Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cann exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, th may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cove

Ground Effects on USB Configurations

C. Edward Lan*
University of Kansas, Lawrence, Kan.

Introduction

RECENT investigations of ground effects on aerodynamic characteristics have been stimulated by the interest in powered-lift STOL airplanes. Early wind-tunnel data on augmentor-wing and externally-blown-flap (EBF) configurations have indicated adverse ground effect; however, the opposite has been found from flight tests of Augmentor-Wing Aircraft C-8A and EBF Aircraft YC-15. This disagreement of wind-tunnel and flight data has prompted Campbell et al.[1] to carefully examine the wind-tunnel data. They found that most of the disagreement could be traced to the wind-tunnel models which were not representative of the aircraft in wing sweep, taper ratio, flap angle, etc., and to the different operating lift coefficients. Therefore, accurate simulation of main aerodynamic mechanisms is important in the investigation of ground effect.

In an effort to study theoretically the ground effects of the jet flap and EBF configurations, Gratzer and Mahal[2] employed the conventional vortex-lattice method with flat wake to simulate the wing circulation lift. They indicated that if the jet reaction lift is less than 30% of the total lift, the wing-alone method of ground effect analysis without directly representing the jet is valid. Stevens and Wingrove[3] used a simple horseshoe vortex to predict the ground effects on C-8A and YC-15 and found that the predicted increase in lift in ground proximity is generally less than that obtained from flight tests. A three-dimensional thin-jet-flap theory with ground effect was presented in Ref. 4. However, no theoretical study of upper-surface-blowing (USB) configurations in ground effect has been published.

The main purpose of this Note is to extend the USB jet-wing interaction theory reported in Ref. 5, to treat the ground effect problem, and to present some calculated results.

Method of Analysis

The basic assumptions made in Ref. 5 are still applicable here. That is: 1) the unperturbed jet flow and freestream are uniform, and the perturbed flowfield in each region is governed by the Prandtl-Glauert equation with Mach numbers M_0 or M_j for the freestream and the jet flow, respectively; 2) the jet is of constant shape; and 3) the effects of fuselage, nacelle, horizontal tail, and wing thickness are not included. The boundary conditions require that: 1) the jet surface be a stream surface; and 2) the static pressure be continuous across it; in addition to 3) the usual wing-surface-tangency condition. To satisfy these three boundary conditions, vortex distributions are used on the wing and jet surfaces. The wake is assumed flat. The jet-flap effect within the present thick-jet formulation and the Coanda jet reaction forces have also been included. For greater detail the reader referred to Ref. 5.

In ground proximity, the additional boundary condition o no flow-through at the ground plane can be satisfied by usin image-vortex distribution with opposite circulation, a illustrated in Fig. 1. In Fig. 1a, the ground height h measured from the wing aerodynamic center, or som reference point. Figure 1b shows that in the present linearize theory, the location of the wing mean surface is taken to be a h_l, where h_l is the ground height of ¾ chord point of th mean aerodynamic chord for clean configurations as used i Ref. 6, and is taken to be the ground height at the trailing edg of the mean aerodynamic chord for configurations with fla deflection. The latter is chosen to account approximately fo the larger wake deflection associated with flap deflection. Th induced velocities on the wing and jet surfaces due to th physical wing and jet vortices are calculated in the usua manner.[5] The effects of the image vortices are twofold. First they induce upwash on the physical wing and jet surfaces. Le $\boldsymbol{v}_t$ be the velocity vector induced by image horseshoe vortice at some point on the wing:

$$\boldsymbol{v}_t = u_i\boldsymbol{i} + v_i\boldsymbol{j} + w_i\boldsymbol{k} \quad (1$$

With the unit normal vector on the wing surface given by

$$\boldsymbol{n} = \boldsymbol{i}\sin\theta + \boldsymbol{k}\cos\theta \quad (2$$

where θ is the pitch attitude angle, the upwash induced by th image vortices is

$$\boldsymbol{v}_t \cdot \boldsymbol{n} = w_i\cos\theta + u_i\sin\theta \approx w_i + u_i\theta \quad (3$$

