NASA Technical Memorandum 4604

Dynamic Ground Effects Flight Test of an F-15 Aircraft

Stephen Corda, Mark T. Stephenson,
Frank W. Burcham, and Robert E. Curry

September 1994

NASA Technical Memorandum 4604

Dynamic Ground Effects Flight Test of an F-15 Aircraft

Stephen Corda
PRC Inc.
Edwards, California

Mark T. Stephenson, Frank W. Burcham,
and Robert E. Curry
Dryden Flight Research Center
Edwards, California

National Aeronautics and
Space Administration

Office of Management

Scientific and Technical
Information Program

1994

CONTENTS

ABSTRACT

Flight tests to determine the changes in the aerodynamic characteristics of an F-15 aircraft caused by dynamic ground effects are described. Data were obtained for low- and high-sink rates between 0.7 and 6.5 ft/sec and at two landing approach speeds and flap settings: 150 kn with the flaps down and 170 kn with the flaps up. Simple correlation curves are given for the change in aerodynamic coefficients because of ground effects as a function of sink rate. Ground effects generally caused an increase in the lift, drag, and nose-down pitching moment coefficients. The change in the lift coefficient increased from approximately 0.05 at the high-sink rate to approximately 0.10 at the low-sink rate. The change in the drag coefficient increased from approximately 0 to 0.03 over this decreasing sink rate range. No significant difference because of the approach configuration was evident for lift and drag; however, a significant difference in pitching moment was observed for the two approach speeds and flap settings. For the 170 kn with the flaps up configuration, the change in the nose-down pitching moment increased from approximately –0.008 to –0.016. For the 150 kn with the flaps down configuration, the change was from approximately –0.008 to –0.038.

NOMENCLATURE

AR	aspect ratio
a_A	axial acceleration, ft/sec^2
a_N	normal acceleration, ft/sec^2
b	wingspan, ft
CAS	Control Augmentation System
C_A	axial force coefficient
C_D	drag coefficient
C_L	lift coefficient
C_M	moment coefficient
C_N	normal force coefficient
C_T	thrust coefficient
DATCOM	Data Compendium
g	acceleration caused by gravity, ft/sec^2
h	height above ground, ft
$\dot{h}$	sink rate, ft/sec
I_X	moment of inertia about the aircraft longitudinal axis, slug-ft^2
I_Y	moment of inertia about the aircraft lateral axis, slug-ft^2
I_Z	moment of inertia about the aircraft yaw axis, slug-ft^2
I_{XZ}	product of inertia, slug-ft^2
n	number of data points
PCA	propulsion-controlled aircraft
PLA	power lever angle, deg
p	roll rate, deg/sec
q	pitch rate, deg/sec
$\bar{q}$	dynamic pressure, lb/ft^2
$\dot{q}$	rate of change of pitch rate, deg/sec^2
r	yaw rate, deg/sec
S	wing planform area, ft^2
W	weight, lb
α	angle of attack, deg
Δ	change in variable
δ	stabilator deflection, deg (negative for downward deflection)
$\%\Delta$	percent change in variable
Λ	wing sweep, deg
θ	pitch attitude, deg

Subscripts

α	derivative with respect to angle of attack, deg^{-1}
δ	derivative with respect to stabilator position, deg^{-1}
GE	ground effect
OGE	out of ground effect
uncorr	uncorrected for changes in angle-of-attack and stabilator position

INTRODUCTION

Aerodynamic characteristics of an aircraft may significantly differ when flying close to the ground rather than when flying up and away.[1,2] Recent research has also determined that dynamic effects influence ground effects (GE).[3–10] These ground effects may significantly impact the performance of aircraft in such flight phases as takeoff and landing, particularly for automatic landings. For this reason, such effects need to be thoroughly understood. Significant discrepancies exist between predicted and measured ground effects for many aircraft. Wind-tunnel and flight test techniques continue to evolve in an effort to provide accurate predictions for new aircraft designs.

Recently, NASA Dryden Flight Research Center (NASA Dryden) conducted the propulsion-controlled aircraft (PCA) flight test program.[11] The PCA program developed technology for emergency landing of aircraft using collective and differential engine thrust. Assuming that the conventional flight control system had been disabled was a basic premise of this program. Flight testing was conducted with the NASA Dryden F-15 flight research aircraft (McDonnell Douglas Corporation, St. Louis, Missouri) (fig. 1). Because the PCA program flew the aircraft to touchdown using flight control limited to that provided by the engines, knowing the aerodynamic characteristics of the F-15 aircraft close to the ground, that is, in ground effect, was important.

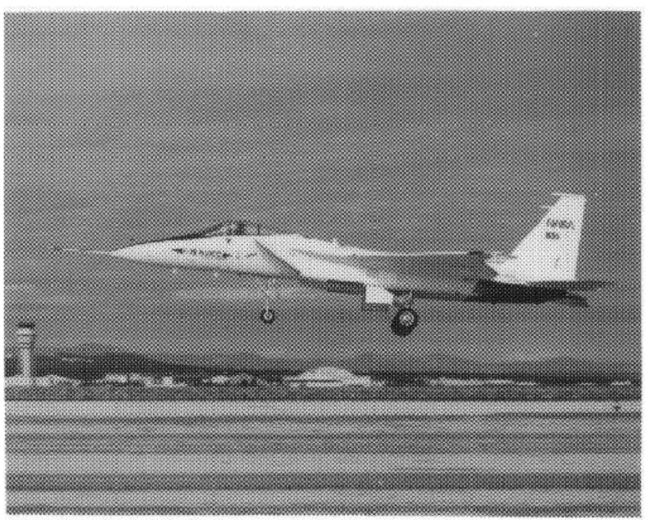


Figure 1. NASA F-15 aircraft performing approach and landing typical of ground effects testing.

Although the F-15 aircraft has been in service for more than 20 years, in-flight dynamic ground effects data have never been obtained. For this reason, a ground effects flight investigation of the NASA Dryden F-15 aircraft was conducted for low- and high-sink rates, $\dot{h}$, between 0.8 and 6.5 ft/sec at two approach speed and flap-setting combinations. These combinations consisted of 150 kn with the flaps down (30° deflection) and 170 kn with the flaps up (0° deflection). The aerodynamic coefficients caused by ground effects were estimated from the flight data. These ground effects data were correlated with the aircraft approach speed, flap setting, and sink rate.

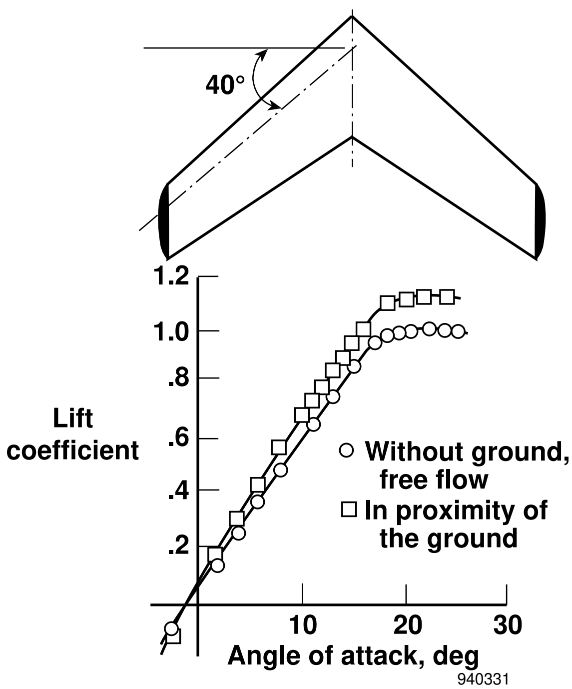
This paper describes the test procedures and results for approaches at 150 kn with the flaps down and 170 kn with the flaps up over sink rates from 0.8 to 6.5 ft/sec. Results are compared to previous flight test and wind-tunnel ground effects data for various wings and for complete aircraft.

GROUND EFFECTS BACKGROUND

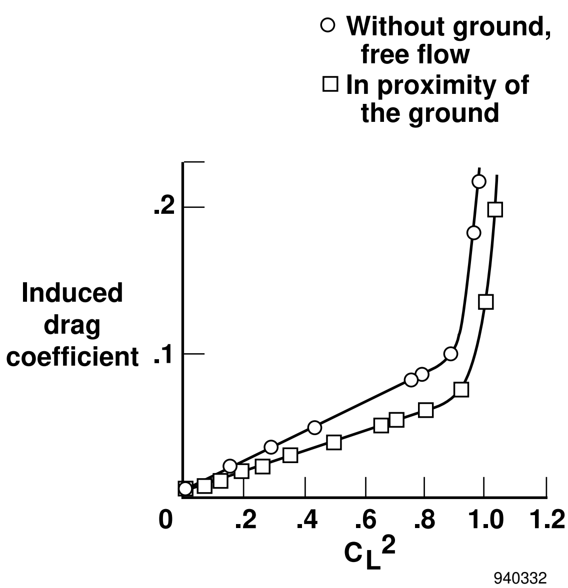
Ground effects may be explained by the interaction of the aircraft wingtip vortices with the ground. This interaction reduces the strength of these vortices. The weakened wingtip vortices reduce the wing downwash which increases the lift and decreases the induced drag, or drag caused by lift.

Figures 2(a) and 2(b) show this change for a 40° sweptback wing. In addition, the reduced downwash at the wing trailing edge increases the angle of attack, α, of the relative wind at the elevator, resulting in a nose-down pitching moment. In a fundamental sense, the change in downwash near the ground results in a different pressure distribution over the wing, tail, and fuselage. This distribution alters the aircraft aerodynamic forces and moments.

Ground effects data can be obtained in the wind tunnel or in flight. In conventional wind-tunnel ground effects testing, measurements are taken for a stationary aircraft model at various fixed ground heights. The results are called static ground effects data. Unfortunately, this static data simulates the aircraft flying near the ground at a constant altitude rather than simulating the transient or dynamic effects of the aircraft descending through a given altitude, termed "dynamic" ground effects data. Ground-based techniques have proved successful in more closely duplicating dynamic effects by using a model that moves toward a stationary or moving ground board in the wind tunnel, thereby simulating the rate of descent.[2–6] Dynamic ground effects wind-tunnel data were obtained for the F-106B (General Dynamics/Convair, Fort Worth, Texas) and the F-15 Short Take-Off and Landing Maneuver Technology Demonstrator (McDonnell Douglas



(a) Lift.



(b) Drag.

Figure 2. Change in lift and induced drag coefficients caused by ground effect.

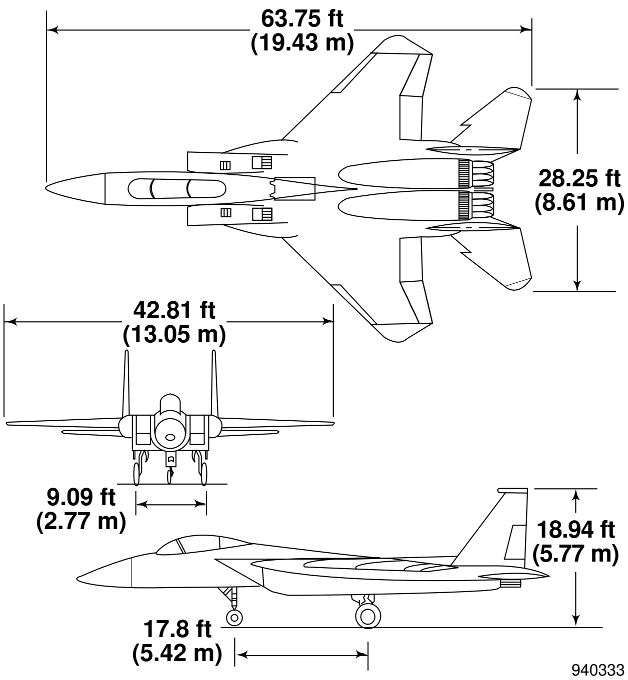
Corporation, St. Louis, Missouri). Note that static conditions, whether in the wind tunnel or in flight, produce significantly different ground effects on an aircraft than those produced by dynamic conditions.

