View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by NASA Technical Reports Server

NASA Technical Memorandum 101708

An In-Flight Investigation of Ground Effect on a Forward-Swept Wing Airplane

Robert E. Curry, Bryan J. Moulton, and John Kresse
Ames Research Center, Dryden Flight Research Facility, Edwards, California

1989

NASA
National Aeronautics and Space Administration
Ames Research Center
Dryden Flight Research Facility
Edwards, California 93523-5000

AN IN-FLIGHT INVESTIGATION OF GROUND EFFECT ON A FORWARD-SWEPT WING AIRPLANE

Robert E. Curry, Bryan J. Moulton, and John Kresse
NASA Ames Research Center
Dryden Flight Research Facility
P.O. Box 273
Edwards, California 93523-5000
U.S.A.

SUMMARY

A limited flight experiment was conducted to document the ground-effect characteristics of the X-29A research airplane. This vehicle has a unique aerodynamic planform which includes a forward-swept wing and close-coupled, variable incidence canard. The flight-test program obtained results for errors in the airdata measurement and for incremental normal force and pitching moment caused by ground effect. Correlations with wind-tunnel and computational analyses were made.

The results are discussed with respect to the dynamic nature of the flight measurements, similar data from other configurations, and pilot comments. The ground-effect results are necessary to obtain an accurate interpretation of the vehicle's landing characteristics. The flight data can also be used in the development of many modern aircraft systems such as autoland and piloted simulations.

NOMENCLATURE

AGL	above ground level
APAS	aerodynamic preliminary analysis system
b	span, ft
C_{L_∞}	lift coefficient, out-of-ground-effect
C_{N_∞}	normal force coefficient, out-of-ground-effect
h	height of airplane above minimum height, wheels on ground, ft
$\dot{h}$	vertical velocity, ft/sec
NASA	National Aeronautics and Space Administration
PANAIR	panel aerodynamics
q	pitch angular rate, deg/sec
α	angle of attack, deg
$\Delta C_{A_{GE}}$	axial force coefficient increment caused by ground effect
$\Delta C_{L_{GE}}$	lift coefficient increment caused by ground effect
$\Delta C_{m_{GE}}$	pitching moment coefficient increment caused by ground effect, reference center of gravity
$\Delta C_{N_{GE}}$	normal force coefficient increment caused by ground effect
$\Delta h_{p_{GE}}$	pressure altitude measurement error caused by ground effect, ft
δ_C	canard position, positive trailing-edge down, deg
δ_{STK}	longitudinal control stick position, positive aft, in.

1. INTRODUCTION

An understanding of ground effects is important for the development of many modern aircraft systems and for accurate interpretation of vehicle flying qualities. These data must include the ground effects on total vehicle forces and moments as well as perturbations of aerodynamic (angle-of-attack (α) and airspeed) sensors which may be used for control system feedback. Valid analytical models of these effects are required to support high fidelity simulators, used for flight-time equivalent pilot training. These models are also required in the development of advanced flight control systems such as autoland.

Ground effects for a variety of planform types such as aft-swept, delta, and low-aspect-ratio wings have been studied in the past (refs. 1–4). Recent studies (refs. 5–7) have indicated substantial variations between ground effects determined from steady-state conditions (constant height above ground) and dynamic conditions (such as landing approaches). Flight testing allows the determination of ground effects under dynamic conditions, which are typically not simulated in wind tunnels or computational analysis.

The X-29A forward-swept wing research airplane was developed and flight-tested to evaluate several concepts for application on future fighter aircraft. A general overview of the goals of the project can be found in references 8 and 9. As part of the flight-test program, a series of maneuvers was conducted to determine the ground effects related to this unique configuration. Flight data were obtained at angles of attack from 6.5 to 8.5° and indicated airspeeds from 145 to 160 kn.

Flight data were obtained from onboard sensors and a ground based optical tracking system during shallow approaches to the runway. The analysis included balancing the vehicle forces and moments and correcting for pilot inputs during the maneuvers. The data were correlated with a limited set of wind-tunnel data, obtained with a fixed ground board in a low-speed wind tunnel. In addition, two numerical techniques, aerodynamic preliminary analysis system (APAS) and panel aerodynamics (PANAIR), were also applied to the configuration in ground effect. The APAS code (ref. 10) uses a constant-pressure panel method with limited modelling capability. The PANAIR code (ref. 11) is a higher-order panel method which offers greater modelling capability but requires more computer resources and user effort.