Note that the backwash contribution $u_i\theta$ is to produc downwash on the wing if θ is positive. Although it is a second-order term, its retention improves the accuracy.[6] Equation (3 is to be incorporated into the wing- and jet-surface-tangenc conditions. Similarly, the image-induced x-perturbatior velocity will be included in the condition of jet-surface static-pressure continuity. Second, the image vortices will induce backwash on the wing to reduce the velocity of freestream. Thus the lifting pressure in ground effect is given by

$$\Delta C_p = 2\gamma_w\cos\alpha(1+u_i) \quad (4)$$

where γ_w is the wing-vortex density and u_i is the backwash induced by the image vortices, usually negative. The term involving u_i in Eq. (4), is again a second-order term.

The aforementioned special consideration for ground effect is concerned only with the wing circulation loading.

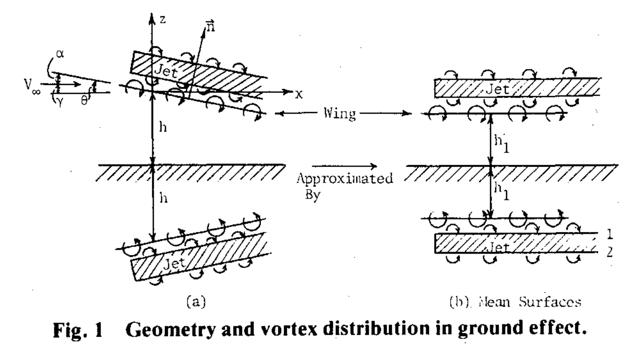

Fig. 1 Geometry and vortex distribution in ground effect.

Received Aug. 8, 1978.
Index category: Aerodynamics.
*Professor, Department of Aerospace Engineering. Member AIAA.

Examination of some available USB force data[7] indicates that the jet reaction lift, and hence, the jet deflection angle, will be reduced if the ground height is small. This possibility has also been suggested by May and Bean.[8] The fundamental idea behind this concept is that as the jet impinges on the ground, the increase in the upstream static pressure would force the jet to deform further in the downstream direction. Since the jet deflection angle is not constrained in the USB case, it would be decreased to accommodate the stronger jet crossflow interaction in ground proximity. This flow problem is difficult to solve exactly. Therefore, the following empirical method will be used.

Because of the similarity between the present case and a round jet in the crossflow, Margason's formula for the round jet trajectory[9] will be used as a first step. After differentiating his equation, the following equation is obtained:

$$\frac{d(x/D)}{d(z/D)} = -\frac{3\mu^2 T}{4\sin^2\delta_j}\left(\frac{z}{D}\right)^2 - \cot\delta_j \tag{5}$$

where $T=\rho_\infty/\rho_j$, $\mu = V_\infty/V_j$, D is the round jet diameter, and δ_j is the jet deflection angle. The first term on the right represents the effect of crossflow interaction. If the two terms on the right are equated and solved for z (denoted by z'_c), it is obtained that

$$|z'_c/D| = (2/3)^{1/2}(\sin 2\delta_j/\mu^2 T)^{1/2} \tag{6}$$

When this expression is used to check against the experimental data on a round jet (see for example, Fig. 12 of Ref. 10), it indicates approximately the straight portion of a deformed jet. However, Eq. (6) is incorrect at $\delta_j = 90$ deg. To fit the experimental data at $\delta_j = 90$ deg, Eq. (6) is adjusted to be

$$|z_c/D| = (2/3)^{1/2}[(0.135+\sin 2\delta_j)/\mu^2 T]^{1/2} \tag{7}$$

The length of the approximately straight portion of the jet is then given by

$$s_c = z_c/\sin\delta_j \tag{8}$$

At this point, it is assumed that there exists a characteristic length of jet, l_c, which would be forced to rotate rigidly by the freestream in the downstream direction to reduce the jet angle, if it touches the ground. Obviously, if the freestream dynamic pressure is low enough, l_c will be small so that the jet will hardly be rotated. Hence it is assumed that

