes. Because V_{MU} is basically the minimum speed achievable in level flight with all engines at takeoff thrust, the points at which the T/W lines intersect the various polars are of interest. The upper intersections define lift coefficients (i.e. $C_{L_{MU}}$) from which values of V_{MU} can be calculated. Figure 11b shows the variation of V_{MU} with wing height for several values of T/W for an airplane with $W/S = 90$ lb/ft^2. It is apparent that the minimum achievable speed depends on wing height and is a strong function of T/W. Quite obviously the high-wing airplane is much better suited to achieving a low value of V_{MU} and the shorter takeoff distance associated with it. For the low-wing airplane it is apparent that flight demonstration of V_{MU} at some height above the ground could provide a substantial advantage particularly at the higher T/W values. The high-wing airplane suffers less from the normal requirement to demonstrate V_{MU} in an actual takeoff and could potentially demonstrate a takeoff ground run approaching half that of the low-wing airplane at $T/W = 0.5$.

To this point, the discussion has been based on potential flow limitations. If viscous effects are considered, it can be expected that the shape of the drag polars will change with upper limits on lift determined by flow separation. Since the presence of the ground tends to worsen this problem, more severe viscous flow limitations would occur at low values of h/b. Generally, this would have the effect of raising V_{MU} although the relationships previously shown would remain qualitatively the same. The precise way in which changes due to viscous effects occur is related to the design and operating characteristics of the particular high lift concept involved and cannot be generalized to any significant extent.

Although substantial effects of ground proximity are apparent for the takeoff situation, the impact on landing performance and handling characteristics is of greater concern. A typical STOL landing profile is shown in Fig. 12, again illustrating the areas where the presence of the ground is important. No obstacle height is shown in this case since it appears more appropriate for STOL operations to define field

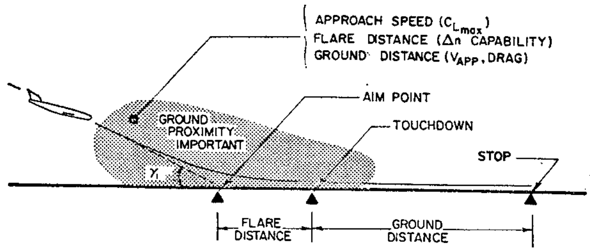

Fig. 12 STOL landing profile.

length requirements (Ref. 5) on the basis of a flareout from the approach path. As indicated in the figure, the areas of concern are: 1) approach speed, 2) flare capability and 3) drag experienced during the ground run. The ground run distance can be expressed conveniently as

$$S_{\mathrm{GROUND}} = (K_v V_{\mathrm{APP}}{}^2/2g)/|\langle a\rangle/g| \tag{4}$$

where the average acceleration $\langle a\rangle$ is expressed by

$$\langle a\rangle/g = \langle T_T\rangle/W - \mu_B - .5K_v(C_{D_T} - \mu C_{L_T})/C_{L_{APP}} \tag{5}$$

and $T =$ engine thrust, $W =$ airplane weight, $\mu_B =$ braking friction coefficient, $K_v = (V_{TD}/V_{\mathrm{APP}})^2$. Subscripts T, APP, and TD indicate conditions during the ground run, during approach and at touchdown, respectively.

The flare maneuver represents the most critical and variable element of the entire landing operation since it is sensitive to piloting technique particularly in crosswinds and gusty air. For present purposes it will be assumed that the flare is carried out at constant speed ($K_v = 1$) and lift coefficient. Realistically this would require some form of autothrottle or its equivalent and would involve substantial changes in angle of attack or some form of direct lift control to maintain constant C_L near the ground. Although this provides a simple basis for calculating flare distance, it does not result in the minimum landing distance since some reduction in speed during the flare ($K_v < 1$) would substantially shorten the ground run. With the above assumption invoked, however, the relation for flare distance becomes:

$$S_{\mathrm{FLARE}} = (V_{\mathrm{APP}}{}^2/2g)(\gamma_1 - \gamma_2)^2/\Delta n|\gamma_1| \tag{6}$$

where, $\gamma_1 =$ flightpath angle in approach (rad.), $\gamma_2 =$ flight path angle at touchdown (rad.), $\Delta n =$ load factor increment in flare.