This paper presents the flight data and compares the results with the wind-tunnel and theoretical predictions. In addition, the results are discussed with respect to the dynamic nature of the flight measurements, data from other configurations, and pilot comments regarding X-29A aircraft landing characteristics.

2. VEHICLE DESCRIPTION

The test vehicle is shown in figure 1. Table 1 gives a summary of the physical characteristics. A more complete description of the vehicle is given in reference 9. The most unusual external features include the forward-swept wing and close-coupled, variable incidence canard. The configuration has relaxed longitudinal static stability which requires the use of a highly augmented digital flight control system. The wing has a full-span trailing-edge flap. Pitch is controlled through a scheduled combination of the canard, wing trailing-edge flap, and the strake flap surfaces (fig. 1). In the "power approach" control system mode, the wing flap and gear are fixed in the down position and pitch control is achieved by the canard and strake flap surfaces. The airdata sensors used in this study were installed on a noseboom.

3. MEASUREMENTS

The principal onboard measurements in this study were inertial rates and accelerations, control surface positions, airdata, and fuel quantities. The data were encoded by a pulse code modulation system with 10-bit resolution and were telemetered to a ground station. The flight data were obtained at rates up to 200 samples/sec. Further details regarding the data acquisition system are found in reference 9.

A cine-theodolite (optical tracking) system was used to determine aircraft position with respect to a fixed ground reference system (ref. 12). Two calibrated motion picture cameras tracked the aircraft as it maneuvered close to the runway. The tracking provided elevation and azimuth values referenced to each camera location. Triangulation of these measurements determined aircraft position. Sink rate, flightpath angle, and other pertinent parameters were derived from the position data. The accuracy of the measurements depended on the distance between the aircraft and the camera installations. Because of the small size of the X-29A aircraft and the shallow approaches used in this experiment, good optical data were available only for approximately the last 50 ft of descent. The optical data were obtained at a rate of 4 samples/sec.

4. FLIGHT MANEUVERS

All maneuvers were flown by the same general procedure, similar to that described in reference 13. While at a constant altitude in the landing pattern, the pilot selected the power approach configuration (wing flap and gear down) normally used for landing the airplane. After the airplane was aligned with the runway, the pilot established a shallow descent at a predetermined sink rate, and optical tracking began. During the descent the pilot minimized use of the control stick and throttle. As the airplane approached the runway and responded to ground effect, the pilot tried to maintain a constant indicated angle of attack using pitch stick inputs. On some maneuvers, the throttle was reduced in order to ensure touchdown. When the airplane leveled off or the main gear touched down, the optical tracking was terminated and the pilot conducted a "go around" maneuver. Ground-effect maneuvers were not attempted if surface winds exceeded 5 kn in any direction.

Figure 2 shows a time history of key parameters from a typical maneuver. In this example, the angle of attack, pitch rate, and canard position indicate an oscillation in the pitch axis during the first few seconds, probably caused by small flightpath adjustments or atmospheric turbulence (note the small amplitude of stick movement). As the airplane descends below 15 ft above ground level (AGL), it begins to flare, as the altitude and vertical speed data show. At the same time, the angle of attack generally decreases, indicating that additional lift is being generated because of ground effect. During the last 10 ft of vertical descent, stick commands diminish while the canard moves to a more positive (trailing-edge down) deflection. This movement is produced by the flight control system. The strake flap surface movement, not shown, is inversely proportional to the canard movement.

A total of 10 maneuvers were attempted over a series of four nonconsecutive test flights. Of these, four maneuvers were not analyzed because of gaps in the optical tracking data or excessive control inputs. For all maneuvers, the normal force coefficient ranged from 0.95 to 1.15 and angle of attack ranged from 6.5 to 8.5° prior to entering ground effect. Because of the limited flight time available for this study, a wider variety of flight conditions was not attempted, and the pilots had little opportunity to practice the technique.

For several reasons, the flight maneuver was a difficult task to perform with precision. In order to maintain quasi-steady flight conditions, the pilot had to monitor the angle-of-attack display inside the cockpit, while simultaneously verifying a safe approach to the runway. The maneuver relies on the increased lift caused by ground effect to help flare the airplane and provide an acceptable touchdown sink rate. The pilot does not experience this effective ground-effect cushion until the last few seconds of the descent.

As a safety precaution, on the first attempts the targeted descent rates prior to encountering ground effect were very shallow (approximately 100 ft/min). As confidence increased, the targeted descent rates were increased to 500 ft/min. In all maneuvers, the sink rate decreased substantially as the airplane descended below about 15 ft AGL ($h/b = 0.55$).