$$\begin{aligned} l_c &= s_c(c\mu^2) \qquad (c\mu^2 < 1) \\ &= s_c \qquad (c\mu^2 \geq 1) \end{aligned} \tag{9}$$

where C is a constant to be determined after correlation with experiment (C is finally chosen to be 19.2). The jet deflection angle δ'_j in ground proximity is then given by

$$\delta'_j + \theta = \sin^{-1}(h'/l_c) \tag{10}$$

where h' is the ground height of the USB flap hinge. Note that in the above equations, D, μ, and T are taken to be the equivalent round jet properties evaluated at the USB flap hinge by the method of Ref. 11 for a turbulent round jet. In addition, δ_j is taken to be the average of the jet angle relative to the chord plane δ_{jc} and that relative to the freestream, or $\delta_j = \delta_{jc} + \alpha/2$. This is because the USB jet is subject to not just the uniform freestream, but also the wing flowfield, which at the USB flap hinge is assumed to be tangent to the chord plane.

Numerical Results and Discussions

Results for some wing-alone cases have been compared with other theoretical methods with very good agreement.[12] Excellent agreement with the thin-jet-flap theory of Ref. 4 in ground effect has also been obtained.[12] Here, only the results for USB configurations will be presented. The available YC-14 data[8] are for a complete configuration. Since the actual jet deflection angle δ_{jc} in free air is not available, and since the correct free-air C_L is important in predicting the ground effect, δ_{jc} is taken to be a value so that at $\alpha = 2$ deg, the lift coefficient in free air will match the experimental value as closely as possible. Using the data at $\alpha = 2$ deg with the thrust

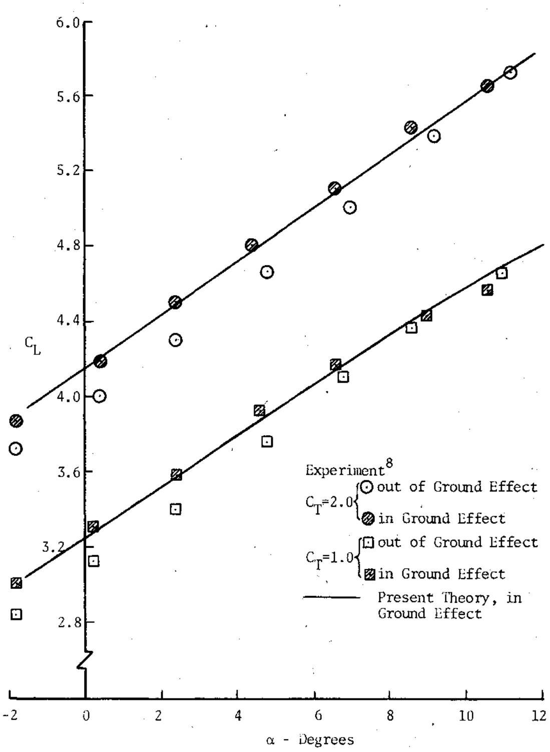

Fig. 2 Comparison of predicted lift curves with experiment for YC-14 landing configuration in ground effect with $h/b = 0.187$.

