Effect of Sink Rate on Ground Effect of Low-Aspect-Ratio Wings

Ray Chung Chang*
Aeronautical Research Laboratory, Taichung, Taiwan
and
Vincent U. Muirhead†
University of Kansas, Lawrence, Kansas

An experimental investigation of dynamic ground effect has been conducted in the University of Kansas wind tunnel using delta wings of 60-, 70-, and 75-deg sweep, the XB-70 wing, and the F-104A wing. Both static and dynamic tests were made at a Reynolds number of 700,000. The investigation was restricted to conditions of constant sink rate (or flight path angle) and angle at attack. Test data have been compared to other test data, including dynamic flight test data of the XB-70 and F-104A. Limited flow visualization tests have been conducted. A significant dynamic effect was found for highly swept delta wings.

Nomenclature

AR	= wing model aspect ratio, b^2/S
b	= wing model span, ft
C_D	= coefficient of drag in ground effect
C_{D_∞}	= coefficient of drag out of ground effect
$\%C_D$	= percent increase in drag coefficient, $[(C_D - C_{D_\infty})/C_{D_\infty}] \times 100$
C_L	= coefficient of lift in ground effect
C_{L_∞}	= coefficient of lift out of ground effect
$\%C_L$	= percent increase in lift coefficient, $[(C_L - C_{L_\infty})/C_{L_\infty}] \times 100$
C_M	= coefficient of pitching moment about the quarter-chord point of the mean aerodynamic chord in ground effect
C_{M_∞}	= coefficient of pitching moment about the quarter-chord point of the mean aerodynamic chord out of ground effect
$\%C_M$	= percent increase in pitching moment coefficient, $[(C_M - C_{M_\infty})/C_{M_\infty}] \times 100$
$\underline{Cr}$	= root chord, ft
$\bar{C}$	= mean aerodynamic chord, ft
h	= ground height; the height of the quarter-chord point of the mean aerodynamic chord above the ground, ft
$\dot{h}$	= sink rate, ft/s
R_N	= Reynolds number based on mean aerodynamic chord
V_∞	= wind-tunnel speed, ft/s
y	= horizontal distance from centerline of wing model, ft
α	= angle of attack
Λ_{LE}	= leading-edge sweep angle

I. Introduction

BEGINNING with the work of Frederick W. Lanchester in 1907, the circulation theory of wing lift and the effect of wing vortices have been under study and development. The effect of the lift of a finite wing in close proximity to the ground was first studied by Weiselsberger[1] and Tani et al.[2] Choliasmenos[3] investigated the ground effect on the lift of a wing with and without boundary-layer control. Abercrombie[4] also investigated the ground effect on wings with high circulation. Both Abercrombie and Choliasmenos used rectangular wings of medium aspect ratio in their studies. Both studies concluded that the magnitude and direction of the interference of the ground on wing lift at a given height was a function of the circulation of the wing when it was out of ground effect. For lift coefficients under about 2, the ground effect was favorable, and for those above 2, unfavorable. Although Abercrombie's theory accounts for high angles of attack, it too is not applicable to low-aspect-ratio and highly swept wings with sharp leading edges. Fox's[5,6] theory provided a good prediction of lift and drag of sharp-edged planar wings near the ground in comparison with static wind-tunnel data. The works of Kemp,[7] Katz and Levin,[8] and Rolls and Koenig,[9] show that the current theoretical methods, static wind-tunnel tests, and flyby flight tests are in reasonable agreement.

Although for highly swept low-aspect-ratio wings, theoretical predictions, static wind-tunnel data, and flyby flight test data are in reasonable agreement, both calculations and experiments were for constant height and do not agree with flight test landing data. Schweikhard[10] and Baker et al.[11] obtained landing data with the aircraft making an approach at constant angle of attack and constant power setting. Five aircraft were tested: F5D-1, F5D-1 with a modified ogee wing, XB-70-1, XB-70-2, and F-104A. As the landing approaches were made, significant changes were found in lift, drag, and pitching moment. The magnitude of these changes did not agree with theoretical and wind-tunnel predictions, indicating a major effect of the sink rate, or so-called dynamic effect, not included in the previous investigations.