The pilots attempted to conduct the maneuvers near the midpoint of the runway in order to minimize distance from the tracking camera installations (fig. 3). Because of the shallow sink rates, it was difficult for the pilot to visually plan his descent to touchdown near the midpoint. On the last flight, ground radar tracking data, monitored in the control room, was successfully used to advise the pilot when to begin his descent. Figure 3 also shows the distance along the runway for the various maneuvers relative to the runway threshold.

5. FLIGHT DATA ANALYSIS

Data from the optical tracking system and aircraft telemetry stream were merged by linearly interpolating the telemetered data to fit the optical data sample times. The center of gravity, weight, and inertias were computed from the fuel quantity data. The acceleration and angular rate measurements were adjusted to the flight center of gravity. The noseboom static pressure and angle-of-attack vane measurements were adjusted for upwash and position error using corrections developed from "out-of-ground-effect" (altitudes above the point where ground effect influences aircraft behavior) flight calibrations. These calibrations were obtained from tower fly-by, radar tracking, and trajectory reconstruction techniques. The accuracy of the static pressure error calibration is approximately 20 ft (pressure altitude).

The effects of ground proximity on airdata measurements were determined by comparing the onboard aerodynamic sensor data (noseboom angle-of-attack vane and static pressure) to data from independent, nonaerodynamic, sources (optical tracking and inertial sensors). Pressure altitude above ground was determined by subtracting the current ground-level ambient pressure from the noseboom static pressure. The test site is at an altitude of approximately 2,300 ft above sea level. Altitude above ground was also determined from nonaerodynamic sensors by subtracting the runway altitude from the optically measured altitude. The runway was modeled as a sloped surface defined in three dimensional space. The optically measured altitude at touchdown on several runs showed the method to be accurate to within 1 ft. An angle-of-attack measurement which does not rely on aerodynamic sensors was made from a combination of the onboard pitch attitude data and the flightpath angle determined from optical tracking data.

The total vehicle normal force, axial force, and pitching moment were determined from the mass, inertias, and accelerations. These values include all aerodynamic forces (including ground effect) and thrust. The pitching moment was adjusted to the reference center of gravity. The contributions of out-of-ground-effect aerodynamics were estimated by the use of a nonlinear aerodynamic database developed from wind tunnel data. This database accounts for control surface positions, angle of attack, angle of sideslip, and pitch rates and has been extensively validated with flight-test results. The database estimates were subtracted from the flight measured forces and moments. The difference generally included a constant offset in the data at altitudes above ground effect. This offset was attributed to the effects of thrust or discrepancies in the database and was subtracted from the results. A nine-point moving average technique was used to fair the final data. This process eliminated extraneous variations in the data from sources such as gusts or inaccuracies in the nonlinear aerodynamic model. Figure 4 shows normal force coefficient data for a typical maneuver.

6. RESULTS AND DISCUSSION

6.1 Airdata Measurements

The difference between noseboom measured pressure altitude AGL and the optically measured altitude AGL represents the static pressure measurement error caused by ground effect (Δh_{PGE}). Results from two maneuvers (fig. 5), indicate an error of up to 7 ft at touchdown. This magnitude is consistent with results from other noseboom systems (ref. 14). The two maneuvers shown in figure 5 were conducted with constant throttle setting. Useful results were not obtained from the other four test maneuvers, which included variations in throttle setting. Changes in engine thrust level appear to produce static pressure measurement errors of sufficient magnitude to mask the errors caused by ground effect.

The comparison of angle-of-attack measurements from the aerodynamic sensor (noseboom vane) to those from nonaerodynamic sensors indicated no sensitivity to ground proximity. After this was determined, the angle-of-attack vane measurement was used in the analysis of the force and moment data.

6.2 Normal Force

Figure 6 shows the flight measured normal force increments from the six analyzed maneuvers. The data indicate that ground effect is negligible at altitudes above 15 ft AGL, or 0.55 h/b. The maximum normal force increment (at touchdown) is about 17-percent greater than the out-of-ground-effect normal force coefficient. The consistency of the results from different maneuvers is excellent. Throttle adjustments were made during three of the maneuvers, but had no significant effect on the data.

The wind tunnel data shown in figure 6 were obtained at an angle of attack of 8° with control surface positions typical of the flight maneuvers (−5°-canard deflection, −12°-strake flap deflection).

The PANAIR program was used to determine the sensitivity of the panel method ground-effect predictions to modelling features for this configuration. In this limited PANAIR analysis, features such as the camber distribution and the orientation of wakes from the wing and canard were varied. The results indicated no strong sensitivities in the ground-effect increments; therefore, the remainder of the analysis was based on a simple flat plate model of the X-29A aircraft planform using the APAS code. As figure 6 shows, the APAS results, using a flat plate model, agree favorably with the wind tunnel data; however, both indicate larger ground effect than the flight data.