The wing sweep, Λ, of an F-15 aircraft is 45° (fig. 3 (a)). A wind-tunnel investigation of ground effects on a 42° sweptback wing revealed that the main effects of ground interference consist of an increase in lift-curve slope, a reduction in induced drag, and a concentration of lift toward the center of a straight wing and near the wingtips of a swept wing.[7] These effects are increased by decreasing ground distance and are relatively independent of angle of attack.

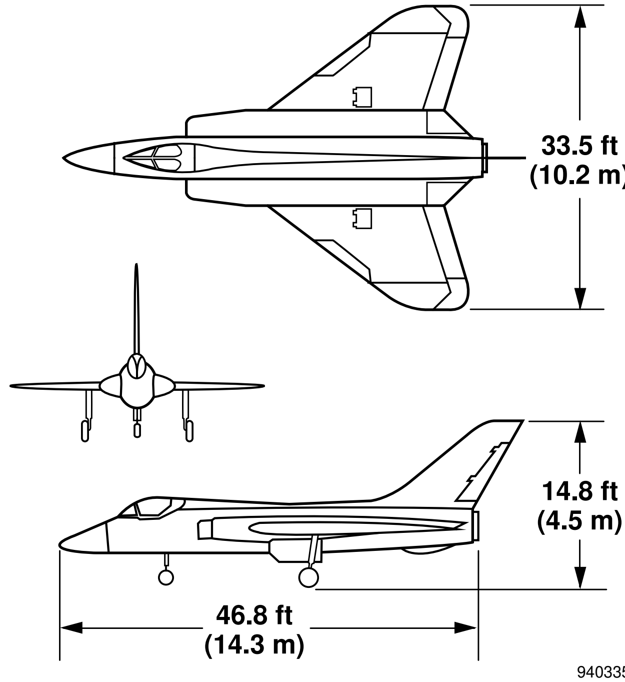
In-flight investigations of ground effects were performed on several aircraft at NASA Dryden over 20 years ago.[8,9] Ground effects data were collected for the F-104A (Lockheed Corporation, Burbank, California), XB-70 (North American, Los Angeles, California), as well as for the F5D-1 and F5D-1 with a modified ogee wing (McDonnell Douglas Corporation, St. Louis, Missouri). Figures 3(b) to 3(f) show these aircraft. The modified F5D-1 has a different wing planform and airfoil section than the conventional F5D-1 (figs. 3(c) and 3(d)). The modified F5D-1 wing planform is similar to that of the Concorde (Aerospatiale, France and British Aerospace, United Kingdom) supersonic transport. Note also that the XB-70 aircraft is substantially larger than the others, but it has an aspect ratio (AR) similar to that of the modified F5D-1 aircraft.

Several in-flight tests have investigated dynamic-ground effects. Recently, the in-flight ground effects characteristics of the forward-swept wing X-29 aircraft (Grumman Aerospace Corporation, Bethpage, New York) were studied (fig. 3(f)).[10] This ground effects investigation of the F-15 aircraft used flight test techniques similar to those used in previous investigations.[8–10]

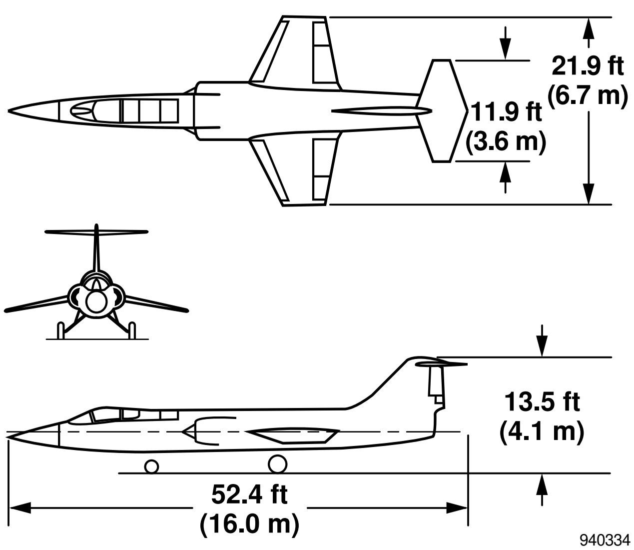
In terms of predictive capability, the U.S. Air Force *Data Compendium* (DATCOM) provides methods for estimating ground effects in the linear lift range on lift, drag, and pitching moment.[12] The method requires a knowledge of the out of ground effects (OGE) aerodynamic data for the aircraft wing; wing and body combination; and tail, with and without flaps. Although partially based on previously reported flight test data[9], the method does not explicitly account for different dynamic effects, such as different aircraft sink rates. This investigation found a significant dependence on changes caused by ground effect with sink rate.



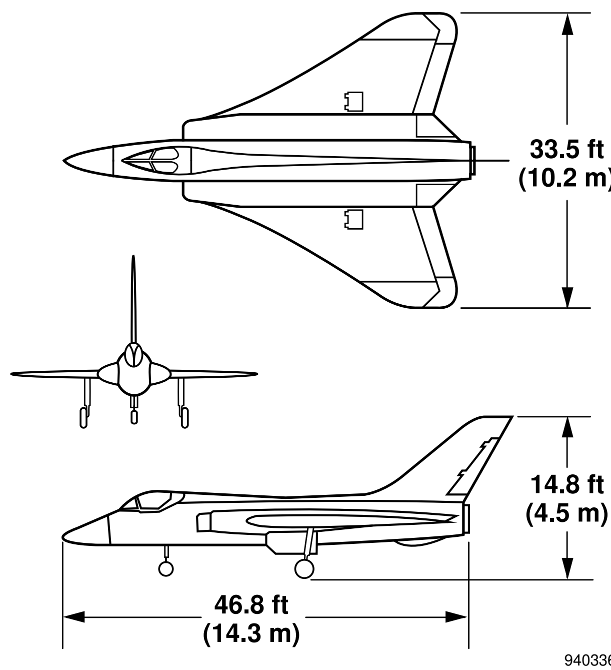
(a) F-15A.



(c) F5D-1.

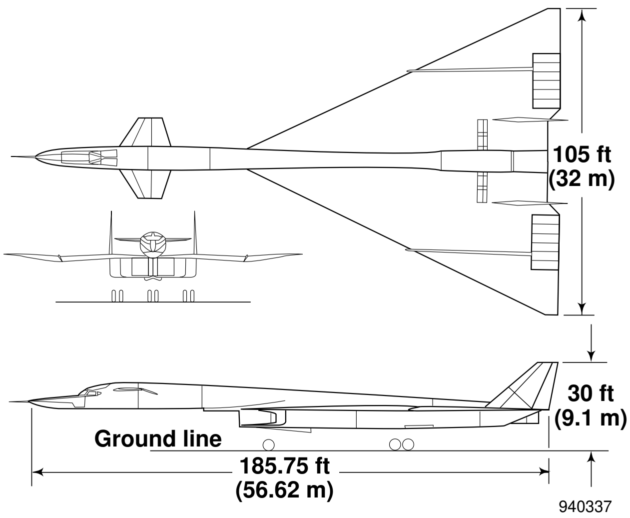


(b) F-104A.

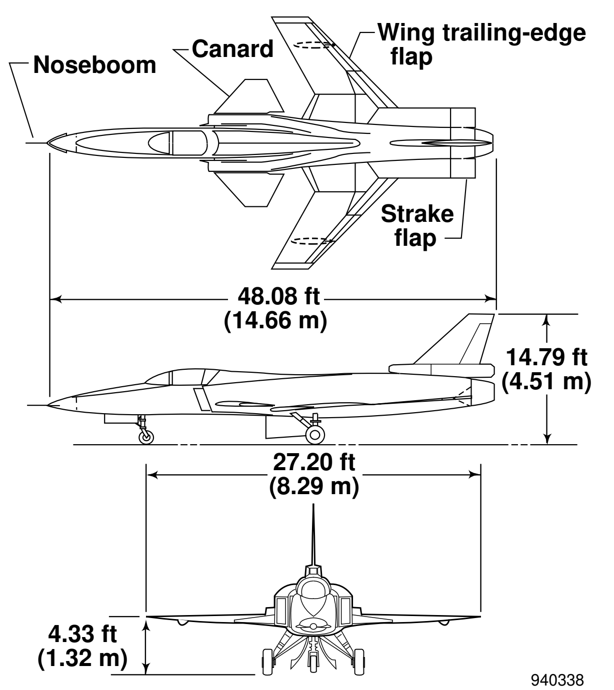


(d) F5D-1 airplane with modified ogee wing.

Figure 3. Ground effects flight test aircraft.



(e) XB-70.



(f) X-29.

Figure 3. Concluded.

AIRCRAFT DESCRIPTION

The NASA Dryden F-15 aircraft was used for the ground effects approach and landing tests (figs. 1 and 3(a)). Table 1 lists its physical characteristics. In addition, the wing has trailing-edge flaps with a maximum downward deflection of 30°. No leading-edge devices exist on the wing.

Table 1. Physical characteristics of the F-15 aircraft.

Characteristics	Dimensions
Wingspan, ft	42.83
Wing planform area, ft^2	608
Aspect ratio	3.02
Wing sweep at quarter chord, deg	45
Length, ft	63.75
Height to top of vertical tails, ft	18.67
Empty weight, lb	30,035
Maximum gross weight, lb	40,835
Maximum internal fuel load, lb	10,800
Engines	2
Engine type	PW 1128
Installed sea level static thrust per engine, lb	18,000

The NASA Dryden F-15 aircraft is a single-seat, preproduction model of the F-15A that has been modified from its fighter role to fulfill its function as a flight research aircraft. These modifications include removing the weapons systems and installing special flight test instrumentation and data acquisition equipment. For example, the aircraft is equipped with a noseboom for airdata measurements, such as angle of attack, angle of sideslip, static pressure, and pitot pressure. This aircraft is powered by two PW1128 low bypass ratio, afterburning turbofan engines (Pratt & Whitney, West Palm Beach, Florida). These engines are upgraded versions of the Pratt & Whitney F100 series engines. Although modified for flight research, the aircraft is representative of any single-seat F-15 aircraft in terms of ground effects evaluation.

Flight Control System

The primary flight control surfaces of the F-15 aircraft consist of conventional, hydraulically actuated ailerons; twin vertical rudders; and horizontal stabilators. These control surfaces are capable of symmetrical or differential movements. The hydraulic actuators receive inputs from a hydromechanical system and an electrical system called the Control Augmentation System (CAS). These systems work together during normal operation, but either system can independently provide sufficient aircraft control.

Because ground effects approaches and landings were performed with the CAS turned on and off, understanding the flying qualities of the aircraft with and without the CAS operating is important. The CAS provides pitch, roll, and yaw axes control augmentation and increased damping in all three axes. The CAS modifies the control surface deflections commanded by the hydromechanical system to provide desired flying qualities. Rudder and stabilator positions are controlled by the CAS. The CAS does not command changes to the ailerons.

With the CAS turned on, the handling qualities of the F-15 aircraft do not vary significantly throughout the flight envelope. Pitch and roll response do not vary appreciably with airspeed, altitude, engine power, or configuration changes.