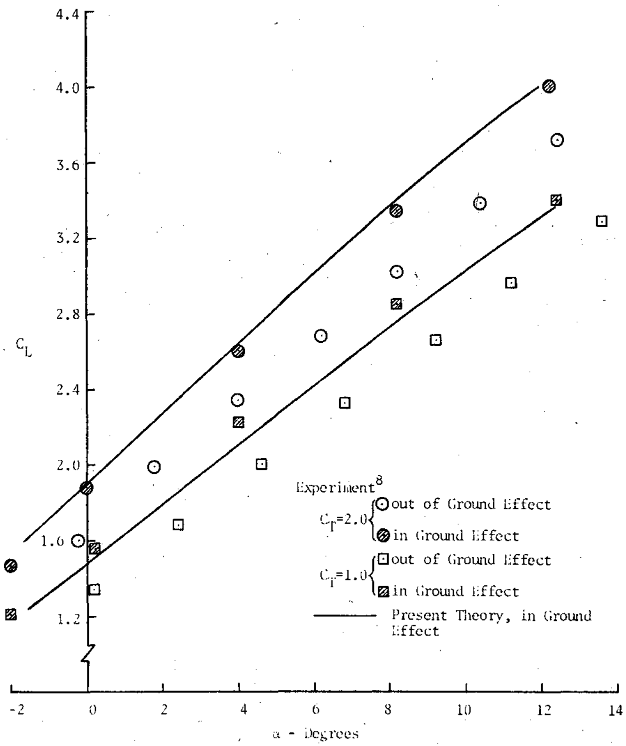

Fig. 3 Comparison of predicted lift curves with experiment for YC-14 takeoff configuration in ground effect with $h/b = 0.187$.

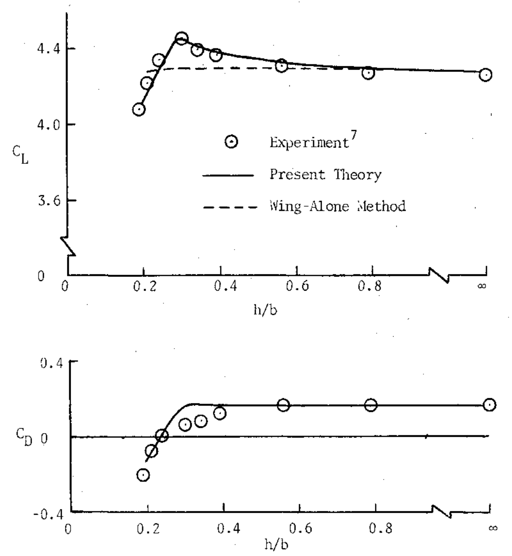

Fig. 4 Comparison of predicted ground effect on longitudinal aerodynamics of a USB landing configuration with $\alpha = 5$ deg and $C_T = 1.8$.

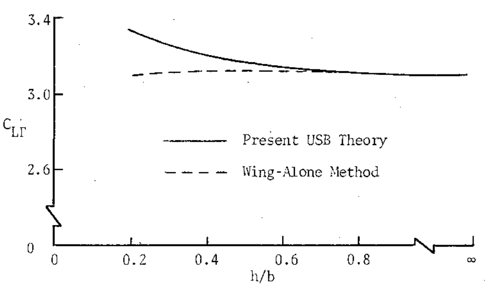

Fig. 5 Comparison of circulation lift in ground effect predicted by USB jet theory and wing-alone method for the configuration of Fig. 4.

coefficient $C_T = 2.0$ in landing configuration for correlation to determine the constant C in Eq. (9), it is found that $C = 19.2$ will provide the best overall results. The predicted lift curves are compared with experimental data in Fig. 2 for the landing configuration (thrust recovery efficiency $\eta = 0.9$) and with experimental data in Fig. 3 for the takeoff configuration ($\eta = 1.0$). It should be noted that the theoretical C_L is obtained by adding the predicted incremental C_L, due to ground effect, to the experimental free-air values. It is seen from Fig. 2 that the predicted ground effect for the landing configuration agrees quite well with experiment. For the takeoff configuration in which the USB flaps are retracted, the ground effect at $C_T = 1.0$ is underpredicted by the theory.