This paper reports on the description of a method to simulate the dynamic landing condition in the wind tunnel. It compares the dynamic wind-tunnel data with static wind-tunnel data in ground effect and the flight test data of Baker et al.[11] Complete details and results are available in Ref. 12. Limited flow visualization tests were conducted to provide preliminary study of the phenomena involved in dynamic ground effect.

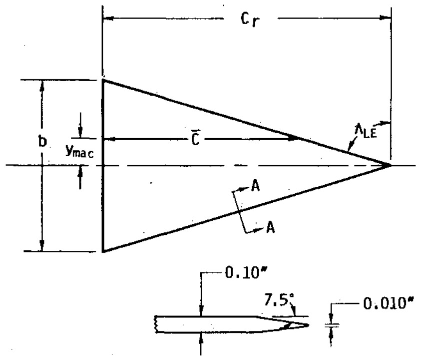
II. Models, Apparatus, and Procedure

Five model wings were tested: 60-, 70-, and 75-deg delta, F-104A, and XB-70 wings (Figs. 1-3). The models were

Received Aug. 14, 1986; revision received Sept. 17, 1986.

*Supervisor, Aerodynamics Department.

†Chairman, Department of Aerospace Engineering. Associate Fellow AIAA.



Wing Model	60° Delta	70° Delta	75° Delta
b(feet)	0.833	0.833	0.803
Cr(feet)	0.722	1.145	1.500
C̄(feet)	0.481	0.763	0.799
y_{mac} (feet)	0.139	0.139	0.134

Fig. 1 Model geometry, delta wings.

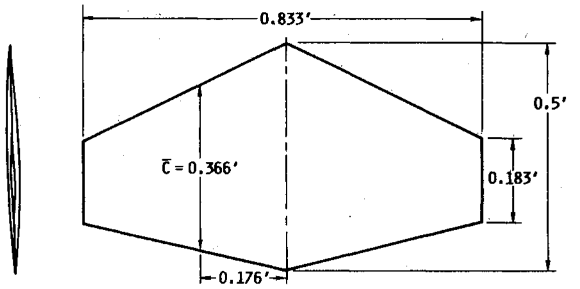


Fig. 2 Model geometry, F-104A wing.

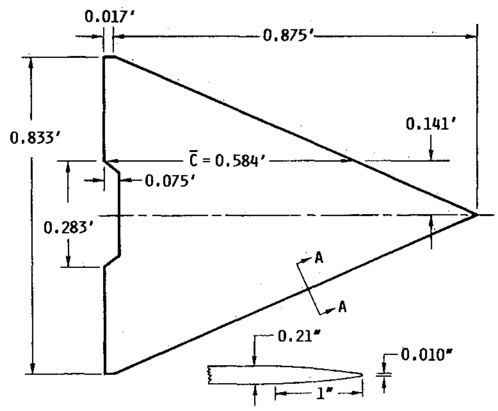


Fig. 3 Model geometry, XB-70 wing.

mounted to a sting support (Fig. 4) through a bracket that determined the angle of attack for the test. The sting support strut was mounted vertically in the wind tunnel in two linear bearings. (Figs. 5 and 6). The sting was free to move vertically between limiting stops. The sting and wing were statically counterbalanced by an external mass. By moving the mass downward, the wing moved upward in the tunnel toward a ground board. No attempt was made to simulate flare and/or change angle of attack during vertical movement. The wing was allowed to pass through a spring-loaded door in the ground board at a steady sinking rate. The final travel of the sting was cushioned as the wing began to open the spring-loaded door.

Both static and dynamic tests were conducted on the five model wings. A test Reynolds number of 7×10^5 was maintained by adjusting wind-tunnel speed. Static tests were conducted at angles of attack of 4, 8, 10, 15, 20, 28, 30, 32, and 34 deg at heights above the ground plane of 1.25, 0.50, 0.33, 0.25, 0.15, 0.125, 0.075, and 0.062 ft. The 1.25-ft position was approximately out of the ground effect.

