A Method for In-Flight Measurement of Ground Effect on Fixed-Wing Aircraft

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A new flight-test method has been developed for evaluating ground effect on fixed-wing aircraft. The method requires the pilot to fly at constant angle of attack and power setting during an approach to the runway at various initial sink rates. With this flight condition, lift, drag, and pitching moment are constant prior to approaching the ground. When ground effect is encountered, changes in flight path, velocity, and control-surface positions are interpreted as changes in lift, drag, and pitching moment, respectively. The fundamental principals and operational problems involved in applying this method are discussed in detail. The advantage of this technique is that the entire ground-effect characteristics of a configuration can be evaluated during a few approaches rather than by means of the multitude of fly-bys required by the classical constant-altitude fly-by method. The method has been applied to two low-aspect-ratio aircraft: a straight-wing and a delta-wing configuration. Some of the results of these tests are presented and compared with wind-tunnel predictions to illustrate the quality of the data produced by this technique.

Nomenclature

a_n = acceleration measured along the vertical axis of the aircraft, g units
a_x = acceleration measured along the longitudinal axis of the aircraft, g units
b = wing span
C_D = drag coefficient
C_L = lift coefficient
C_m = pitching-moment coefficient
D = drag
g = acceleration due to gravity
h = height of quarter chord above the ground
$\dot{h}$ = vertical velocity
$\ddot{h}$ = vertical acceleration
L = lift
q = dynamic pressure, $\rho V^2/2$
S = wing area
T = aircraft net thrust
t = time
V = true airspeed
W = aircraft weight
$\dot{x}$ = horizontal velocity
$\ddot{x}$ = horizontal acceleration
α = angle of attack
γ = flight-path angle
ΔC_D = drag-coefficient increment due to ground effect
ΔC_L = lift-coefficient increment due to ground effect
δ_e = longitudinal control-surface deflection
Θ = pitch attitude
ρ = atmospheric density

Subscript

i = initial value

Introduction

HISTORICALLY, as the Mach number of modern high-speed aircraft increases, so do the take-off and landing speeds and the associated ground runs. Since runway lengths cannot increase indefinitely, it is appropriate that every possible means of reducing these speeds be investigated. In this regard, ground effect, which results from the change of flowfield in the presence of the ground, can significantly influence the takeoff and landing characteristics.

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First, it would be well to review the nature of the aerodynamic changes that occur when an aircraft of low aspect ratio approaches the ground. Figure 1 shows a typical example of the characteristic aerodynamic changes caused by ground effect. The angle of attack and the drag and pitching moment coefficients are shown as functions of the lift coefficient. Note that the angle of attack required to generate a given lift coefficient decreases as the aircraft nears the ground. Similarly, the drag coefficient decreases while the pitching moment becomes more negative (i.e., nose down). It should be emphasized that these remarks are true only for constant lift coefficient. For, if angle of attack is held constant, the lift coefficient increases, causing the drag and moment coefficients to either increase or decrease, depending on the characteristics of the particular aircraft. The change in pitching moment is significant in that it greatly affects the magnitude of the actual lift increment that can be generated by the aircraft in flight. Since additional nose-up control is required to counteract the pitching-moment change, a considerable amount of lift is lost, because all conventional tailed and delta-winged aircraft produce a down load or negative lift increment when nose-up control is applied. Thus, the actual increment of lift due to ground effect is less for trimmed flight than for untrimmed model tests in the wind tunnel. This characteristic must be fully appreciated before estimates of in-flight ground-cushioning effect can be made from wind-tunnel data.