With the CAS turned off, the mechanical flight control system of the aircraft still provides adequate flying qualities through pitch and roll ratio changes and through an aileron and rudder interconnect. For the PCA flight study which simulated a total loss of hydraulic pressure, however, eliminating flight control surface movement unless the pilot moved the stick or rudder pedals was desired. As a result, the pitch and roll ratios emergency position was selected so that the pitch and roll ratio changes were fixed. In this CAS-off, pitch and roll ratios emergency configuration, hereafter referred to only as CAS-off, flying qualities and stability were degraded for performing precise maneuvers, such as air-to-air tracking or landing. The aircraft feels less solid and more sluggish in pitch and roll because of the reduced damping. During landing, stick forces were high; pitch and roll response was slow; roll rate, p, was reduced; and flare capability was greatly reduced. In general, stabilized approaches and landings in the CAS-off mode were more difficult than in the CAS-on mode, but they were still safe.

Instrumentation

The NASA Dryden F-15 aircraft is equipped with standard flight research instrumentation for airdata, stability and control, and propulsion. Airdata measurements for the ground effects evaluation included aircraft altitude, velocity, and angle of attack. These data were measured with the aircraft noseboom. Aircraft stability and control measurements included stabilator position, longitudinal stick force, pitch angle, pitch rate, q, and normal and axial accelerations, a_A. Propulsion-related measurements included the throttle power lever angle (PLA) and compressor speed for each engine. Fuel weight was also measured during approaches to calculate the aircraft total weight.

Altitude information was available from three sources: an onboard radar altimeter, the aircraft noseboom-mounted pitot-static system, and a ground-based optical tracker for some flights. The radar altimeter used an onboard radar transmitter and receiver to indicate true height above the ground, h. Pressure altitude was available from noseboom static pressure measurements. Optical tracking of the aircraft also provided height above the ground data as well as attitude, velocity, and rate data.

FLIGHT TEST PROCEDURE

The flight test procedure for the ground effects landings consisted of flying stabilized, constant glide slope approaches into ground effect on the main runway at Edwards Air Force Base, California. The glide slope angle was held constant for the approaches at a value between 0.5° for some approaches to as high as 2° for others. Once in ground effect, the pilot attempted to maintain a constant pitch attitude, θ, or angle of attack and to minimize pitch inputs and throttle movements until touchdown if possible. This attempt resulted in an approach with nearly constant angle of attack and power setting. This flight test procedure is similar to the procedure used by other researchers.[8–10] At the pilot's discretion, pitch inputs were applied very near touchdown to stop an unsafe sink rate or sudden nose-down pitching moment. Roll inputs were permitted during the approaches and landings to maintain a wings-level attitude. Figure 4 shows the F-15 landing attitude.

Ground effect evaluations were made for two approach configurations: a 150 kn with the flaps down (30° deflection) approach and a 170 kn with the flaps up (0° deflection) approach. Approaches were made with the landing gear down. In addition for the landings, the engine inlets were set in the emergency position, locking the inlet ramps in the full-up position. This inlet position eliminated pitching moments caused by movement of the inlet ramps that would have occurred with normal inlet operation. Normal CAS-on

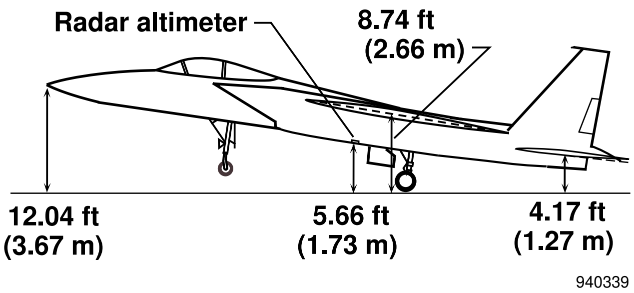


Figure 4. The F-15 landing attitude at an angle of attack of 8°.

and CAS-off approaches were flown at both approach configurations.

DATA ANALYSIS

Rigid body, steady-state equations of motion were used in this analysis. The aircraft was assumed to be flying a constant angle-of-attack approach at a constant thrust setting. Aerodynamic coefficients for lift, drag, and moment were calculated from the mass, accelerations, and inertias of the aircraft. The sum of the forces in the normal direction is as follows:

$$C_N - W\cos\theta/(S\bar{q}) = (W/g)a_N/(S\bar{q}) \quad (1)$$

where C_N is the normal force coefficient, W is the aircraft weight, θ is the aircraft pitch attitude, S is the wing planform area, $\bar{q}$ is the freestream dynamic pressure, g is the acceleration caused by gravity, and a_N is the normal acceleration of the aircraft. Aircraft weight and inertias were determined using the fuel weight data and the known aircraft empty weight.

Similarly, the sum of the forces in the axial direction is as follows:

$$C_T - C_A + W\sin\theta/(S\bar{q}) = (W/g)a_A/(S\bar{q}) \quad (2)$$

where C_T is the thrust coefficient, C_A is the axial force coefficient, and a_A is the axial acceleration of the aircraft.

The equations for the lift and drag coefficients, C_L and C_D, are as follows:

$$C_L = C_N\cos\alpha - C_A\sin\alpha \quad (3)$$

$$C_D = C_N\sin\alpha + C_A\cos\alpha \quad (4)$$

where α is the angle of attack.

The moment coefficient, C_M, is calculated from the rate of change of pitch rate, $\dot{q}$; roll and yaw rates, p and r; and moments of inertia. Equation (5) gives the moment coefficient.

$$C_M = \dot{q} \cdot I_Y + p \cdot r(I_X - I_Z) + (p^2 - r^2)I_{XZ} \quad (5)$$

The I_X is the moment of inertia about the aircraft longitudinal axis. The I_Y is the moment of inertia about the aircraft lateral axis. The I_Z is the moment of inertia about the aircraft yaw axis. The I_{XZ} is the product of inertia.

The rate of change of pitch rate is calculated from the slope of the pitch rate as a function of time. Filtering the pitch rate data was necessary to obtain a smoother curve for this differentiation. The moments of inertia are calculated as a function of aircraft weight.

The analysis technique used to determine the change in the aerodynamic coefficients caused by ground effect is described next. This technique is similar to the one used for the X-29 forward-swept wing aircraft ground effects evaluation.[10] This analysis technique is the same for the lift, drag, and moment coefficients and is detailed here for the lift coefficient only.

First, the out of ground effect lift coefficient, $C_{L,OGE}$, is calculated. This coefficient is obtained by taking the average of the coefficient calculated as a function of height above the ground from approximately 100 to 40 ft, which is approximately one wingspan above the ground.

$$C_{L,OGE} = \left[\sum_{i=1,n} C_{L,OGE,i}\right]/n \quad (6)$$

where n is the number of data points.

The lift coefficient below an altitude of one wingspan, $C_{L,GE}$, contains an increment caused by ground effect. The difference at a specific altitude between the ground effect coefficient and the averaged, out of ground effect coefficient is given by

$$\Delta C_{L,GE,uncorr} = C_{L,GE} - C_{L,OGE} \quad (7)$$

where the subscript "uncorr" specifies that the value has not been corrected for angle-of-attack and stabilator effects.

This increment caused by ground effect is calculated as a function of height above the ground from a height of approximately one wingspan to the ground. In calculating the difference in the lift coefficients, the thrust and weight terms are assumed to be constant for the maneuver. As a result, the thrust and weight terms in equations (1) and (2) cancel out, allowing the axial and normal force coefficients to be calculated from the aircraft accelerations.

Ideally by maintaining a constant pitch attitude, the changes in the aerodynamic coefficients are limited to those resulting from ground effect. On the other hand during flight, turbulence and necessary pitch inputs by the pilot to maintain a constant pitch attitude in ground effect resulted in unwanted influences caused by the stabilator moving and the angle of attack changing. As a result, subtracting the stabilator and angle-of-attack effects from the ground effect coefficients was necessary.

For example, the lift coefficient was corrected using equation (8).

$$\Delta C_{L,GE} = \Delta C_{L,GE,uncorr} - C_{L,\alpha}\Delta\alpha_{GE} - C_{L,\delta}\Delta\delta_{GE} \quad (8)$$

where $C_{L,GE,uncorr}$ is the lift coefficient caused by ground effect uncorrected for stabilator movement and angle-of-attack change. The $\Delta\alpha_{GE}$ and $\Delta\delta_{GE}$ are the changes in angle-of-attack and stabilator position. The $C_{L,\alpha}$ and $C_{L,\delta}$ are the derivatives of the out of ground effect lift coefficient with respect to angle-of-attack and stabilator position. Stabilator deflection, δ, is negative for downward deflection.

Values for $C_{L,\alpha}$ and $C_{L,\delta}$ were obtained from the database used in the NASA Dryden F-15-piloted flight simulator. Although these derivatives are themselves a function of angle-of-attack and stabilator position, the lift and moment derivatives are relatively constant for the range of angle-of-attack and stabilator positions used in the ground effect approaches and landings. It was also assumed that these aerodynamic derivatives were not affected by or changed because of ground effect. The nominal angle-of-attack and stabilator position used to define the lift and moment coefficient derivatives were 8° and –5°. Values used for $C_{L,\alpha}$ and $C_{L,\delta}$ were 0.065 and 0.005/deg. Values used for $C_{M,\alpha}$ and $C_{M,\delta}$ were –0.0021 and –0.00072/deg. The drag coefficient derivative with respect to stabilator position, $C_{D,\delta}$, was zero. The derivative with respect to angle of attack, $C_{D,\alpha}$, was calculated as a function of angle of attack.

The change in angle of attack while in ground effect is calculated using equation (9).

$$\Delta\alpha_{GE} = \alpha_{GE} - \alpha_{OGE} \quad (9)$$

where α_{OGE} is the out of ground effect angle of attack of the aircraft, averaged from approximately 100 ft to a height of one wingspan (40 ft) above the runway. The α_{GE} is the aircraft angle of attack calculated in ground effect, below 40 ft. The same procedure is used to calculate the change in stabilator position. A computer code was written that followed the analysis described by this procedure. The flight data were processed with this code to obtain the corrections to the aerodynamic coefficients caused by ground effect.

RESULTS AND DISCUSSION

The F-15 ground effects data were obtained for 24 landings during 7 flights (tables 2 and 3). Twelve landings occurred in the flaps down, 150-kn configuration. In addition,12 landings occurred in the flaps up, 170-kn configuration. The CAS was turned off for 16 landings and turned on for 8 landings. Approaches were flown with the landing gear down. The approaches and landings were flown by three test pilots.

Table 2. Summary of F-15 ground effects landings.