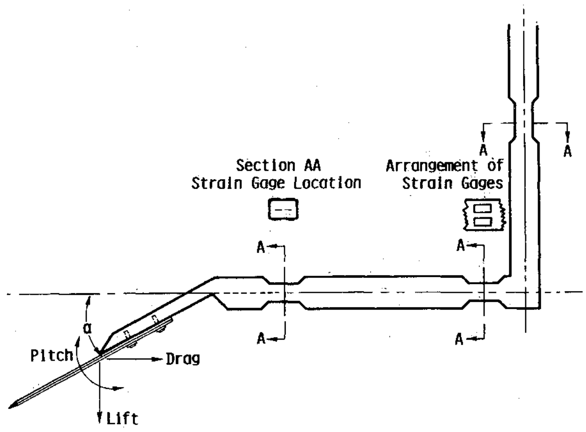


Fig. 4 Sting support and strain gage arrangement.

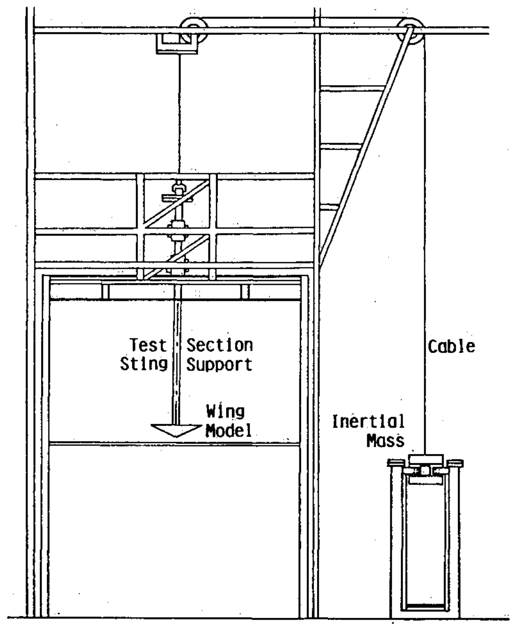


Fig. 5 Airstream view of test stand.

Dynamic tests were made at angles of attack of 10, 15, 20, 24, and 28 deg at three sink speeds: 2, 4, and 6 ft/s. These provided flight path angles of 0.67, 1.33, and 2.00 deg. The F-104A and XB-70 wings were also tested at 4 and 8 deg in order to compare with available flight data at an angle of attack of 9.3 deg, based on the flight path.

Flow visualization tests were made with neutrally buoyant helium bubbles (Fig. 7) and tufted wire grid.

III. Results and Discussion

Figures 8–10 present the percentage change of lift, drag, and pitching moment with height above the ground board for the 79-deg delta wing at an angle of attack of 22.1 deg. As the minimum ground height was approached, the static tests yielded almost 100% increase in lift, 55% increase in drag, and 100% increase in pitching moment (negative) over the dynamic test values.

Lift data for the F-104A are given in Figs. 11 and 12. In Fig. 11 the static wind-tunnel data, dynamic wind-tunnel data, and flight-test data show the same trend with change in angle of attack at a given height. The data are nearly of the same magnitude. The increase in lift in ground effect over lift out of ground effect decreases rapidly with increasing angle of attack. A comparison of the F104-A data at a constant angle of attack and changing ground height shows close agreement between the three sets of test data and Lan's[13] quasi-vortex-lattice method.

Lift data for the XB-70 are presented in Figs. 13–15. The dynamic wind-tunnel data (Fig. 13) show close agreement with the flight-test data at an angle of attack of 9.3 deg. Below a height of one-half wingspan above the ground, the static wind-tunnel data show a rapid increase in lift over the dynamic data. At an h/b of 0.4 and below, the flight-test data and the dynamic wind-tunnel data show much better agreement than either show with the static wind-tunnel test data.

Figures 16 and 17 summarize the ground effect data for the five wings tested at an angle of attack of 12.1 deg and an h/b of 0.3 and 0.4. It can readily be seen that the dynamic effects play an increasing role on lift as sweepback is increased and aspect ratio is decreased. The F-104A data display only a small variation due to the dynamic conditions. The XB-70, 70-deg delta, and 75-deg delta wings show a large difference between the static and dynamic data.