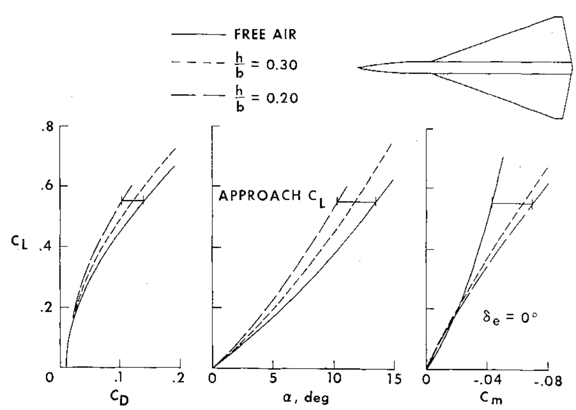

Fig. 1 Ground effect for a typical low-aspect-ratio configuration.

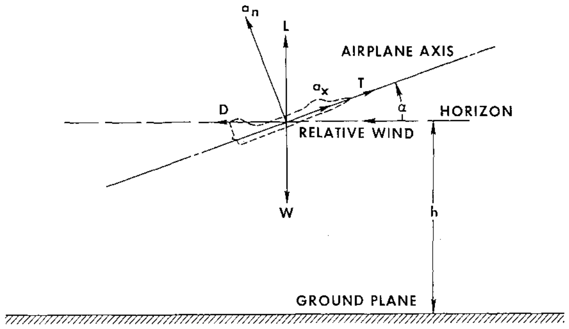

Fig. 2 Force diagram of fly-by method.

In general, the evaluation of ground effect is complicated by the relatively small magnitudes of the lift, drag, and moment increments due to ground effect, which makes these increments extremely sensitive to small variations in some of the critical parameters such as control-surface positions, angles of attack, and height above the ground. Heretofore, flight measurement of ground effect has been a rather elusive and time-consuming task, with results that did not always justify the effort invested. Therefore, a means is needed to measure ground effect rapidly and easily with sufficient accuracy and consistency to verify wind-tunnel measurements and to establish enough confidence to permit the application of ground effect to the take-off and landing problem. This paper describes a new method of measuring ground effect and its applications to the XB-70 and F-104 aircraft.

Test Methods

Several means of evaluating ground effect have been attempted or proposed. The most common method is the constant speed and altitude fly-by at varying heights above the ground, with the intent of evaluating the change in angle of attack, drag, and pitching moment at constant lift coefficient in and out of ground effect. A similar flight technique with a different means of evaluating the data has been used recently at the NASA Ames Research Center to measure ground effect on an F-5D airplane modified with an ogee wing.[1] In this fly-by technique, the lift and drag coefficients were evaluated by measuring the weight, angle of attack, thrust, and the normal and longitudinal accelerations by using the following equations,[2] derived from the basic force diagram shown in Fig. 2:

$$C_L = (W/qS)(a_n \cos\alpha + a_x \sin\alpha) - (T/qS) \sin\alpha \quad (1)$$

$$C_D = (W/qS)(a_n \sin\alpha - a_x \cos\alpha) + (T/qS) \cos\alpha \quad (2)$$

The height above the ground is determined by phototheodolite tracking, onboard camera,[3] or radar altimeter.

The fly-by method has two basic deficiencies. First, it requires a large number of passes to establish ground-effect data as a function of height and angle of attack. Second, its repeatability is in question because it relies on onboard measurements such as speed, angle of attack, weight, longitudinal and normal acceleration, and thrust. In general, the accuracy of some of these measurements is no better than 2 to 5%, which is the same order of magnitude as the ground effect that is being measured.

A new technique of measuring ground effect is proposed that does not rely on onboard measurements as the primary source of data, negates the requirement for thrust measurement, and requires only a few passes to obtain the data. Instead, the required data are obtained almost entirely from precise external tracking. The method requires the pilot to fly a shallow, descending approach to the runway at constant angle of attack and power setting. If ground effect is present, the increment in lift will cause the aircraft to flare or round out, the change in drag will cause it to accelerate or decelerate, and the change in pitching moment will require additional longitudinal control-surface input to hold the aircraft at constant angle of attack. The change in the sink rate and horizontal acceleration can be interpreted as the change in lift and drag coefficients caused by ground effects, and the change in the pitching moment can be determined from the change in the longitudinal control-surface position. Variation in ground effects with angle of attack may be checked by performing these maneuvers at different speeds. The initial sink rate and power setting must be established carefully under no-wind conditions to insure that the aircraft is truly established on an equilibrium glide slope and not in a slowly varying condition such as a phugoid-type oscillation.