The wind tunnel and panel methods are based on a steady aerodynamic configuration at constant height above the ground. The lower normal force increments observed in flight could be the result of a lag in the aerodynamic flow field as the airplane approached the ground. Figure 7 shows the flight measured normal force increments as a function of the vertical velocity at $h = 9$ ft AGL. There is a slight indication that the normal force increments approach the steady-state data as the sink rate decreases. However, vertical velocity varied continuously during the flight maneuvers, and the data of figure 7 are based only on the instantaneous value of sink rate. It was not possible to obtain flight data at a constant sink rate throughout a flight maneuver for two reasons. First, the reduction in sink rate is at least partially a result of ground effect, and second, it is clearly necessary to have a low sink rate at touchdown.

Figure 8 shows the X-29A airplane ground-effect data compared with steady-state and dynamic wind tunnel data from other configurations, compiled in reference 5. The dynamic data for the XB-70 and F-104 airplanes were validated with flight-test measurements. Figure 8 shows that the differences caused by dynamic effects can be as significant as differences caused by planform variations. All configurations show a decrease in the ground effect caused by dynamics, although this decrease is minimal for the F-104 aircraft.

6.3 Pitching Moment and Axial Force

The flight and wind tunnel measurements of pitching moment increment caused by ground effect are shown in figure 9. It was found that even slight power adjustments during the flight maneuvers produced pitching moments which masked the ground-effect characteristics. Therefore, data from several maneuvers which included power adjustments could not be used. The flight data show variations at altitudes well above 30 ft AGL (out-of-ground-effect), presumably because of turbulence or other features which were not accounted for in the analysis. The magnitude of the ground-effect increments are small with respect to the total untrimmed pitching moments at these conditions, which may also account for some of the scatter in the flight data. The ground-effect increment at 9 ft AGL is about 0.01 nose down, equivalent to the pitching moment created by an angle-of-attack change of only 0.3°.

The flight and wind-tunnel data agree poorly. The discrepancies may be because of dynamic maneuver effects, as discussed in the normal force data, or the use of a static ground plane in the wind tunnel testing. The data are insufficient to explain the poor correllation of results. In figure 10, flight and wind-tunnel data at a height of 9 ft AGL are shown as a function of angle of attack.

Flight measurements of axial force increments caused by ground effect were inconclusive. The measurements were clearly sensitive to any variation in power setting and no reasonable trends could be developed from the data. Wind-tunnel measurements of axial force, also shown in figure 10, indicate that values at the flight-test conditions may be very small with respect to axial force of the total vehicle.

6.4 Pilot Comments Related to Landing

During early flight tests of the X-29A airplane, pilots commented that the airplane tends to float excessively if the landing flare is initiated too early, requiring the pilot to force the airplane down with forward stick inputs. As discussed in reference 15, this undesirable characteristic has been identified in other aircraft which, like the X-29A, incorporate pitch rate command, attitude hold flight control systems.

Data from the present analysis indicate moderate levels of lift and nosedown pitching moments caused by ground effect. It should be noted that the canard generates positive trim lift when used to balance nosedown ground-effect pitching moments. This is contrary to most configurations with aft-located longitudinal control surfaces. This additional trim lift may account for some of the float tendencies noted by the pilots.

7. CONCLUDING REMARKS

The flight-test program was successful in determining ground effects related to airdata measurements, normal force, and pitching moment of the X-29A airplane. The results were obtained from a minimal amount of total flight time (ten landing approaches). A longer flight program may have allowed a wider variation of flight conditions and would have allowed greater pilot proficiency in conducting the test maneuver.

The static pressure measurement error caused by ground effect was identified and is consistent with other aircraft which use noseboom systems. The angle-of-attack measurement was found to be insensitive to ground effect. The flight-measured normal forces in ground effect were up to 17-percent greater than the out-of-ground-effect values. The increases predicted by computational or wind-tunnel methods were substantially greater than those encountered in flight. This discrepancy has been demonstrated for other configurations and has been attributed to the dynamic nature of the flight maneuver. The difference between dynamic and steady-state ground-effect results can be of equal magnitude to differences related to configuration.