Ground effects flight	Flight test mission	Landings: 150 kn, flaps down	Landings: 170 kn, flaps up	CAS status
1	670	2	2	Off
2	671	2	2	Off
3	672	1	1	On
4	673	2	2	On
5	674	2	2	On
6	675	1	1	On
7	685	2	2	Off

Table 3. Calculated changes in aerodynamic coefficients caused by ground effect (h/b = 0).*

Flight and landing	Speed and flap setting**	Sink rate, ft/sec	$\Delta C_{L,GE}$	$\Delta C_{D,GE}$	$\Delta C_{M,GE}$
670 / 1	150 / F↓	4.0	0.040 ±0.020	0.100 ±0.010	–0.013 ±0.002
670 / 2	170 / F↑	5.1	0.040 ±0.010	0.010 ±0.005	–0.007 ±0.001
670 / 3	150 / F↓	5.1	0.065 ±0.015	0 ±0.005	–0.012 ±0.001
670 / 4	170 / F↑	4.5	0.075 ±0.025	0.030 ±0.010	–0.009 ±0.005
671 / 1	150 / F↓	4.0	0.050 ±0.010	0.015 ±0.015	–0.007 ±0.003
671 / 2	150 / F↓	3.4	0.085 ±0.015	0.015 ±0.015	–0.017 ±0.002
671 / 3	170 / F↑	2.9	0.065 ±0.005	0.030 ±0.005	–0.014 ±0.003
671 / 4	170 / F↑	3.3	0.070 ±0.010	0.015 ±0.015	–0.011 ±0.003
672 / 1	170 / F↑	4.0	0.050 ±0.010	0.040 ±0.010	–0.008 ±0.002
672 / 2	150 / F↓	1.3	0.120 ±0.020	0.030 ±0.030	–0.034 ±0.003
673 / 1	170 / F↑	5.7	0.050 ±0.010	0.010 ±0.010	–0.007 ±0.003
673 / 2	150 / F↓	6.5	—	—	–0.007 ±0.003
673 / 3	150 / F↓	2.0	0.090 ±0.005	—	–0.016 ±0.002
673 / 4	170 / F↑	1.6	0.120 ±0.005	—	–0.014 ±0.002
674 / 1	150 / F↓	0.7	0.150 ±0.020	—	–0.037 ±0.003
674 / 2	150 / F↓	0.9	0.100 ±0.010	0.030 ±0.010	–0.028 ±0.006
674 / 3	170 / F↑	0.8	0.095 ±0.005	0.033 ±0.010	–0.016 ±0.001
674 / 4	170 / F↑	3.4	0.065 ±0.005	0.012 ±0.005	–0.008 ±0.001
675 / 1	170 / F↑	6.1	0.055 ±0.015	0 ±0.020	–0.008 ±0.002
675 / 2	150 / F↓	5.9	0.080 ±0.020	0 ±0.020	–0.008 ±0.002
685 / 1	170 / F↑	1.7	0.120 ±0.010	0.010 ±0.010	–0.008 ±0.002
685 / 2	170 / F↑	2.5	0.060 ±0.010	—	–0.008 ±0.002
685 / 3	150 / F↓	6.3	0.120 ±0.010	0.020 ±0.005	–0.013 ±0.001
685 / 4	150 / F↓	5.7	0.040 ±0.010	–0.010±0.010	–0.009 ±0.001

*h/b is the height above the ground divided by the wingspan.
**Speed and flap settings: 170/F↑ = 170 kn approach with the flaps up.
150/F↓ = 150 kn approach with the flaps down.

Figure 5 shows an example time history for an approach for landing 4 of flight 674. The approach was at 170 kn with the flaps up and the CAS turned on. This example represents one of the best approaches and landings flown during the test program. The average values of the parameters calculated out of ground effect (OGE average) are also shown.

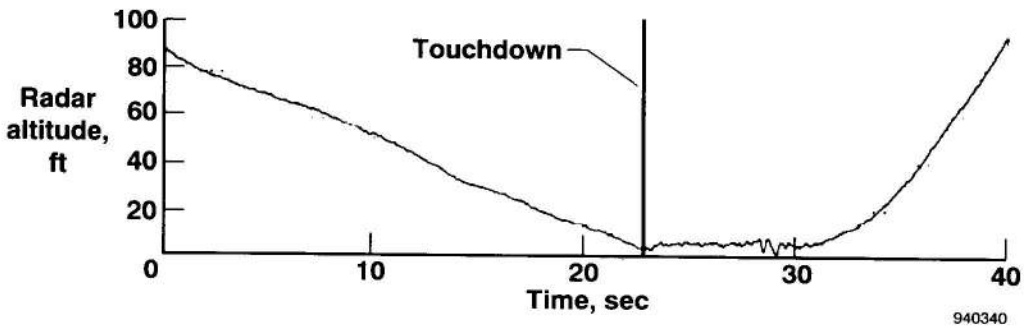
Figure 5(a) shows the radar altitude as a function of time. Note that touchdown is at a radar altitude of approximately 6 ft (time of approximately 23 sec), the height above the ground of the radar altimeter in the aircraft at touchdown (fig. 4). The actual height above the ground of the aircraft wing at touchdown was approximately 9 ft (fig. 4). The height above the ground of the radar altimeter at touchdown was subtracted from these data so that the height above the ground at touchdown was zero.

Figure 5(b) shows airspeed as a function of time. The approach is very stable with a constant airspeed of approximately 166 kn. This approach is ideal because no power changes were required and few stabilator position changes were needed (figs. 5(c) through 5(e). Figure 5(c) shows that the engine is nearly idle at a constant compressor speed of approximately 10,900 rpm to beyond touchdown. The pilot did not make any pitch inputs from approximately 30 ft above the ground to touchdown, as shown by the zero longitudinal stick force in figure 5(d). The left and right stabilator positions in figure 5(e) and the pitch rate in figure 5(f) are fairly constant until approximately 20 ft above the ground (time of approximately 18 sec), where a continuous increase in the pitch rate because of ground effect is seen along with the compensating, downward deflection of the stabilators.

Below approximately 20 ft, some differential deflection of the stabilators occurs as the pilot compensates for roll upsets using lateral stick to maintain a wings-level attitude, and the CAS acts to counter the nose-down pitching moment. Figure 5(g) shows a stabilized, very shallow flightpath angle, or glide slope, of approximately –1.2°. A constant angle of attack of approximately 10° is shown in figure 5(h) until approximately 20 ft above the ground. At 20 ft, or approximately one-half the wingspan, the nose of the aircraft pitches down and the angle of attack decreases because of ground effect. Figure 5(i) shows the aircraft pitch attitude. The pitch is nearly constant at approximately 9.7° with some small oscillations before the pitch down occurs at approximately 20 ft.

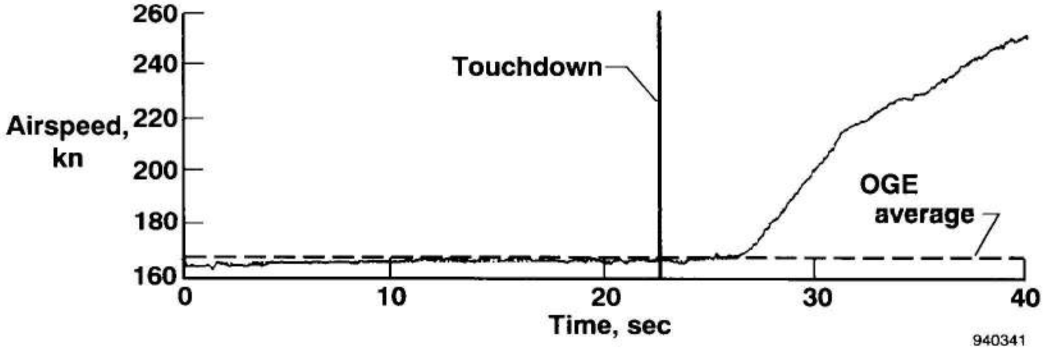
Pilots' Comments

As expected, pilots commented that the approaches and landings were more difficult to fly "hands off" when the air was turbulent. Roll upsets could usually be corrected by the pilot without applying pitch inputs. The CAS-off approaches were difficult to fly, especially in turbulence. The aircraft short period longitudinal oscillation was difficult to damp with the CAS-off mode.

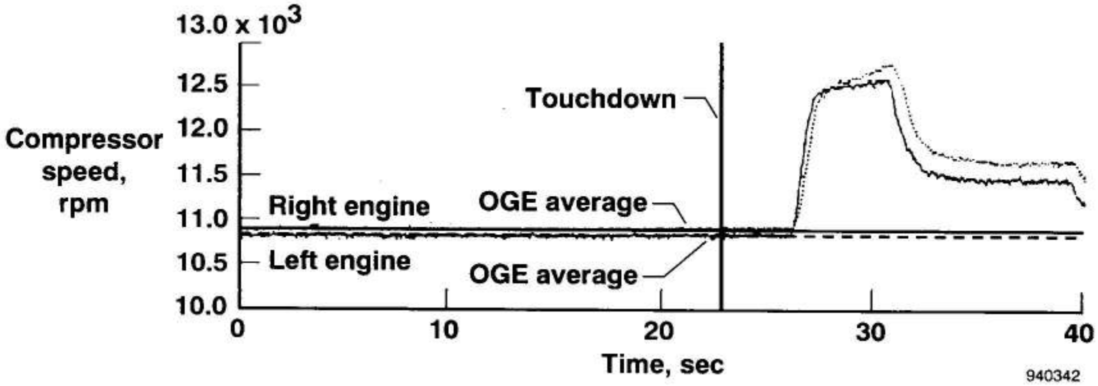


(a) Radar altitude.

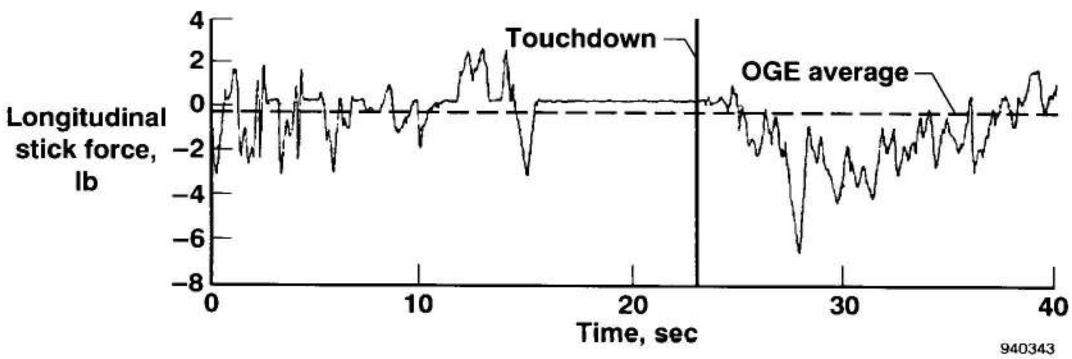
Figure 5. Time histories of flight data from F-15 ground effects for landing 4 of flight 674.



(b) Airspeed.

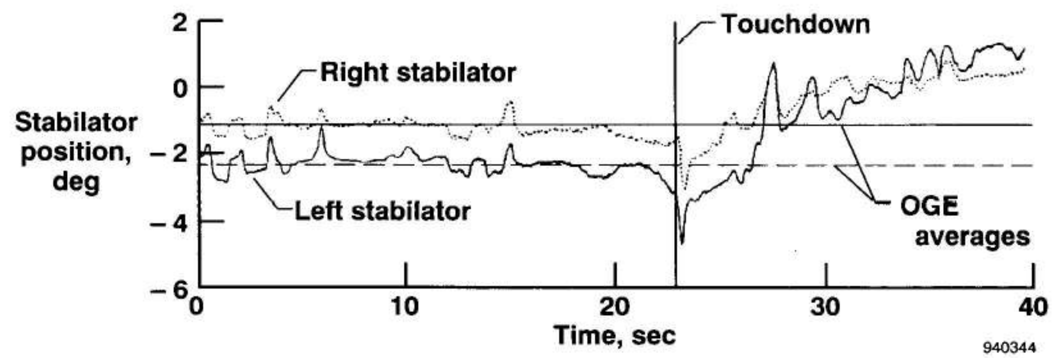


(c) Engine compressor speed.