A tufted wire grid behind the 70-deg delta wing was observed during static and dynamic tests by use of a video camera. The lateral locations of the vortex core centers during the tests were determined and plotted as shown in Fig. 18. The dynamic tests were made at a fixed wing angle of at-

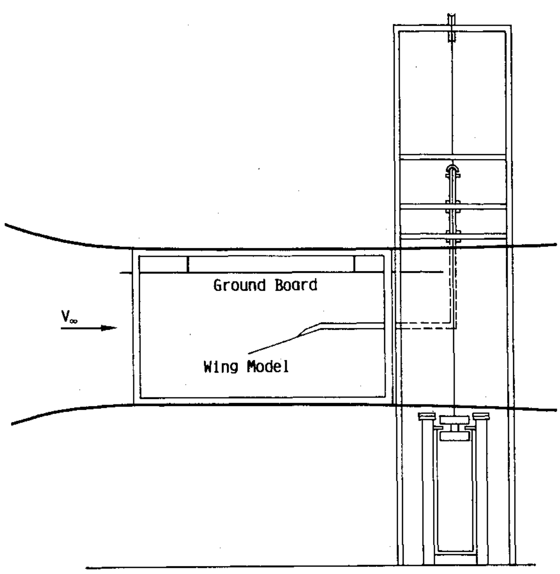


Fig. 6 Side view of test stand.

Fig. 7 Flow visualization using helium bubbles.

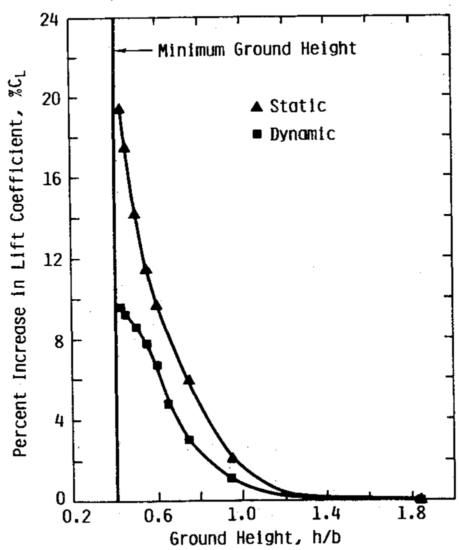


Fig. 8 Comparison of lift increments for static and dynamic wind-tunnel ground effect data for 70-deg delta wing at 22.1-deg angle of attack and $\dot{h}/V_\infty = 2$.

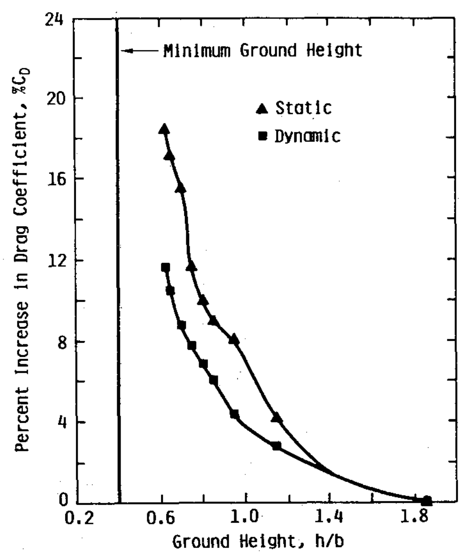


Fig. 9 Comparison of drag increments for static and dynamic wind-tunnel ground effect data for 70-deg delta wing at 22.1-deg angle of attack and $\dot{h}/V_\infty = 2$.