REFERENCES

1. Furlong, G. Chester, and Thomas V. Bollech, National Advisory Committee on Aeronautics, *Effect of Ground Interference on the Aerodynamic and Flow Characteristics of a 42 Degree Sweptback Wing at Reynolds Numbers up to* 6.8×10^6, 1955, Technical Report 1218.
2. Baker, P.A., W.G. Schweikhard, and W.R. Young, NASA, *Flight Evaluation of Ground Effect on Several Low-Aspect-Ratio Airplanes*, 1970, TN D-6053.
3. Rolls, L. Stewart, and David G. Koenig, NASA, *Flight-Measured Ground Effect on a Low-Aspect-Ratio Ogee Wing Including a Comparison With Wind-Tunnel Results*, 1966, TN D-3431.
4. Snyder, C. Thomas, Fred J. Drinkwater III, and A. David Jones, NASA, *A Piloted Simulator Investigation of Ground Effect on the Landing Maneuver of a Large, Tailless, Delta-Wing Airplane*, 1970, TN D-6046.
5. Chang, Ray Chung, and Vincent U. Muirhead, NASA, "Investigation of Dynamic Ground Effect," *Proc. NASA ARC Ground-Effects Workshop*, 1985, CP-2462.
6. Kemmerly, Guy T., and John W. Paulson, Jr., "Exploratory Evaluation of Moving-Model Technique for Measurement of Dynamic Ground Effects," *J. Aircraft*, vol. 25, no. 6, June 1988, pp. 557–562.
7. Lee, Pai-Hung, C. Edward Lan, and Vincent U. Muirhead, "Experimental Investigation of Dynamic Ground Effect," *J. Aircraft*, vol. 26, no. 6, June 1989, pp. 497–498.
8. Putnam, Terrill W., NASA, *X-29 Flight Research Program*, 1984, TM-86025.
9. Sefic, W., and C. Maxwell, NASA, *X-29A Technology Demonstrator Flight Test Program Overview*, 1986, TM-86809.

10. Bonner, E., W. Clever, and K. Dunn, NASA, *Aerodynamic Preliminary Analysis System II, Part I - Theory*, 1981, CR-165627.

11. Carmichael, R. L., and L.L. Erickson, AIAA, "PANAIR - A Higher Order Panel Method for Predicting Subsonic or Supersonic Linear Potential Flows About Arbitrary Configurations," June 1981, 81-1255.

12. Taylor, Albert E., U.S. Air Force Flight Test Center, "Evaluation of Take-off and Landing Facility," 1958, Tech. Memo. FTFF-TM-58-12.

13. Schweikhard, W.G., "A Method for In-Flight Measurement of Ground Effect on Fixed-Wing Aircraft," *J. Aircraft*, vol. 4, no. 2, Mar.–Apr. 1967, pp. 101–104.

14. Parks, Edwin K., NASA, *Flight-Test Measurement of Ground Effect for Powered-Lift STOL Airplanes*, 1977, TM-73256.

15. Gera, J., NASA, *Dynamics and Controls Flight Testing of the X-29A Airplane*, 1986, TM-86803.

Table 1. Physical characteristics of the X-29A aircraft.

Reference area, ft^2	185.0
Reference span, ft	27.2
Reference chord, ft	7.215
Aspect ratio	4.0
Quarter chord wing sweep angle, deg	−33.73
Reference center of gravity	Fuselage station 451
Empty weight, lb	13,948
Useful load, lb	3,882
Fuel load, lb	3,662
Gross weight, lb	17,830
Engine	GE-404-400
Sea-level static thrust, lb	16,012

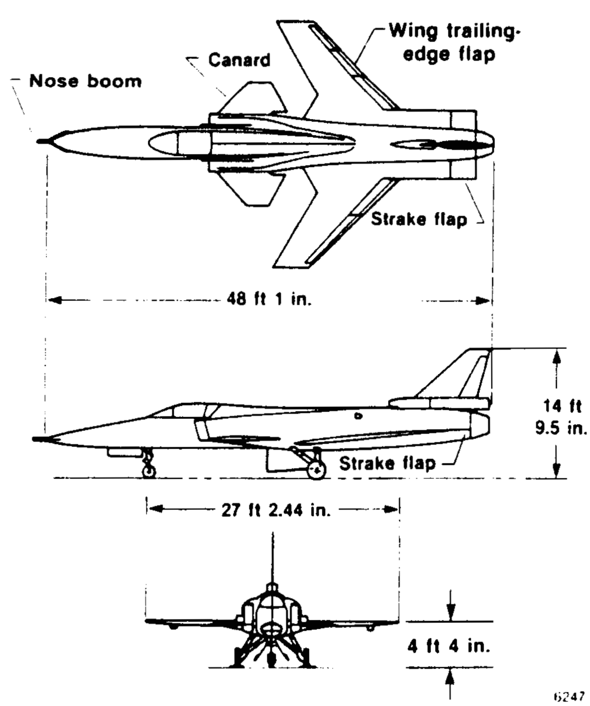

Figure 1. The X-29A airplane.