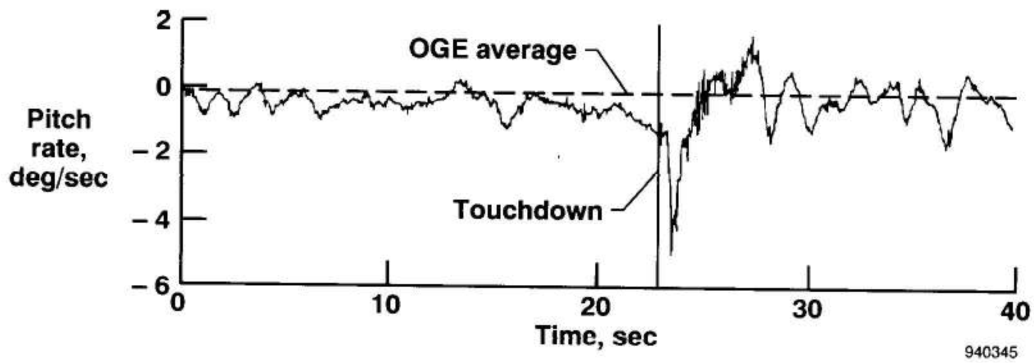


(d) Longitudinal stick force.

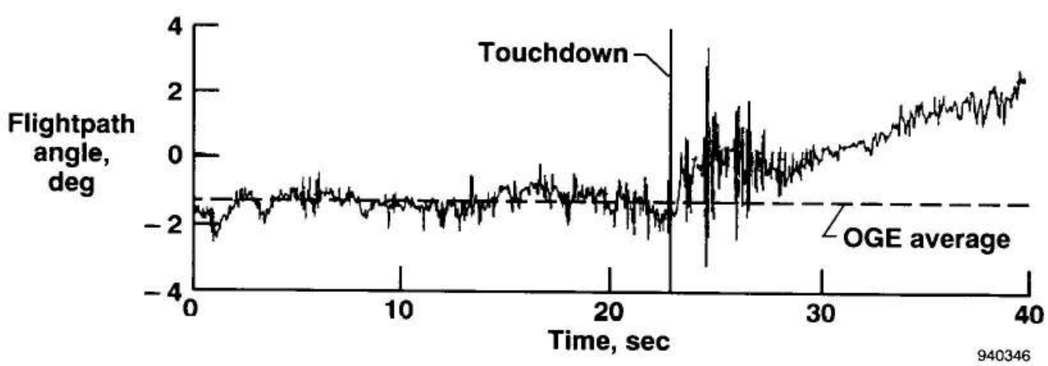
Figure 5. Continued.



(e) Stabilator deflection.

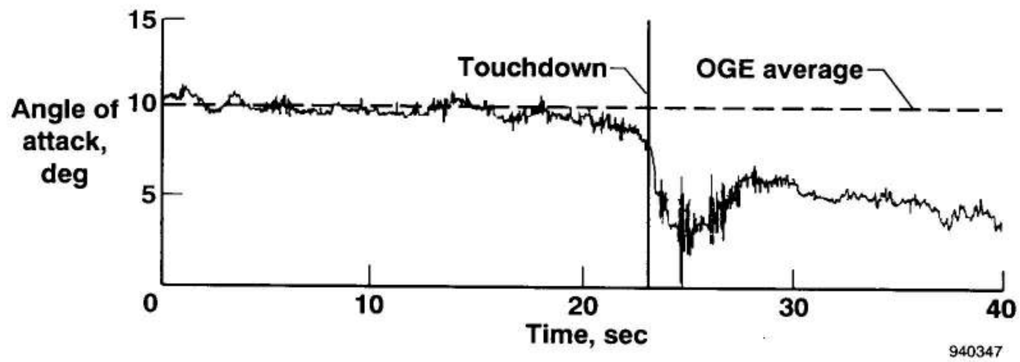


(f) Pitch rate.

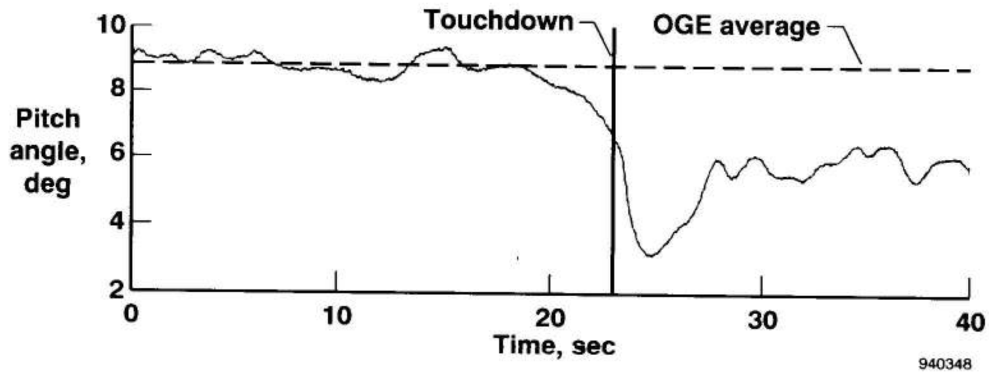


(g) Flightpath angle.

Figure 5. Continued.



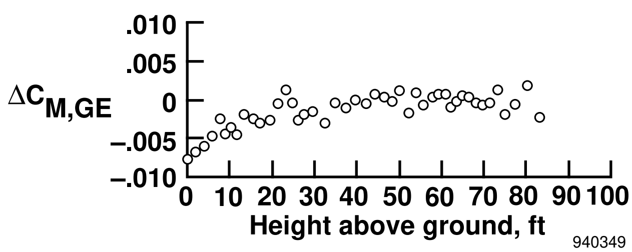
(h) Angle of attack.



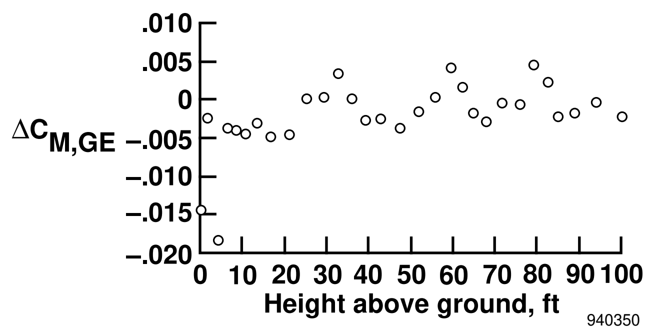
(i) Pitch attitude.

Table 5. Concluded.

Figures 6 shows the effects of flying the approach with the CAS turned on and with CAS turned off. The change in the moment coefficient because of ground effect is plotted as a function of height above the ground. The CAS-off approach is less damped longitudinally, resulting in a short period of oscillation during the approach. In general, CAS-on flight data provided a better estimate of the change in the aerodynamic coefficients than the CAS-off flight data.



(a) Control augmentation system turned on.



(b) Control augmentation system turned off.

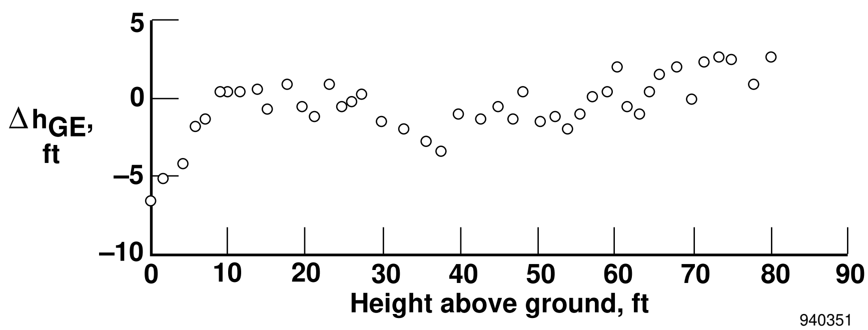
Figure 6. Comparison of change in F-15 pitching moment because of ground effect as a function of height above the ground.

The pilots generally felt a moderate to significant pitch down of the nose of the aircraft in ground effect. Sometimes the pilot had to apply brisk aft stick motions to prevent damaging the aircraft. In instances where the approach was very stabilized “hands off” and the sink rate was very low, the pilots experienced significant “float” in ground effect. In addition, touchdown sometimes required forward stick motions.

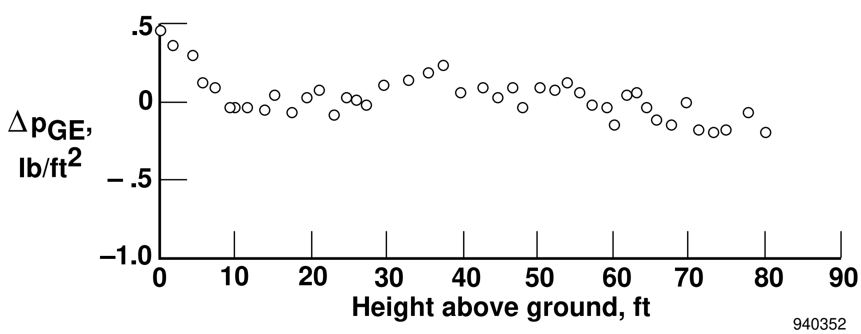
Noseboom Pressure Corrections

Again for landing 4 of flight 674, figure 7 shows the error in the noseboom-measured static pressure because of ground effect. These errors are defined as the difference between the value from the noseboom-measured pressure and the value using the actual static pressure. The error in the pressure altitude deduced from the noseboom static pressure, Δh_{GE}, was plotted as a function of height above the ground (fig. 7(a)). The noseboom pressure altitude has an error because of ground effect of approximately 6.5 ft at touchdown. This pressure altitude error is typical of noseboom systems and was not critical to this investigation because radar or optically measured altitudes were used for height above the ground data.

On the other hand, noseboom-derived static and dynamic pressure errors could be important in calculating ground effect aerodynamic coefficients. Figures 7(b) and 7(c) show the errors because of ground effect for the noseboom static and dynamic pressures, Δp_{GE} and Δq_{GE}. At touchdown, the static and dynamic pressure errors are approximately 0.5 and 0.025 lb/ft^2. These values were typical for the landings analyzed. Although these errors were small, dynamic pressure correction was applied to these flight data.

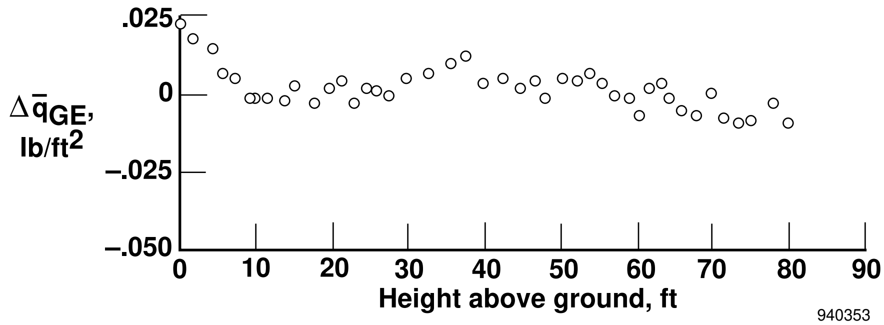


(a) Pressure altitude.



(b) Static pressure.

Figure 7. Error corrections in F-15 noseboom-measured static pressure because of ground effect.



(c) Dynamic pressure.

Figure 7. Concluded.

Angle-of-Attack and Elevator Change Corrections

Figures 8 through 10 show the effect of the ground effects corrections on the aerodynamic coefficients for the lift, drag, and moment coefficients for landing 4 of flight 674. Parts (a) in these figures show the change of the uncorrected coefficient data as a function of height above the ground. The uncorrected change of the lift and drag coefficient data in figures 8(a) and 9(a) are scattered about zero. The uncorrected change of the moment coefficient data in figure 10(a) is zero all the way to touchdown, indicating that the aircraft is in a trimmed configuration. The change in the aerodynamic coefficient because of ground effect (*h* less than 40 ft) is not apparent in any of these uncorrected data.