The key to the success of this method lies in the fact that it does not depend on onboard acceleration and angle measurements or on the determination of thrust, but rather it utilizes the acceleration measurements obtained by smoothing and differentiating precision ground tracking position data. Small gusts and turbulence have a large effect on the measured accelerations, but they do not affect the flight path significantly because of their transient and cyclic nature.

The Askania cinetheodolite runway tracking system at the Air Force Flight Test Center was used for this investigation. This system, as shown schematically in Fig. 3, utilizes two precision Askania cameras which simultaneously track the craft during its approach. By knowing the baseline in addition to the aircraft azimuth and elevation from these stations, the flight track of the aircraft can be determined accurately. The accuracies of a two-station solution with this system are better than ± 1 ft in height and horizontal position, thus meeting the 1-ft accuracy in position desired for this method. The attitude of the aircraft can also be measured by this system so that attitude in combination with flight-path angle can be used to cross check the onboard angle-of-attack instrumentation through the relationship $\alpha = \Theta - \gamma$. In this way, it is possible to detect any variations in angle of attack that might be caused by changes in the direction of the flowfield on the angle-of-attack vane in the presence of the ground. Tests made to validate this method indicated no significant effects of this type.

Method of Analysis

By assuming an initial steady-state glide at constant angle of attack and thrust, the principle of the proposed constant-angle-of-attack approach technique is apparent when the force diagram shown in Fig. 4 is examined. By summing forces in the vertical and horizontal directions, the following equations are obtained:

$$L \cos\gamma - W + T \sin(\alpha + \gamma) - D \sin\gamma = (W/g)\ddot{h} \quad (3)$$

$$T \cos(\alpha + \gamma) - D \cos\gamma - L \sin\gamma = (W/g)\ddot{x} \quad (4)$$

For small angles of attack and glide slopes, the cosine terms

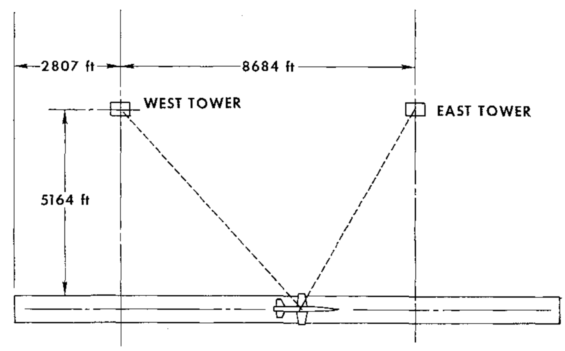

Fig. 3 Air Force Flight Test Center runway tracking system.

are near unity and the sine terms are essentially equal to the radian values of the angles. Using these approximations in Eqs. (3) and (4) gives

$$L - W + T(\alpha + \gamma) - D\gamma = (W/g)\ddot{h} \quad (5)$$

$$T - D - L\gamma = (W/g)\ddot{x} \quad (6)$$

Multiplying Eq. (6) by $-\gamma$ and adding to Eq. (5) results in

$$L + L\gamma^2 = (W/g)(\ddot{h} - \ddot{x}\gamma) - T\alpha + W$$

Multiplying Eq. (5) by γ and adding to Eq. (6) gives

$$T - D - D\gamma^2 = (W/g)(\ddot{x} + \ddot{h}\gamma) - T\alpha\gamma - T\gamma^2 + W\gamma$$