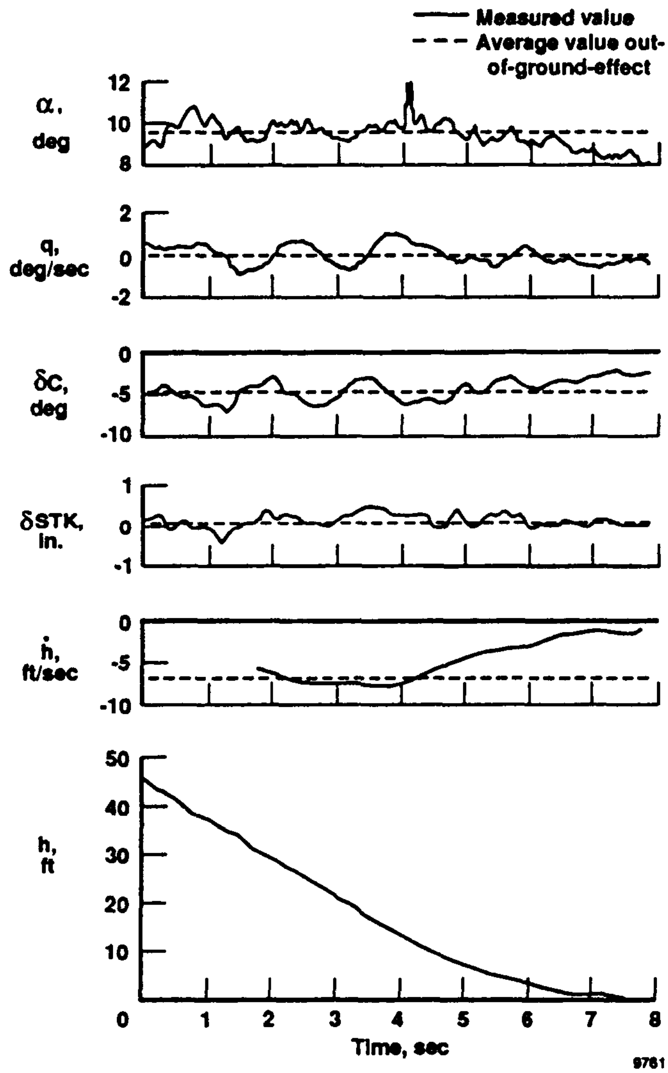

Figure 2. Time history of ground-effect flight-test maneuver.

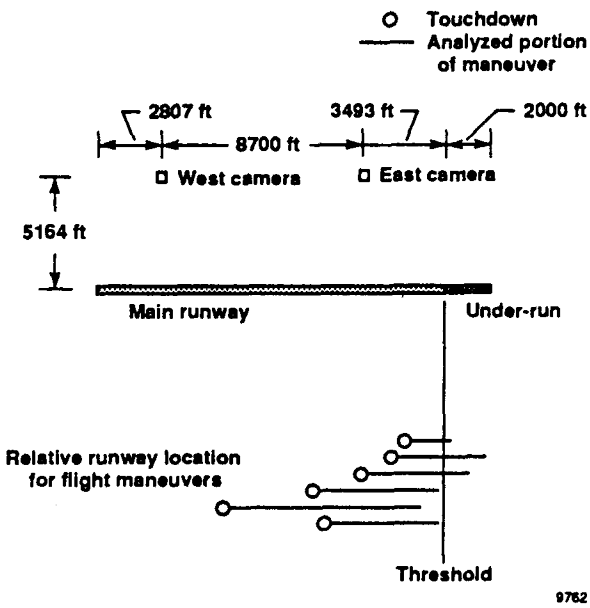

Figure 3. Runway and optical tracking system layout and relative location of ground-effect maneuvers.

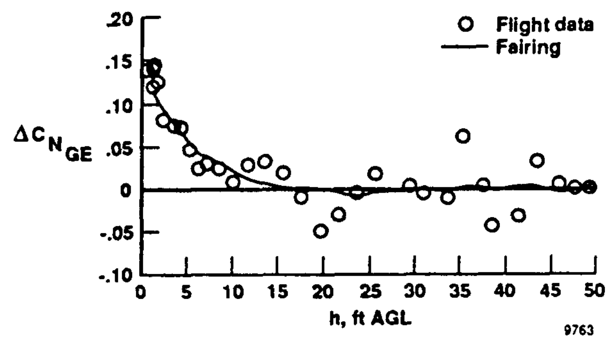

Figure 4. Flight data with fairing.