The corrections for changes in angle-of-attack and stabilator position are shown in parts (b) and (c) of figures 8 through 10. Part (b) is obtained by subtracting the angle-of-attack increment from the uncorrected change of the aerodynamic coefficient. Part (c) is obtained by subtracting the stabilator increment from the uncorrected change of the aerodynamic coefficient.

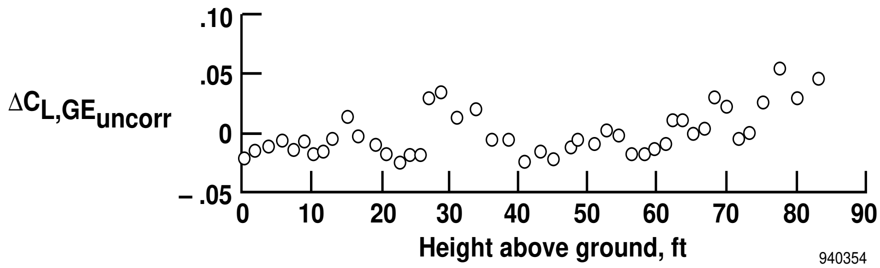
The ground effect increment for lift coefficient is made evident by the angle-of-attack correction (fig. 8(b)). At touchdown, the stabilator deflection correction has a small influence in defining the increment in lift coefficient (fig. 8(c)). For the drag coefficient increment, the angle-of-attack and stabilator corrections have a small and approximately equal affect (figs. 9(b) and 9(c)). Corrections are larger and still approximately equal for the moment coefficient increments (figs. 10(b) and 10(c)).

Figures 8(d), 9(d), and 10(d) show the final, corrected data for the change of the aerodynamic coefficients. The increment because of ground effect was nearly zero until a height of approximately one wingspan or less above the ground. The lift coefficient increased by approximately 0.065 (fig. 8(d)). The drag coefficient increased by approximately 0.012 because of the increase in lift (fig. 9(d)). A pitch down moment coefficient increase of approximately –0.008 occurred because of ground effect (fig. 10(d)).

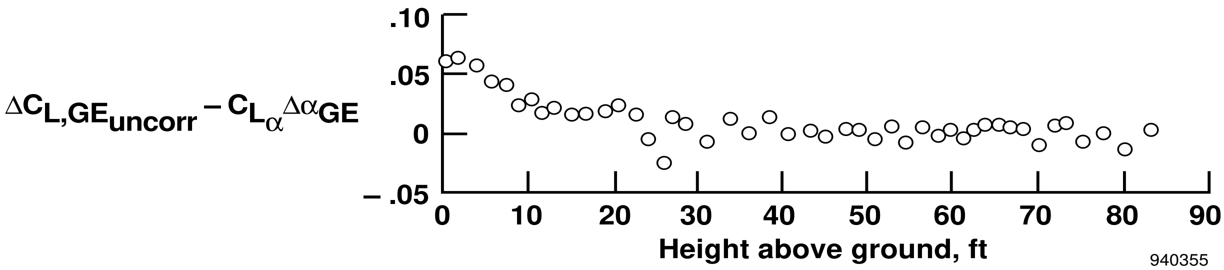
Table 3 summarizes the calculated changes in the aerodynamic coefficients because of ground effect for all of the landings. The error bands are representative of the accuracy in the curve fitting of the data.

Approach Speed, Flap Setting, and Sink Rate Effects

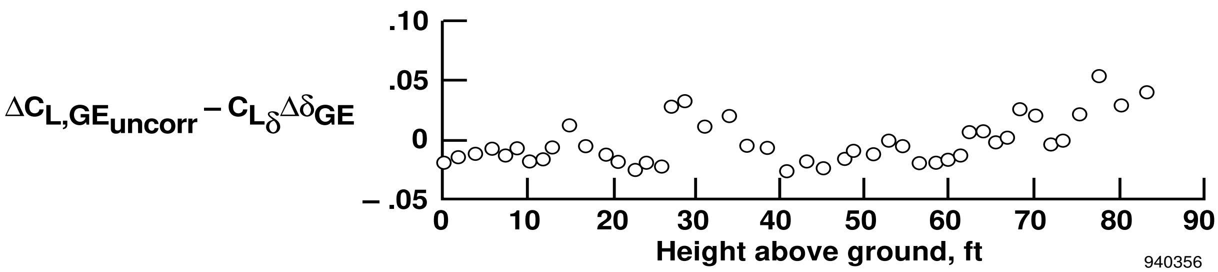
Figure 11 shows the F-15 ground effects flight data plotted as a function of approach speed, flap setting, and sink rate. Table 3 is a tabulation of these data. Figures 11(a), 11(b), and 11(c) show the changes because of ground effect of the lift, $\Delta C_{L,GE}$; drag, $\Delta C_{D,GE}$; and pitching moment, $\Delta C_{M,GE}$, coefficients as a function of sink rate. Changes in the aerodynamic coefficients were calculated at touchdown.



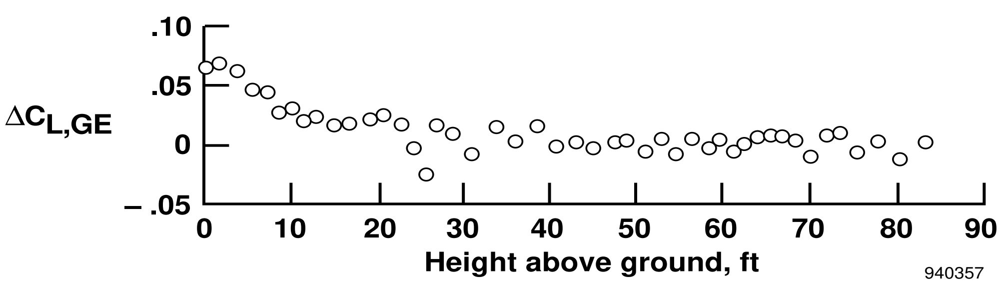
(a) Uncorrected.



(b) Corrected for angle of attack.

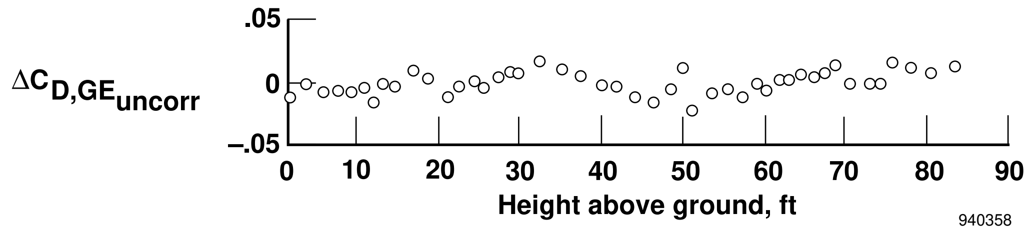


(c) Corrected for stabilator deflection.

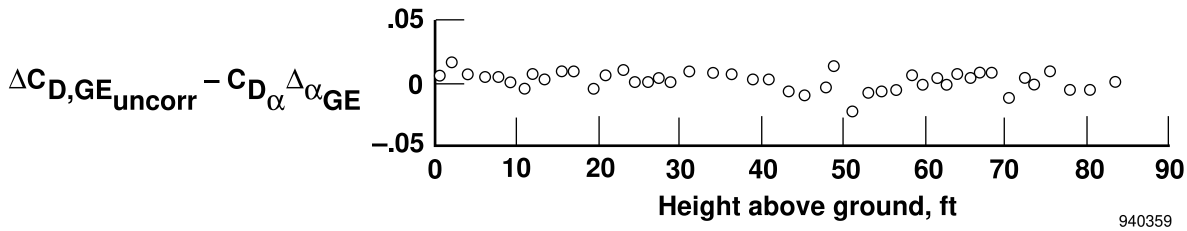


(d) Corrected for angle of attack and stabilator deflection.

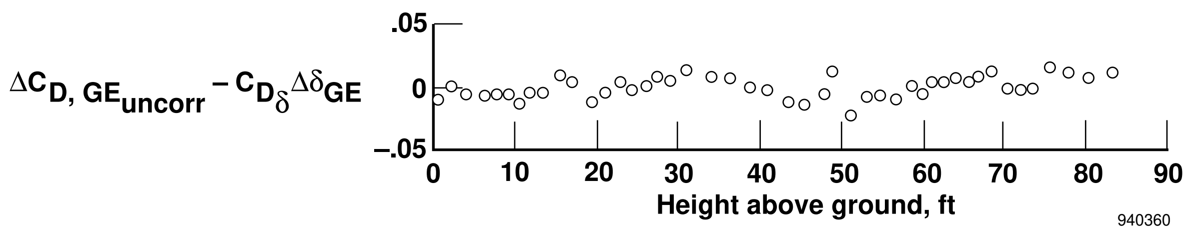
Figure 8. Change in F-15 lift coefficient because of ground effect as a function of height above the ground.



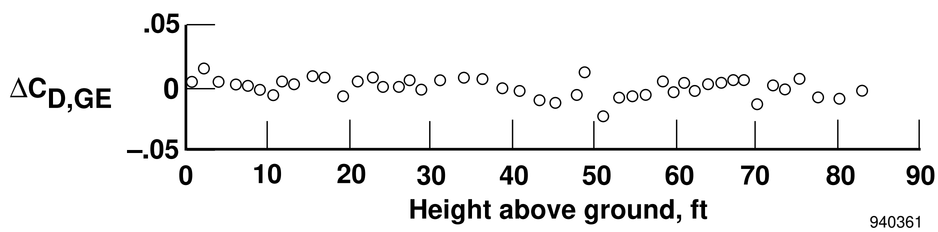
(a) Uncorrected.



(b) Corrected for angle of attack.

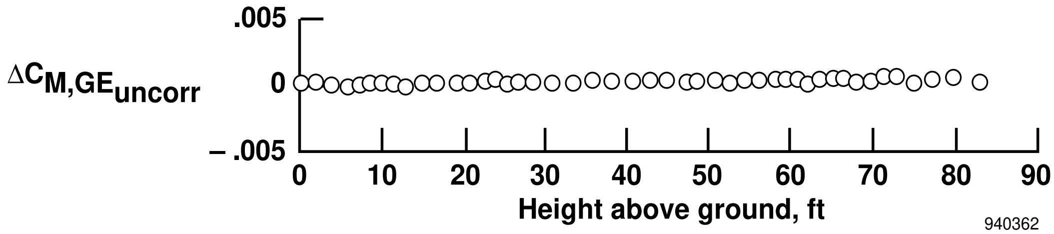


(c) Corrected for stabilator deflection.

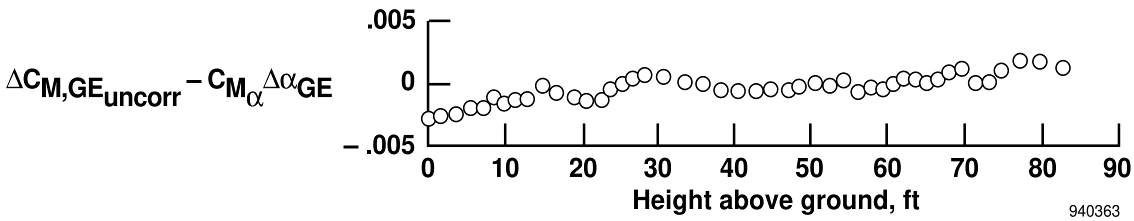


(d) Corrected for angle of attack and stabilator deflection.