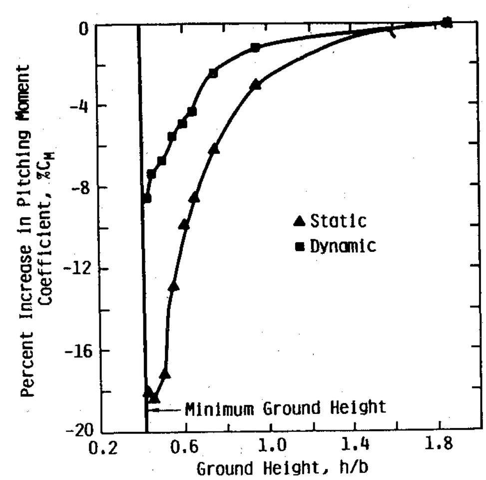


Fig. 10 Comparison of pitching moment increments for static and dynamic wind-tunnel ground effect data for 70-deg delta wing at 22.1-deg angle of attack and $\dot{h}/V_\infty = 2$.

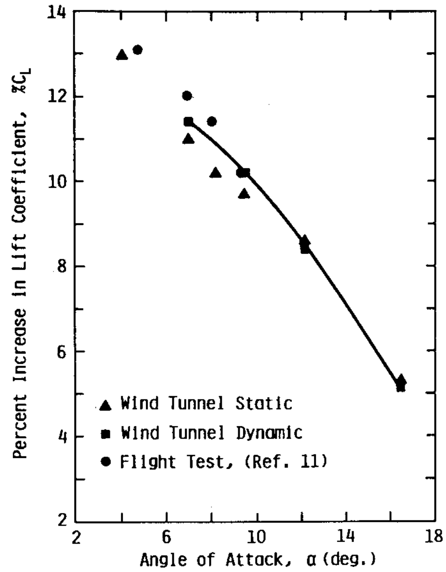


Fig. 11 Comparison of lift increments for static and dynamic wind-tunnel data with flight test data for F-104A, $h/b=0.40$.

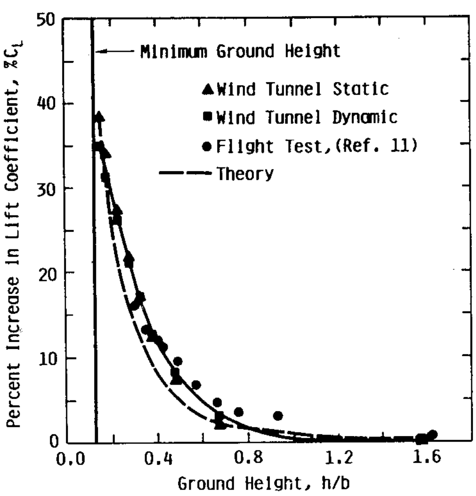


Fig. 12 Comparison of lift increments for static and dynamic wind-tunnel data with flight test and vortex-lattice calculations (Ref. 13) for F-104A at 6.9-deg angle of attack.

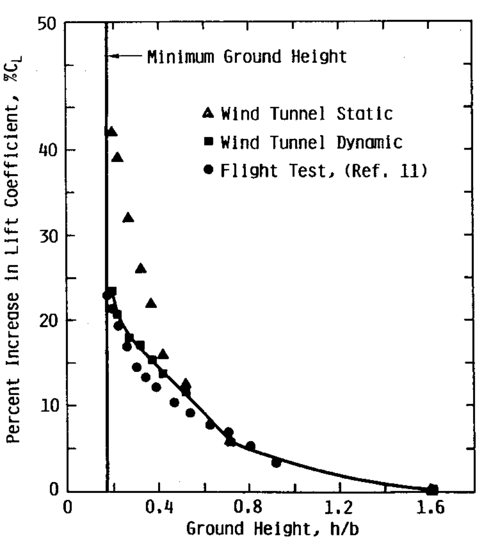


Fig. 13 Comparison of lift increments for static and dynamic wind-tunnel data with flight test data for XB-70 at 9.3-deg angle of attack.