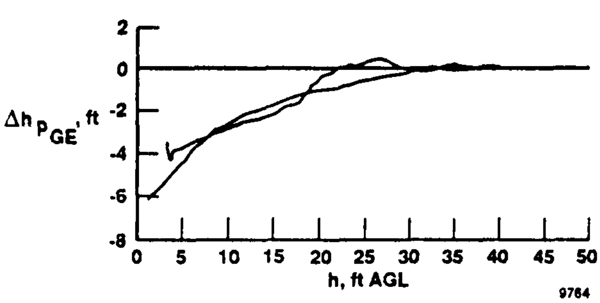

Figure 5. The $\Delta h_{p_{GE}}$ during two maneuvers.

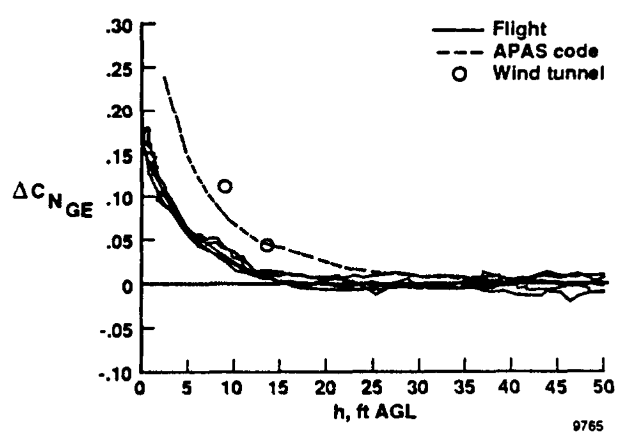

Figure 6. The $\Delta C_{N_{GE}}$ as a function of height AGL.

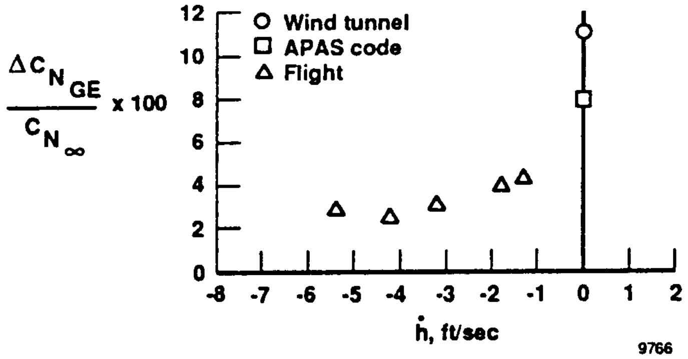

Figure 7. Percentage increase in normal force coefficient caused by ground effect as a function of instantaneous vertical velocity.

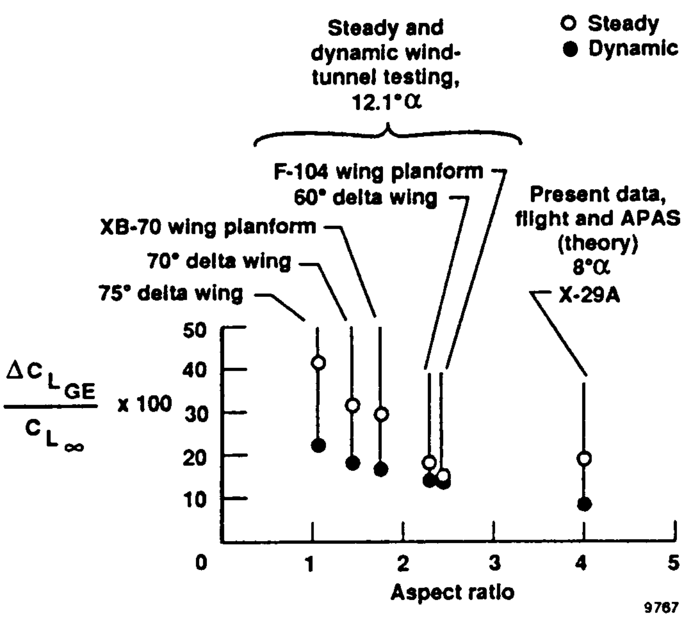

Figure 8. Percentage increase in lift coefficient caused by ground effect under dynamic and steady-state conditions for a variety of configurations. Data for delta wing, XB-70, and F-104 aircraft from reference 5.