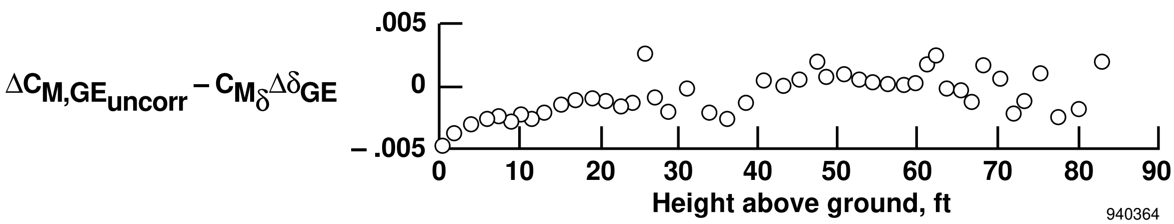
Figure 9. Change in F-15 drag coefficient because of ground effect as a function of height above the ground.



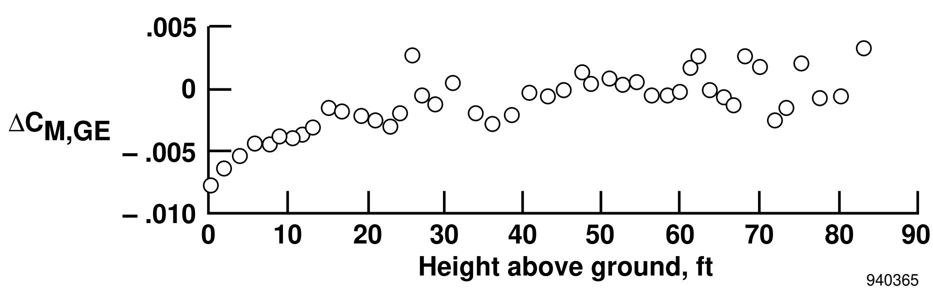
(a) Uncorrected.



(b) Corrected for angle of attack.

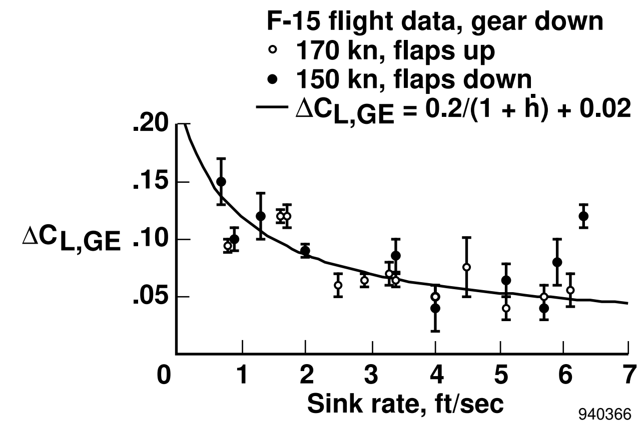


(c) Corrected for stabilator deflection.

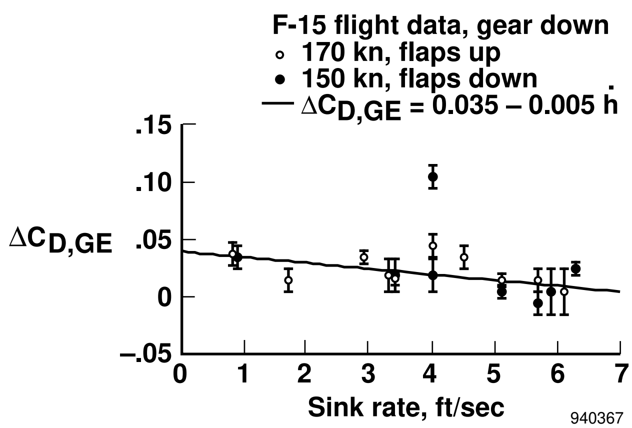


(d) Corrected for angle of attack and stabilator deflection.

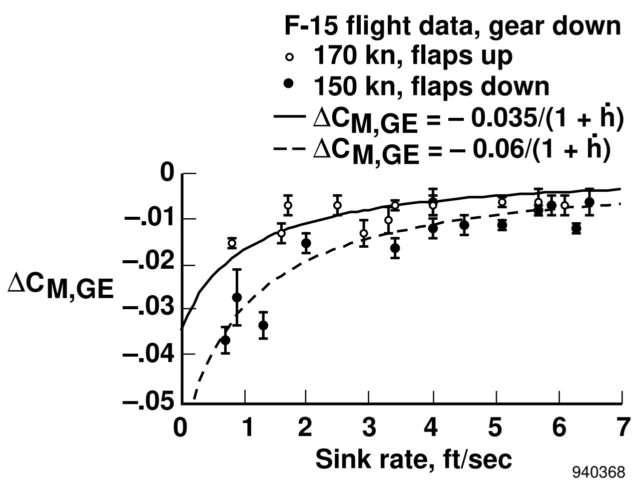
Figure 10. Change in F-15 pitching moment coefficient caused by ground effect as a function of height above the ground.



(a) Lift.



(b) Drag.



(c) Moment.

Figure 11. Effect of approach speed, flap setting, and sink rate on change in F-15 aerodynamic coefficients caused by ground effect.

Two approach speed and flap-setting combinations were flown: 150 kn with the flaps down (30° deflection) and 170 kn with the flaps up (0° deflection). The sink rate varied because of several factors. The primary contributors being pilot technique and atmospheric turbulence. Sink rates ranged from 0.7 (42 ft/min) to 6.5 ft/sec (390 ft/min). For reference, the F-15 landing gear has a maximum sink rate capability of approximately 10 ft/sec (600 ft/min).

In general, figure 11 shows that ground effect becomes increasingly significant as sink rate decreases. The changes in the lift coefficient (fig. 11(a)) and the nose-down pitching moment (fig. 11(c)) increase with decreasing sink rate. These data also show that the changes because of ground effect decreases and approaches zero as the sink rate increases. The change in the lift coefficient more than doubles from approximately 0.05 to over 0.1 as the sink rate decreases toward zero. The change in the nose-down pitching moment coefficient doubles from –0.008 to –0.016 for the 170 kn with the flaps up configuration and more than quadruples from –0.008 to –0.038 for the 150 kn with the flaps down configuration as the sink rate varies from the maximum to the minimum values.

The trends are not as clear for the drag coefficient (fig. 11(b)). The change in drag increased with decreasing sink rate from 0 to approximately 0.03. The large increase in drag at a sink rate of approximately 4 ft/sec may result from data scatter because of the greater sensitivity of calculating the small change in the drag force caused by ground effect.

Figure 11 also shows that the 150 kn with the flaps down approach results in significant ground effects. This difference is most apparent for pitching moment (fig. 11(c)). Here, the 150 kn with the flaps down values are approximately twice that of the 170 kn with the flaps up values at the lower sink rates. This increase may result from a camber effect because of the flaps being down.

The camber effect may be explained as follows: In general, ground effect reduces the downwash at the tail, hence the effective, local angle of attack increases which cause an increase in the lift at the tail. This increase in lift at the tail results in an increase in nose-down pitching moment for both approach configurations. For a highly cambered airfoil, such as a flapped wing, or a wing at high angle of attack, pronounced loss of lift because of ground effect relative to the uncambered wing occurs.[2] If the center of pressure of the wing is ahead of the aircraft center of gravity, this loss of lift on the main wing produces an increase in the nose-down pitching moment. This difference in lift is not evident in figure 11(a), but a marked increase in the nose-down pitching moment is seen in figure 11(c) for the 150 kn with the flaps down configuration versus the 170 kn with the flaps up configuration.

In addition, figure 11 shows simple correlation curves that have been fit through the ground effects data. These curves give the change in lift, drag, and pitching moment coefficients because of ground effect as a function of sink rate. The equations for the change in lift, drag, and moment are given next. Equation (10) applies to changes in lift.

$$\Delta C_{L,GE} = 0.2/(1+\dot{h}) + 0.02 \qquad (10)$$

Equation (11) applies to changes in drag.

$$\Delta C_{D,GE} = 0.035 - 0.005\dot{h} \qquad (11)$$

Equation (12) applies to changes in moment for the 150 kn with flaps down configuration.

$$\Delta C_{M,GE} = -0.06/(1+\dot{h}) \qquad (12)$$

Equation (13) applies to the changes in moment for the 170 kn with the flaps up configuration.

$$\Delta C_{M,GE} = -0.035/(1+\dot{h}) \qquad (13)$$

Previous Ground Effect Data Comparison

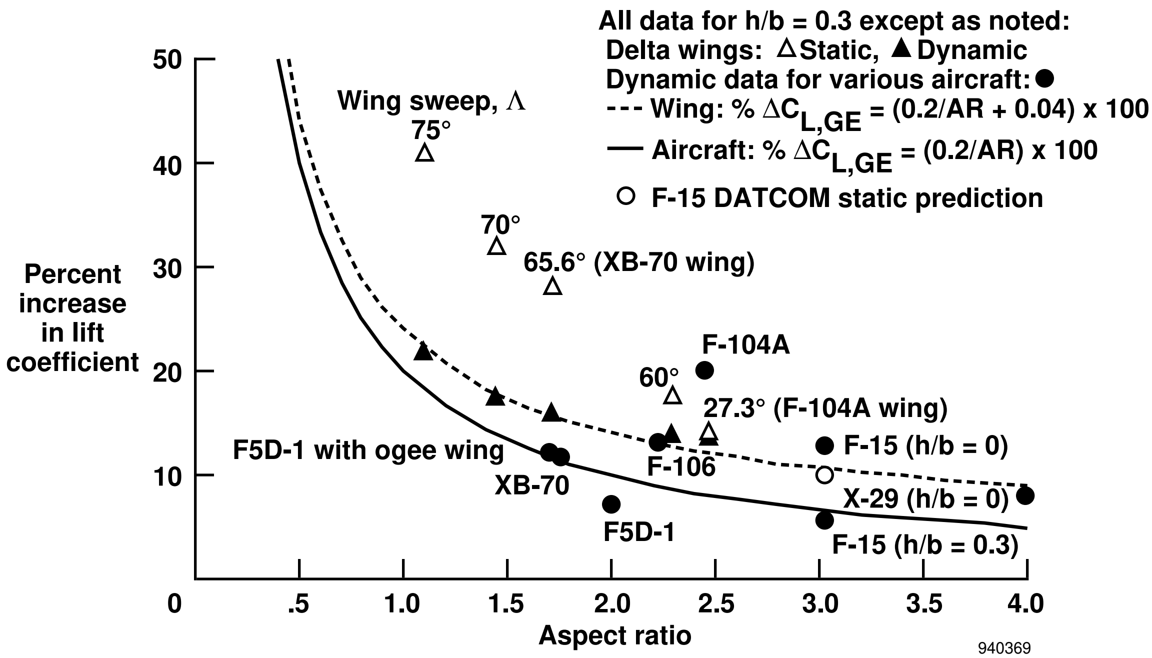
The F-15 ground effects lift data resulting from this investigation were compared to other wind-tunnel and flight data for various wings and for complete aircraft.[4,9,10] Data were not available for comparing drag and pitching moment. Wings data was available for several delta wings, including an XB-70 wing. Figure 3 shows the different aircraft configurations. Table 4 summarizes the data for the aircraft used in this comparison.