From the preceding discussion it is apparent that the total landing distance is primarily dependent on approach speed since both the flare distance and the ground run are directly proportional to $V_{\mathrm{APP}}{}^2$. Although the drag characteristics near the ground are not too important, neglecting ground effects in this case can decrease the calculated ground run distance up to about 15%. However it should be noted that the magnitude of the effect will depend on the use of reverse thrust, braking friction, μ_B, and the effectiveness of wing spoilers in reducing lift during the ground run. As indicated previously the flare distance is sensitive to the piloting technique and for a given V_{APP}, is critically dependent on the load factor increment, Δn, that can be used effectively over this segment. For a given airplane wing loading, allowable combinations of $V_{\mathrm{APP}}{}^2$ and Δn are determined by the maximum lift available near the ground. The following discussion will show some of the considerations involved in selecting the approach speed and the limitations associated with ground effects for the STOL landing operation.

Figure 13 gives the fundamental relationship between angle of attack and wing height as a function of airplane trimmed lift coefficient for a typical STOL configuration, employing the externally blown flap concept. The calculations are based on a landing approach condition for which the power setting corresponds to $T/W = 0.24$. For an airplane configuration

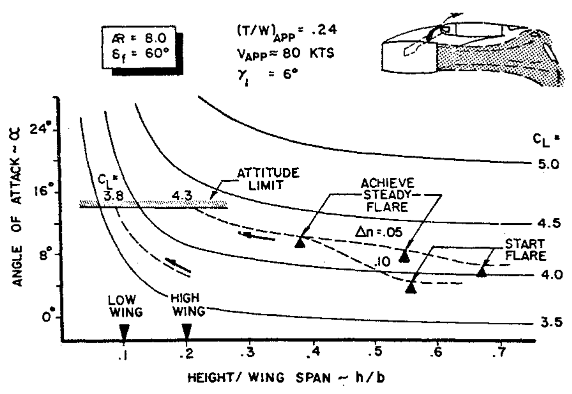

Fig. 13 Ground effects on landing.

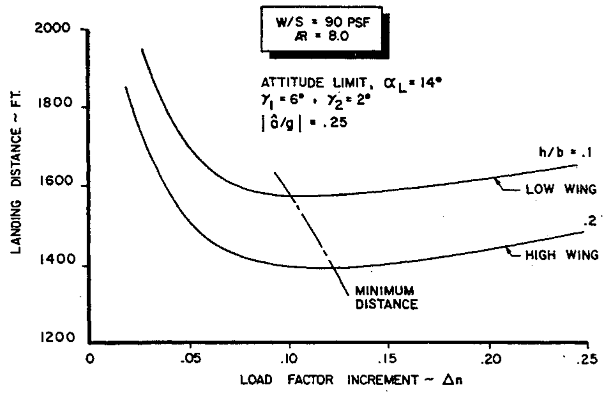

Fig. 14 Landing performance.