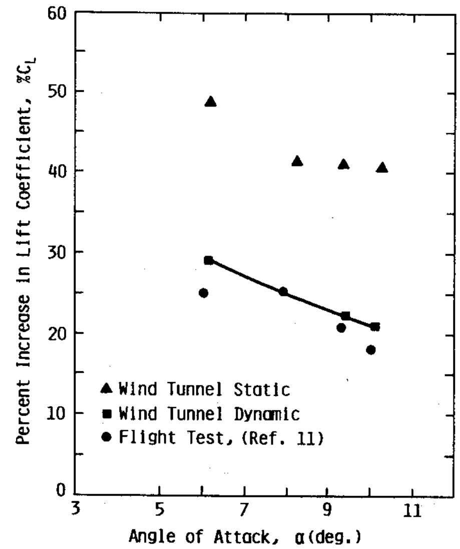


Fig. 14 Comparison of lift increments for static and dynamic wind-tunnel data with flight test data for XB-70, $h/b=0.20$.

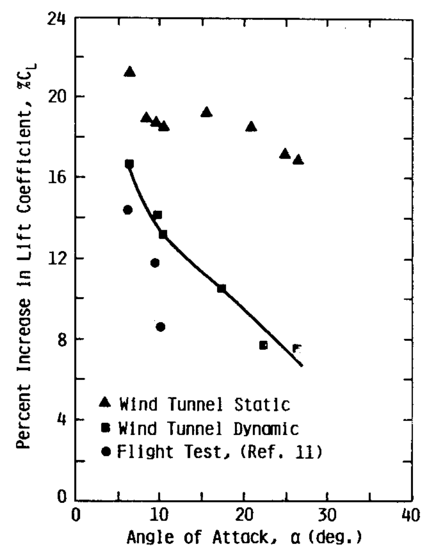


Fig. 15 Comparison of lift increments for static and dynamic wind-tunnel data with flight test for XB-70, $h/b=0.40$.

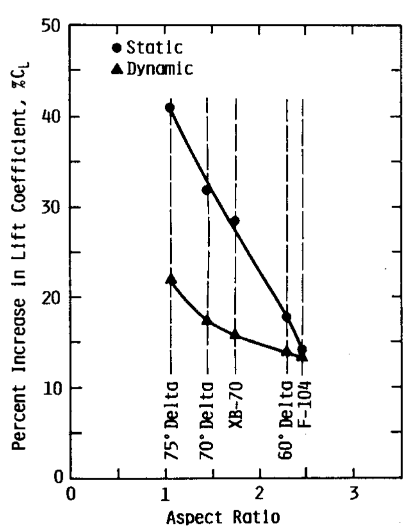


Fig. 16 Incremental lift coefficient vs aspect ratio for static and dynamic ground effect measured in the wind tunnel at 12.1-deg angle of attack and $h/b=0.3$.

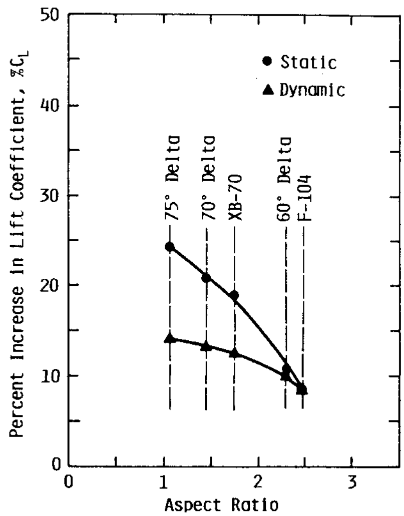


Fig. 17 Incremental lift coefficient vs aspect ratio for static and dynamic ground effect measured in the wind tunnel at 12.1-deg angle of attack and $h/b=0.4$.

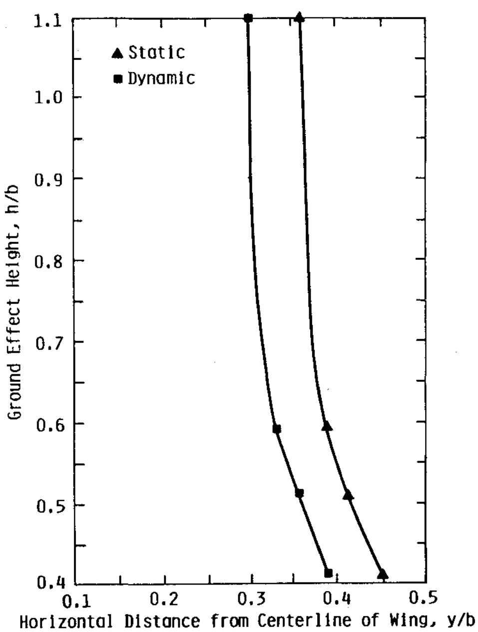


Fig. 18 Comparison of location of the vortex core center for static and dynamic ground effect for 70-deg delta wing at 22-deg angle of attack.

tack of 20 deg. The comparison shows that during the dynamic testing the vortices have moved inboard relative to the static test positions. The change in vertical position was not accurately determined.