By dropping the terms containing the second-order products of small angles, the following expressions evolve:

$$L - (W - T\alpha) = (W/g)(\ddot{h} - \ddot{x}\gamma) \quad (7)$$

$$T - D = (W/g)(\ddot{x} + \ddot{h}\gamma) + W\gamma \quad (8)$$

Since weight, thrust, and angle of attack are each constant for the proposed method, it is possible to define the following increments in lift and drag coefficient due to ground effect:

$$\Delta C_L = \{[L - (W - T\alpha)]/qS\} - \{[L_i - (W - T\alpha)]/qS\}$$

$$\Delta C_D = -\{[(T - D)/qS] - [(T - D_i)/qS]\}$$

which, from Eqs. (7) and (8), become

$$\Delta C_L = (W/g)[(\ddot{h} - \ddot{x}\gamma)/qS] \quad (9)$$

$$\Delta C_D = -(W/qS)[(\ddot{x}/g) + (\ddot{h}\gamma/g) + \Delta\gamma] \quad (10)$$

where

$$\Delta\gamma = \gamma - \gamma_i$$

For comparative purposes it is convenient to normalize the ground effect in terms of the initial lift coefficient, so that Eqs. (9) and (10) may be expressed as percentage increases of the initial C_L in the forms

$$\frac{\Delta C_L}{C_{L_i}} (\%) = 100\left(\frac{\ddot{h}}{g} - \frac{\ddot{x}}{g}\gamma\right)\frac{q_i}{q} \quad (11)$$

$$\frac{\Delta C_D}{C_{L_i}} (\%) = -100\left(\frac{\ddot{x}}{g} + \frac{\ddot{h}}{g}\gamma + \Delta\gamma\right)\frac{q_i}{q} \quad (12)$$

These expressions are the working relationships used in the present analysis of the constant-angle-of-attack method. Since the γ and $\ddot{x}$ terms are usually quite small, their products and products with higher-order terms may be neglected. Also, the ratio q_i/q becomes unity so that Eqs. (11) and (12) may be simplified to

$$(\Delta C_L/C_{L_i})\ (\%) = 100(\ddot{h}/g)$$

$$(\Delta C_D/C_{L_i}) = -100[(\ddot{x}/g) + \Delta\gamma]$$

Processing and analyzing the ground-effect data is particularly critical because the magnitudes of the lift and drag increments are quite small in comparison with the total lift and drag of the airplane. The problem is one of measuring small differences between large numbers to an acceptable accuracy. For instance, if a typical lift increment in and out of the ground effect is less than 10% and this difference is to be measured to a 5% accuracy, the total lift must be measured to 0.5%. Thus, any disturbances that cause small variations in the lift make the evaluation of ground effect very difficult. Since disturbances caused by turbulence and pilot technique cannot be avoided in flight, these data must be carefully evaluated and interpreted.

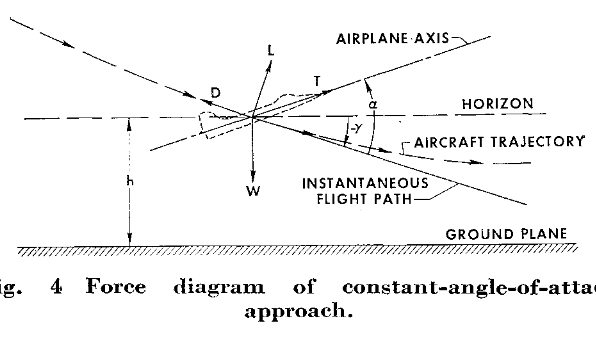

Fig. 4 Force diagram of constant-angle-of-attack approach.