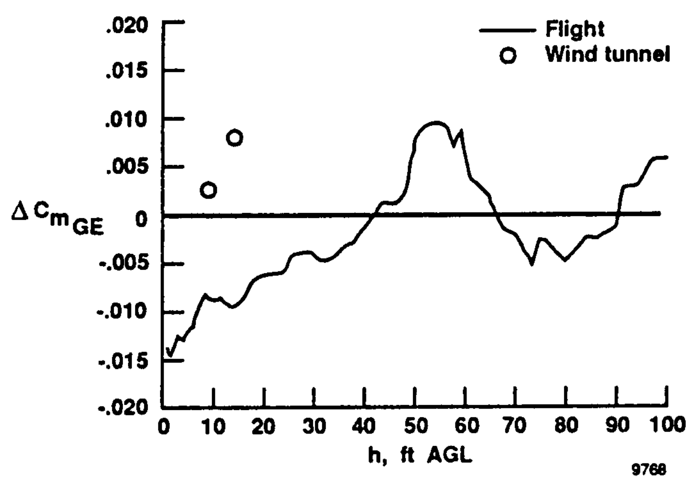

Figure 9. The $\Delta C_{m_{GE}}$ as a function of height AGL.

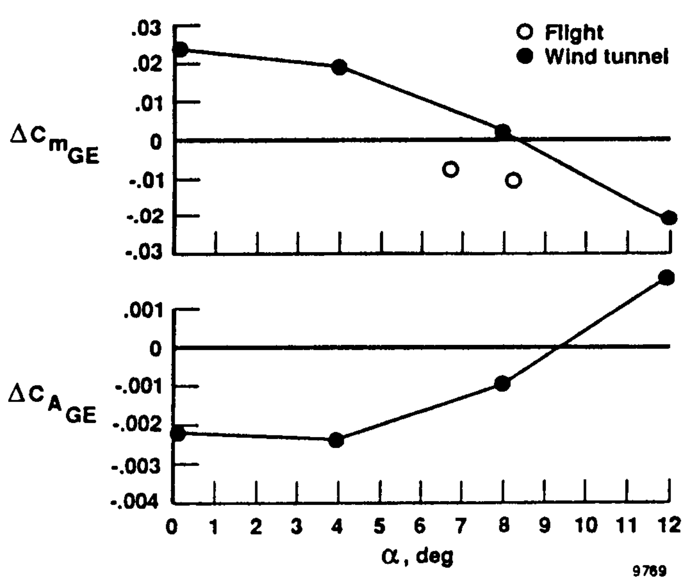

Figure 10. Variation in $\Delta C_{m_{GE}}$ and $\Delta C_{A_{GE}}$ as a function of angle of attack.

Report Documentation Page

NASA National Aeronautics and Space Administration

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-101708		

4. Title and Subtitle

An In-Flight Investigation of Ground Effect on a Forward-Swept Wing Airplane

5. Report Date

September 1989

6. Performing Organization Code

7. Author(s)

Robert E. Curry, Bryan J. Moulton, and John Kresse

8. Performing Organization Report No.

H-1573

10. Work Unit No.

RTOP 505-60-21

9. Performing Organization Name and Address

NASA Ames Research Center
Dryden Flight Research Facility
P.O. Box 273, Edwards, CA 93523-5000

11. Contract or Grant No.

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, DC 20546

13. Type of Report and Period Covered

Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for presentation as paper no. 23 at AGARD Fluid Dynamics Panel Symposium, "Aerodynamics of Combat Aircraft, Controls and of Ground Effect," Madrid, Spain, October 2–5, 1989.

16. Abstract

A limited flight experiment was conducted to document the ground-effect characteristics of the X-29A research airplane. This vehicle has a unique aerodynamic planform which includes a forward-swept wing and close-coupled, variable incidence canard. The flight-test program obtained results for errors in the airdata measurement and for incremental normal force and pitching moment caused by ground effect. Correlations with wind-tunnel and computational analyses were made.

The results are discussed with respect to the dynamic nature of the flight measurements, similar data from other configurations, and pilot comments. The ground-effect results are necessary to obtain an accurate interpretation of the vehicle's landing characteristics. The flight data can also be used in the development of many modern aircraft systems such as autoland and piloted simulations.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Flight testing Forward-swept wing Ground effect X-29A aircraft	Unclassified — Unlimited Subject category 02

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	14	A02

NASA FORM 1626 OCT 86

**For sale by the National Technical Information Service, Springfield, VA 22161-2171.*