Figures 12(a) and 12(b) show the percent increase in the lift coefficient caused by ground effect, $\%\Delta C_{L,GE}$, as a function of aspect ratio, AR, and wing sweep, Λ, for the various wings and aircraft. The percent increase in lift coefficient is defined as the difference between the lift coefficients in and out of ground effect divided by the out of ground effect lift coefficient. Static and dynamic data for various wings and various aircraft are shown. These data are for a height above the ground divided by a wingspan of 0.3. These F-15 data are for the 170 kn with the flaps up configuration from landing 4 of flight 674.

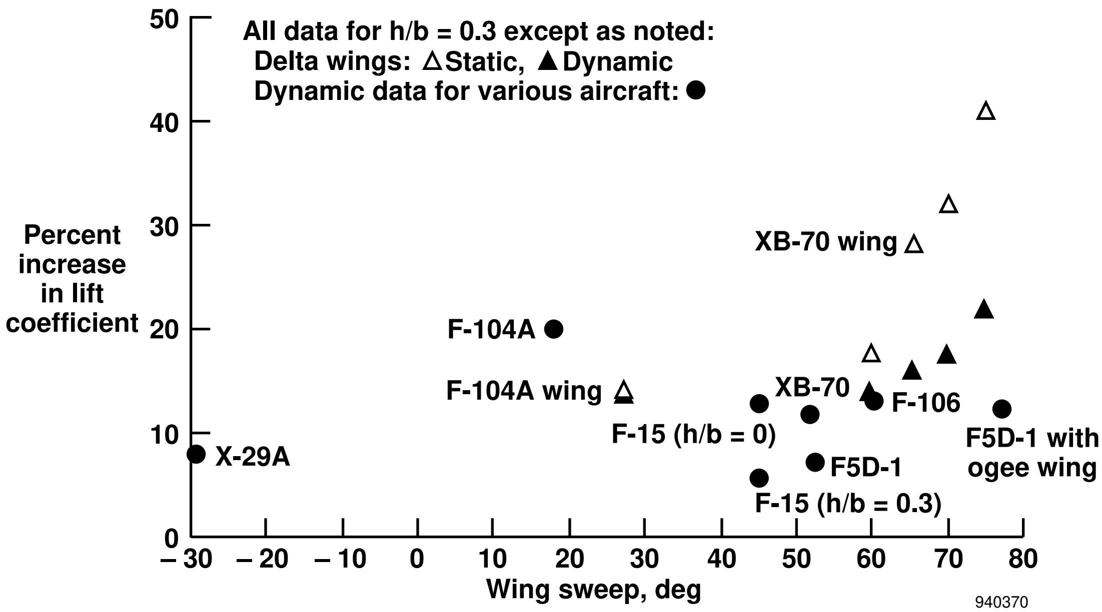
Table 4. Summary of data for aircraft used in ground effects correlation.

Aircraft	Wingspan, ft	Wing sweep, deg	Aspect ratio	Dynamic $\%\Delta C_L$ at $h/b = 0.3$	Data type
F-15	42.83	45	3.02	5.6	Flight
F-106B	38.3	60.25	2.24	13.0	Wind tunnel[5]
F-104A	21.9	18.1	2.45	20.0	Flight[9]
F5D-1	33.5	52.5	2.00	7.3	Flight[9]
F5D-1 ogee*	33.5	77.0	1.7	12.2	Flight[9]
XB-70	105.0	51.8	1.75	11.7	Flight[9]
X-29A	27.2	–29.3**	4.00	8.0***	Flight[10]

* F5D-1 modified with an ogee wing
** Forward swept wing
*** ($h/b = 0$)



(a) Aspect ratio.



(b) Wing sweep.

Figure 12. Percent increase in lift coefficient caused by ground effect for various wings and for various aircraft.

The lift coefficient increase for an *h/b* = 0 at touchdown and 0.3 are shown for the F-15 aircraft. Note that the F-15 percent of change in the lift coefficient increases from approximately 5.6 percent at an *h/b* = 0.3 to approximately 12.9 percent at touchdown (*h/b* = 0). In general, the F-15 flight data correlate well with the available aircraft dynamic ground effects data.

Correlation curves for the wing and for the aircraft are shown in figure 12(a) for the percent change in lift coefficient because of ground effect as a function of aspect ratio. These curves are given by equation (14) for the wing and equation (15) for the aircraft.

$$\%\Delta C_{L,GE} = (0.2/AR + 0.04) \times 100 \qquad (14)$$

$$\%\Delta C_{L,GE} = (0.2/AR) \times 100 \qquad (15)$$

Deviations of the aircraft data may result from differences in sink rate for the different landings or other configuration factors, such as wing sweep and vortex lift. These wing data were obtained at the same sink rate and correlate well.

Figure 12 also shows the U.S. Air Force DATCOM prediction for the change in the lift coefficient at an *h/b* = 0.3 for the F-15 aircraft. The prediction calls for an increase in lift coefficient of approximately 10 percent. In fact, a value of 5.6 percent was obtained from flight. Again, note that the U.S. Air Force DATCOM method is a static ground effects prediction, and these flight data are for dynamic ground effects.

These data show a decrease in the percent of change in lift coefficient as aspect ratio increases or wing sweep decreases. The changes in lift appear to approach nearly constant values for aspect ratios greater than approximately 3 and wing sweeps less than approximately 40° although data in these regions are scarce.

Wing data show the large difference between static and dynamic ground effects. Static values are approximately twice as great as the dynamic values at the lower aspect ratios and larger wing sweeps. Static and dynamic values converge as aspect ratio increases and wing sweep decreases.

Dynamic data show the difference between ground effect for a wing and for a complete aircraft. Both curves are similar; however, the aircraft values are lower than the wing values by a constant of approximately 4 percent. The lower values for the aircraft probably result from fuselage effects. The fuselage is probably not significantly affected by ground effect, and it also reduces the available wing area that can be influenced by ground effect versus a wing.

CONCLUSIONS

An in-flight investigation of dynamic ground effect was conducted for the F-15 aircraft. Data were collected for 24 landings on 7 test flights. Dynamic ground effects data were obtained for high- and low-sink rates.

Ground effect becomes increasingly significant as the sink rate decreases. For the F-15 aircraft, the change in the lift coefficient because of ground effect doubled from approximately 0.05 to 0.10 as the sink rate decreased from approximately 6.5 to 0.7 ft/sec. For this same decrease in sink rate, the change in the nose-down pitching moment increased from approximately –0.008 to –0.016 for the 170 kn with the flaps up configuration. An increase from approximately –0.008 to –0.038 occurred for the 150 kn with the flaps down configuration. The drag coefficient increased from 0 to approximately 0.03 over this sink rate range because of the increase in lift.

Changes caused by ground effect depend on the approach speed and flap setting of the aircraft. The difference was quite apparent in the change of the nose-down pitching moment. In this case, the 150 kn with the flaps down values were approximately twice those of the 170 kn with the flaps up values obtained at the lower sink rates. This increase may result from a camber effect because of the flaps.

The F-15 ground effects flight data for lift compared well to previously collected ground effects wind-tunnel and flight test data for various wings and for complete aircraft. A simple correlation with aspect ratio fit the wing and aircraft data well.

Dryden Flight Research Center
National Aeronautics and Space Administration
Edwards, California, May 6, 1994

REFERENCES

[1]Hoerner, Sighard F. and Borst, Henry V., *Fluid-Dynamic Lift*: *Practical Information on Aerodynamic and Hydrodynamic Lift,* 2nd edition, published by Liselotte A. Hoerner, Brick Town, New Jersey, 1985.

[2]Chang, Ray C. and Muirhead, Vincent U., "Investigation of Dynamic Ground Effect," *Proceedings of the 1985 NASA Ames Research Center's Ground-Effects Workshop*, NASA CP-2462, Aug. 20, 1985, pp. 363–393.

[3]Lee, Pai-Hung, Lan, C. Edward, and Muirhead, Vincent U., *An Experimental Investigation of Dynamic Ground Effect*, NASA CR-4105, 1987.

[4]Lee, Pai-Hung, Lan, C. Edward, and Muirhead, Vincent U., "Experimental Investigation of Dynamic Ground Effect," *J. of Aircraft*, vol. 26, no. 6, June 1989, pp. 497–498.

[5]Kemmerly, G.T., Paulson, J.W., Jr., and Compton, M., "Exploratory Evaluation of Moving-Model Technique for Measurement of Dynamic Ground Effects," *J. of Aircraft*, vol. 25, no. 6, June 1988, pp. 557–562.

[6]Paulson, John W., Jr., Kemmerly, Guy T., and Gilbert, William P., "Dynamic Ground Effects," *Aerodynamics of Combat Aircraft Controls and of Ground Effects*, AGARD CP-465, 1990, pp. 21-1–21-12.

[7]Furlong, G. Chester and Bollech, Thomas V., *Effect of Ground Interference on the Aerodynamic and Flow Characteristics of a 42° Sweptback Wing at Reynolds Numbers Up to* 6.8×10^6, NACA TR-1218, 1955.

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

[9]Baker, Paul A., Schweikhard, William G., and Young, William R., "Flight Evaluation of Ground Effect on Several Low-Aspect Ratio Airplanes," NASA TN D-6053, 1970.

[10]Curry, Robert E., Moulton, Bryan, J., and Kresse, John*, An In-Flight Investigation of Ground Effect on a Forward-Swept Wing Airplane*, NASA TM-101708, 1989.

[11]Burcham, Frank W., Jr., Maine, Trindel A., Fullerton, C. Gordon, and Wells, Edward A., *Preliminary Flight Results of a Fly-by-Throttle Emergency Flight Control System on an F-15 Airplane*, NASA TM-4503, 1993.

[12]McDonnell Douglas Corporation, *USAF Stability and Control DATCOM*, U.S. Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, Oct. 1960 (Revised Apr. 1976).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
September 1994

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Dynamic Ground Effects Flight Test of an F-15 Aircraft

5. FUNDING NUMBERS
WU-533-02-31

6. AUTHOR(S)
Stephen Corda, Mark T. Stephenson, Frank W. Burcham, and Robert E. Curry

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Dryden Flight Research Center
P.O. Box 273
Edwards, California 93523-0273

8. PERFORMING ORGANIZATION REPORT NUMBER
H-1999

9. SPONSORING/MONOTORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-4604

11. SUPPLEMENTARY NOTES
Stephen Corda, PRC Inc., Edwards, California; Mark T. Stephenson, Frank W. Burcham, and Robert E. Curry, NASA Dryden Flight Research Center, Edwards, California.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified—Unlimited
Subject Category 02

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Flight tests to determine the changes in the aerodynamic characteristics of an F-15 aircraft caused by dynamic ground effects are described. Data were obtained for low- and high-sink rates between 0.7 and 6.5 ft/sec and at two landing approach speeds and flap settings: 150 kn with the flaps down and 170 kn with the flaps up. Simple correlation curves are given for the change in aerodynamic coefficients because of ground effects as a function of sink rate. Ground effects generally caused an increase in the lift, drag, and nose-down pitching moment coefficients. The change in the lift coefficient increased from approximately 0.05 at the high-sink rate to approximately 0.10 at the low-sink rate. The change in the drag coefficient increased from approximately 0 to 0.03 over this decreasing sink rate range. No significant difference because of the approach configuration was evident for lift and drag; however, a significant difference in pitching moment was observed for the two approach speeds and flap settings. For the 170 kn with the flaps up configuration, the change in the nose-down pitching moment increased from approximately –0.008 to –0.016. For the 150 kn with the flaps down configuration, the change was from approximately –0.008 to –0.038.

14. SUBJECT TERMS
Aircraft aerodynamics; Aircraft approach and landing; F-15 aircraft; Flight testing; Ground effect; Propulsion-controlled aircraft

15. NUMBER OF PAGES
26

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
Unlimited