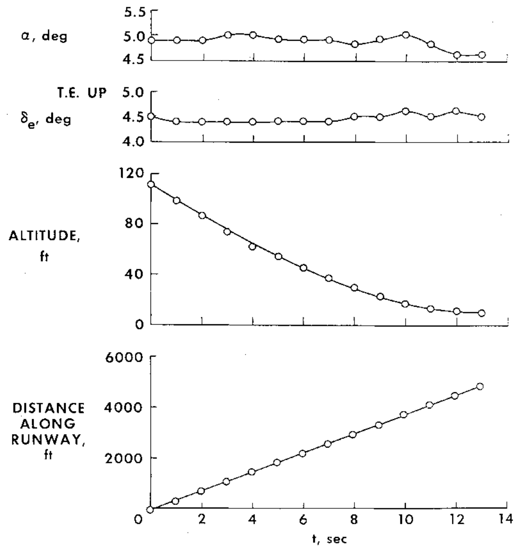

Fig. 5 Time history of a constant-angle-of-attack approach by an F-104 airplane.

An example of the type of raw data that might be expected is shown in the time history of an F-104 constant-angle-of-attack approach in Fig. 5. Note the small variation in angle of attack α and horizontal-stabilizer deflection δ_e. The pilot held the angle of attack constant within $\pm 0.2°$, which is representative of what can be expected. The decrease in rate of sink and velocity indicates any significant change in lift and drag due to ground effect. Slopes are obtained by graphical or numerical differentiation from the altitude and position data to obtain the sink rate and horizontal velocity. These data are then plotted against the height of the quarter chord in terms of span, as shown in Fig. 6. This format provides a common nondimensional basis for direct comparison of the results of other runs from higher and lower initial sink rates. In general, the higher the initial sink rate, the lower the aircraft comes to the ground before leveling off. Thus, a family of curves is formed which allows the curves to be related to each other, thereby assisting in obtaining proper fairings of the data. The slopes of these curves are read: however, these slopes do not result in a direct evaluation of the accelerations $\ddot{x}$ and $\ddot{h}$. Therefore, the accelerations must be derived by using the following equations:

$$\ddot{h} = \frac{dh}{dt}\,\frac{1}{[d(h/b)b]/[d(dh/dt)]} \quad (13)$$

$$\ddot{x} = \frac{dh}{dt}\,\frac{1}{[d(h/b)b]/[d(dx/dt)]} \quad (14)$$

These expressions are then used in Eqs. (11) and (12) to obtain lift and drag increments due to ground effect.

Test Results

The results of this analysis on the F-104 airplane are shown in the center plots of Fig. 6. Note that a significant amount of ground effect is generated not only close to the ground but also at heights well in excess of the classical one wing span

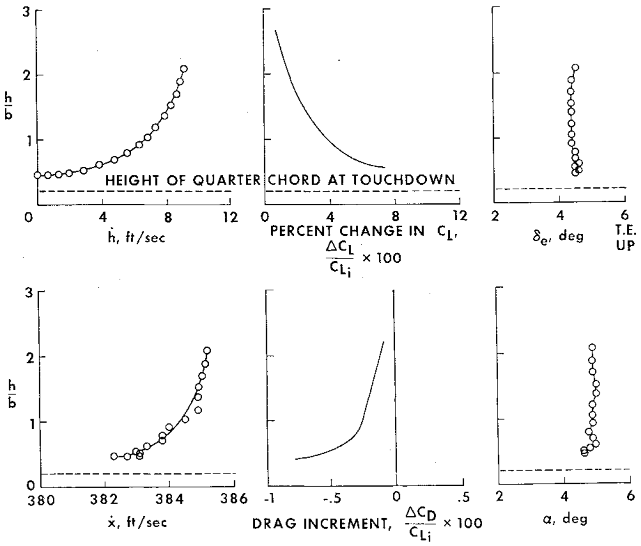

Fig. 6 Summary of F-104 ground-effect data.

that is usually regarded as the upper limit of ground effect. Note also that there is little pitching-moment change indicated by the change in stabilizer position. This condition is likely a result of the high tail being relatively free from the influence of the downwash of the wing. The exact cause of these characteristics is not fully known at this time and is a subject for further research. Because of the small span, the large ground effect takes hold in the last few feet before the aircraft reaches the ground. This characteristic is evidenced by other data that show that the aircraft does not touch down until initial sink rates greater than 20 fps are used. Because of obstructions and convective currents, it has been difficult to obtain precise optical resolution very near the ground, which makes comparisons with wind-tunnel data, obtained for touchdown conditions, more difficult than at greater heights. However, preliminary results indicate that high ground-cushioning effects $\Delta C_L/C_{L_i}$ of about 40% are being obtained for the F-104 airplane.