having an attitude limit of 14° at touchdown, it is apparent that the presence of the ground produces severe limitations on the magnitude of lift available. Wing height values at touchdown representative of low-wing and high-wing configurations are referenced which determine the lift levels achievable in these two cases; namely, $C_L = 3.8$ and $C_L = 4.3$, respectively. The way in which the ground effect and attitude limits affect the landing performance of the airplane is also conveniently shown in Fig. 13. The angle of attack required as a function of wing height is typically given by a dashed line (referred to as the flare characteristic) for a specified value of Δn during the flare. The flare is to be considered as progressing timewise from right to left along the flare characteristic. For each of the two values of Δn shown, arrowheads designate two significant points corresponding to the initiation of flare and the achievement of a steady condition in the flare. For the high-wing case where the C_L at touchdown is 4.3, the values of approach C_L are 3.9 and 4.1 corresponding to Δn values of 0.10 and 0.05, respectively. A similar analysis carried out for the low-wing case shows essentially the same behavior where the values of approach C_L are about 3.45 and 3.60 corresponding to the same values of Δn given above. In addition to the obvious differences in approach speed for the two configurations, there are other important factors to consider. For either configuration, the angle of attack change $\Delta\alpha_1$ to initiate the flare increases substantially with the increase of Δn. For the high wing, $\Delta\alpha_1 = 2°$ when $\Delta n = 0.05$ and $\Delta\alpha_1 = 6°$ when $\Delta n = 0.10$ so that serious difficulty can be expected in executing flare maneuvers using load factors much above $\Delta n = 0.10$. Of further importance is the total change in angle of attack $\Delta\alpha_F$ from the start of the flare to touchdown. For the high wing the total change, $\Delta\alpha_F = 8°$ for $\Delta n = 0.05$ and $\Delta\alpha_F = 10°$ for $\Delta n = 0.10$. For the low wing, analysis shows that the corresponding values of $\Delta\alpha_F$ become 14° and 16°. It can also be observed that the required rate of change of angle of attack $\dot{\alpha}$ may be a limiting factor from a controllability standpoint. Since $\dot{\alpha}$ is directly proportional to $d\alpha/dh$ along the flare characteristic, it can be observed that the pitching rate required near touchdown is much larger for the low-wing airplane.

The preceding example indicates clearly that higher values of Δn in the flare result in higher approach speeds and therefore larger ground distances. Since there is an opposite effect on flare distance, the trade between flare distance and ground distance would be expected to result in an optimum value of Δn corresponding to minimum total landing distance. Figure 14 shows that this is indeed the case. The variation of landing distance with Δn in the flare is shown for a wing loading, W/S, of 90 lb/ft^2 and indicates a minimum near $\Delta n = .10$, for both the low-wing and high-wing configurations. However, substantially lower values of Δn may be used without significant increases in distance. On the other hand, the low-wing airplane requires appreciably larger landing distances; about 13% in this comparison. In view of other configuration trades which can be exercised to allow operation into short fields, this may not be decisive. However, setting field length design objectives below 2000 ft will require lift coefficients that quickly exceed practical attitude and pitch rate limits for systems with wing circulation lift and only a modest amount of direct lift.

Design Considerations

Before concluding the discussion of ground proximity effects, attention should be directed to the possible impact of the other high lift system configuration parameters on the short field performance potential of STOL airplanes. From the designer's point of view, the interest is in the special requirements arising because of ground proximity effects, over and above those which would normally be considered in the airplane design.

The preceding discussion has shown the influence of wing position and attitude limits on performance near the ground. Although the high wing has substantial low-speed performance advantages for both takeoff and landing, there are unfavorable configuration and performance aspects to be considered. For example, the high wing necessitates a landing gear arrangement which tends to be heavy, to limit touchdown attitude and to adversely affect drag. Other factors such as engine to ground clearance, cruise drag, structural integrity, airline acceptability, etc., make the choice of wing location subject to complex tradeoff procedures.

The discussion related to Fig. 5 has already pointed out some of the effects of wing planform differences involving sweep, aspect ratio, and flap span ratio. There it was noted that increasing sweep resulted in larger attitude changes near the ground for the same lift. Although not shown, detailed analysis indicates that the shape of the drag polar and pitching moment curves are not significantly changed. However when separation effects occur, no such general conclusions are possible, particularly in relation to pitching moment. Recognizing the above and the need to achieve acceptable approach attitude and $C_{L_{\max}}$, the designer will be inclined to select as small a sweep as possible within the restrictions imposed by cruise speed, ride quality, etc.

Within the practical range of wing aspect ratios. Fig. 5a shows that this parameter has little effect on lift loss near the ground. Theoretical analysis shows that the ground proximity effects on the induced drag polar generalize best when plotted as $C_L/\pi AR$ vs $C_D/\pi AR$ with h/b as the wing height parameter. This accounts for the primary variations and no other significant effect of aspect ratio near the ground should be expected. Since pitching moment effects on the wing are closely related to the section characteristics, aspect ratio is not important in relation to wing-alone pitching characteristics. On the other hand, the downwash variations at the tail such as shown in Figs. 5 and 6 are greatly influenced by aspect ratio. While not indicated here, the aspect ratio influence can be generalized by plotting ε vs $C_L/\pi AR$ with h/b again as the independent parameter. Again no other significant influence of aspect ratio is apparent. The important conclusion from the designer's standpoint is that the selection of STOL airplane aspect ratio can be based on the normal design tradeoffs with little reference to ground proximity effects.