Comparison with the landing configuration data given in Ref. 7 is presented in Fig. 4. The free-air jet angle is taken to be 42 deg. Also shown is the dashed curve predicted by the wing-alone method. In the latter, the angle of attack is taken to be such that the total free-air C_L can be obtained with the flap configuration correctly simulated, and the jet reaction lift is assumed to be unchanged from the free-air value. It is seen that the present USB theory predicts the ground effect quite well. According to the theory, the jet deflection angle starts to be reduced at about $h/b = 0.3$. The wing-alone method is seen to be incapable of predicting the ground effect of USB configurations. As shown in Fig. 5, the wing-alone method does not predict the large increase in circulation lift $C_{L\Gamma}$ predicted by the USB theory when the ground is approached. One important reason for the discrepancy is that the USB theory predicts less backwash on the wing due to the image vortex system. This is illustrated in Fig. 1b. As usual, the image-wing vortices will induce backwash on the physical wing. However, the image-jet vortices will either induce backwash (from surface 2) or increase the longitudinal velocity (from surface 1). In general, the effect of jet surface is dominant because it is closer to the physical wing and the vortex strength is much larger. Therefore, the net backwash due to the image-vortex system for the same free-air C_L is reduced.

Concluding Remarks

The ground effects on USB configurations may involve changes in both the circulation forces and the jet reaction forces. In this Note, a theoretical method to predict these effects has been presented. The predicted results agree well with available experimental data. It has also been shown that the wing-alone method is not capable of predicting the ground effects of USB configurations.

Acknowledgment

This research was supported by NASA Grant NSG 1139 through the Langley Research Center.

References

[1] Campbell, J.P., Hassell, J.L., Jr., and Thomas, J.L., "Ground Effects on Lift for Turbofan Powered-Lift STOL Aircraft," *Journal of Aircraft,* Vol. 15, Feb. 1978, pp. 78-84.

[2] Gratzer, L.B. and Mahal, A.S., "Ground Effects in STOL Operation," *Journal of Aircraft,* Vol. 9, March 1972, pp. 236-242.

[3] Stevens, V.C. and Wingrove, R.C., "STOL Ground Effect Determined from Flight Data," AIAA Paper 77-576, AIAA/NASA Ames V/STOL Conference, Palo Alto, Calif., June 6-8, 1977.

[4] Goldhammer, M.I., Lopez, M.L., and Shen, C.C., "Methods for Predicting the Aerodynamic and Stability and Control Characteristics of STOL Aircraft, Vol. I, Basic Theoretical Methods," Air Force Flight Dynamic Laboratory, Wright-Patterson Air Force Base, Ohio Rept. AFFDL-TR-73-146, Dec. 1973.

[5] Lan, C.E. and Campbell, J.F., "A Wing-Jet Interaction Theory for USB Configurations," *Journal of Aircraft,* Vol. 13, Sept. 1976 pp. 718-726.

[6] Lan, C.E., "Some Applications of the Quasi-Vortex-Lattice Method in Steady and Unsteady Aerodynamics," NASA SP-405, Paper No. 21, May 1976.

[7] Thomas, J.L., Hassell, J.L., Jr., and Nguyen, L.T., "Aerodynamic Characteristics in Ground Proximity," *Proceedings of NASA Conference on Powered Lift Aerodynamics and Acoustics, NASA SP-406,* Paper No. 9, May 1976, pp. 145-158.

[8] May, F.W. and Bean, G.E., "Aerodynamic Design of the Boeing YC-14 Advanced Medium STOL Transport (AMST)," AIAA Paper 75-1015, 1975 Aircraft Systems and Technology Meeting, Los Angeles, Calif., Aug. 4-7, 1975.

[9] Margason, R.J., "The Path of a Jet Directed at Large Angles to a Subsonic Free Stream," NASA TN D-4919, Nov. 1968.

[10] Campbell, J.F. and Schetz, J.A., "Analysis of the Injection of a Heated Turbulent Jet into a Cross Flow," NASA TR R-413, Dec. 1973.

[11] Lan, C.E., "Theoretical Aerodynamics of Over-Wing Blowing Configurations," *Journal of Aircraft,* Vol. 14, June 1977, pp. 517-518.

[12] Lan, C.E., "A Theoretical Investigation of Ground Effects on USB Configurations," The University of Kansas Center for Research Inc., Lawrence, Kan., Tech. Rept. CRINC-FRL-281-3, Aug. 1978.