On the other hand, the XB-70 results are much more conventional. As shown in Fig. 7, ground effects begin at about one wing span above the ground and increase to more modest values of incremental lift than for the F-104 airplane. Because of the elevon required to counteract the nose-down pitching moment, a significant amount of ground-induced lift is sacrificed, as indicated by the difference between the trimmed and untrimmed curves. However, the 4% that remains is sufficient to cause the aircraft to flare during the constant-angle-of-attack approach, which reduces the sink rate from 11 to 1.5 fps. When the flight data are adjusted to the untrimmed condition tested in the wind tunnel, the data compare favorably.

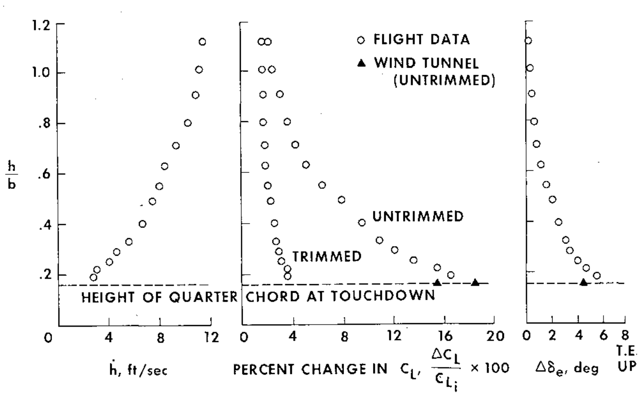

Fig. 7 Summary of XB-70 ground-effect data at $\alpha = 9.5°$.

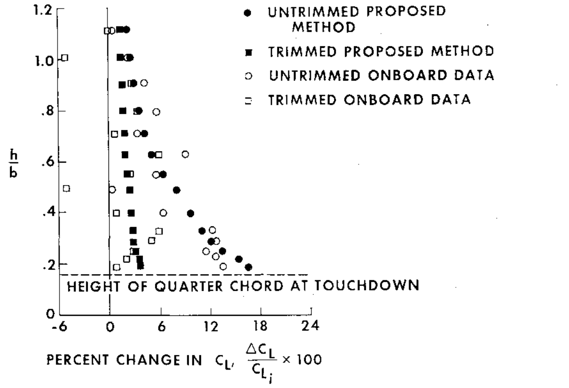

Fig. 8 Comparison of ground-effect results; onboard accelerometer vs photo tracking.

Direct measurement of accelerations by sensors onboard the aircraft might be considered as an alternate method of obtaining the flight data, since this would greatly reduce the effort required to work up the data. Unfortunately, attempts to utilize this technique with available instrumentation have not been too rewarding, as shown in Fig. 8, in which the data from the previous figure are indicated as shaded symbols. The open symbols are the data derived from onboard accelerometers, and only vaguely resemble the more consistent data derived from precision tracking cameras.

Conclusions

A new technique of measuring ground effect has been developed and validated on two low-aspect-ratio aircraft of widely different configurations. Satisfactory results have been obtained with a considerable savings in flight-test time and data-analysis effort over fly-by methods used previously. However, it has been shown that precision tracking, low atmospheric turbulence, and a high level of pilot proficiency in performing the required maneuver are essential for obtaining good data. Before proposing the constant-angle-of-attack technique as being generally applicable to all aircraft, further testing must be done on higher aspect ratio configurations.

References

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