As shown by these results, the vortex behavior affects the lift, drag, and pitching moment of the wing. The limited tufted wire grid tests demonstrated that vortex lag occurred during the dynamic tests. During these limited visual tests, vortex breakdown did not occur in the proximity of the wing. Further experimental investigations are needed to determine the strength and position of the vortices under various conditions.

A comparison of the limited flight test data on the B-70, static wind-tunnel data, and dynamic wind-tunnel data indicates that the method of dynamic testing developed provides more realistic data in the landing phase than the static wind-tunnel data in ground effect.

IV. Conclusions

The dynamic wind-tunnel simulation that was developed provided a method to simulate the landing condition more realistically than either static wind-tunnel testing in ground effect or constant altitude flyby testing.

A significant dynamic effect was found for highly swept delta wings, and good correlations of the effect were obtained between wind-tunnel and flight data. The wing vortices exhibited a lag during the dynamic tests.

Acknowledgments

The authors wish to express their appreciation to Dr. Chuan-Tau Edward Lan for his advice and assistance during the investigation.

References

[1]Weiselsberger, C., "Wing Resistance Near the Ground," NACA TM77, April 1922.

[2]Tani, I., Taima, M., and Simidu, S., "The Effects of Ground on the Aerodynamic Characteristics of a Monoplane Wing," Tokyo Imperial University, Japan, Aero Research Institute Rept. 156, Sept. 1937.

[3]Choliasmenos, C. J., "An Experimental Investigation and Theoretical Analysis of the Ground Effect on the Lift of a Wing With and Without Boundary Layer Control," Thesis, Univ. of Kansas, Lawrence, 1962.

[4]Abercrombie, J. M., "The Lift of High Circulation Wings in Ground Effect," Thesis, Missouri Univ., St. Louis, 1967.

[5]Fox, C. H., "An Analytical Method for Predicting the Lift and Drag for Slender Sharp-Edge Delta Wings in Ground Proximity," M.S. Thesis, Virginia Polytechnic Institute and State Univ., Blacksburg, 1969.

[6]Fox, C. H., "Prediction of Lift and Drag for Slender Sharp-Edge Delta Wings in Ground Proximity," NASA TN D-4891, 1969.

[7]Kemp, W. P., Lockwood, V. E., and Phillips, W. P., "Ground Effects Related to Landing of Airplanes With Low-Aspect-Ratio Wings," NASA TN D-3583, Oct. 1966.

[8]Katz, J. and Levin, D., "Measurements of Ground Effect for Delta Wings," *Journal of Aircraft,* Vol. 21, June 1984, pp. 441–443.

[9]Rolls, L. S. and Koenig, D. G., "Flight Measured Ground Effect on a Low-Aspect-Ratio Ogee Wing Including a Comparison With Wind-Tunnel Results," NASA TN D-3431, 1966.

[10]Schweikhard, W., "A Method for In-Flight Measurement of Ground Effect on Fixed-Wing Aircraft," *Journal of Aircraft*, Vol. 4, March–April 1967, pp. 101–104.

[11]Baker, P., Schweikhard, W., and Young, W., "Flight Evaluation of Ground Effect on Several Low-Aspect-Ratio Airplanes," NASA TN-D-6053, Oct. 1970.

[12]Chang, R. C., "An Experimental Investigation of Dynamic Ground Effect," Dissertation, Univ. of Kansas, Lawrence, 1985.

[13]Lan, C. E., "VORSTAB—A Computer Program for Calculating Lateral-Directional Stability Derivatives with Vortex Flow Effect," NASA CR-172501, Jan. 1985.