The influence of flap span ratio b_f/b is recognized to be important in relation to many aspects of STOL airplane design. To meet lateral control requirements, which may be particularly difficult for some STOL configurations (e.g., the externally blown flap), various trades must be made between the lateral control and trailing edge flap arrangement, which could involve the use of an outboard flaperon. Figure 5c shows that the loss in lift near the ground for part-span flap configurations is somewhat larger than for the full-span case, particularly at lower lift coefficients. Of more importance is the influence of flap span on downwash at the tail. This is shown by comparing Figs. 6 and 7 from which it can be concluded that a part-span flap produces a much larger variation of downwash as the airplane approaches the ground. This may require a larger range of stabilizer and/or elevator movement for the part-span flap. The above factors can be expected to lead the designer to very serious consideration of the full-span flap incorporating an outboard flaperon for lateral control.

Other wing geometric parameters which might be expected to influence aerodynamic characteristics near the ground are wing taper ratio and dihedral angle. While studies show that they may influence the details, it is difficult to find significant ground effects due to these parameters over their practical range.

Horizontal tail location has always been an important factor in configuration selection and this is particularly important for the STOL airplane. Figures 6 and 7 show the effect of tail height on downwash at the tail location as a function of wing height above ground. It is apparent that at the same C_L, the low tail experiences substantially more change in downwash as the airplane approaches the ground. This produces a large stabilizing effect which can provide a means of compensating for wing-alone pitching moment changes. Thus proper selection of tail location can give desirable airplane characteristics and avoid excessive use of control near the ground.

Finally we consider the influence of ground proximity effects on the selection of the STOL concept itself. Previous discussion has pointed out the physical basis for judging the validity of the circulation lift theory as applied to the STOL concepts of Fig. 1. From this it can be inferred that arrangements using some form of powered lift in addition to circulation lift on the wing will exhibit less change in aerodynamic characteristics near the ground than the system with circulation lift only. In this context all the arrangements of Fig. 1 can be considered in the former category depending on the amount of excess momentum at the wing trailing edge. As long as the jet momentum level is relatively low, the jet reaction can be added more or less independently to the forces associated with circulation. When the momentum is relatively large, then large interactions between the jet flow, the circulation flow, and the ground will occur leading to large ground proximity effects. Of further importance, however, is the way in which this momentum is distributed. If the lateral distribution is fairly uniform along the span (e.g. the jet flap) larger ground effects for a given C_μ can be anticipated since the jet itself sustains circulation lift. When the jets are concentrated, smaller interactions occur producing less adverse ground effects. Based on these considerations, an attractive choice of STOL concept for moderate C_μ levels is one deriving most of the lift from the wing with the remainder provided by appropriately directed, concentrated jets such as represented by Concept 4 in Fig. 1. Other arrangements, similar in concept but perhaps more acceptable from an overall standpoint, which closely approximate the performance characteristics of Concept 4, can be postulated to provide near-minimum ground effects while effectively meeting the many conflicting requirements of STOL operation.

Conclusions

Significant results of an extensive theoretical study of ground proximity effects on STOL airplanes have been presented. This approach is shown to be a powerful tool for determining the effects of wide variations in the important airplane parameters. Data from properly conducted wind-tunnel tests are generally in excellent agreement with theory.

The results of these studies show that the important influences of ground proximity on STOL airplane operation and design are due to wing height, tail height, flap span ratio, and wing sweep. The selection of the basic configuration concept, particularly the high lift system, can be critical depending on the design and performance objectives. The concept using a high lift wing with modest engine thrust deflection, either directly or through jet impingement on the flap, appears attractive for a STOL airplane required to operate from 2000-ft fields.

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