20. FLIGHT STUDIES OF GROUND EFFECTS ON AIRPLANES

WITH LOW-ASPECT-RATIO WINGS

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SUMMARY

The ground effects on two aircraft with low-aspect-ratio delta wings, the F5D-1 and the XB-70A, were measured in flight tests. In a companion program, both small and full-scale models and several wind tunnels were used to document the ground effects for the F5D-1. These flight tests indicated ground effects were not a problem in landing either of these vehicles. The limited wind-tunnel program indicated that scale effects were not of first-order importance in defining ground effects, and that wind-tunnel tests provide reasonable agreement with the values in flight. A simulation study, using a fixed-cockpit projection-type simulator, performed in conjunction with these studies indicated levels of moment and lift changes which would be unsatisfactory from the pilot's viewpoint; however, some possible alleviating features were noted.

INTRODUCTION

For low-aspect-ratio wing designs the effect of ground proximity on longitudinal aerodynamics is becoming recognized as contributing significantly to take-off and landing characteristics. The increase in lift due to the ground effect helps to reduce the long ground rolls associated with the high take-off speeds of these aircraft. But on the other hand, the pitching-moment changes due to these ground effects may adversely affect the pilot's ability to make an accurate flare during landing or the rotation maneuver during take-off. For example, preliminary fixed-cockpit simulation studies of the landing characteristics of a large, low-aspect-ratio aircraft indicated that the pilots had difficulty in making precise landings when the anticipated ground effects were programed into the simulation. The fact that the simulator study indicated a control problem while none has been encountered in low-aspect-ratio aircraft currently flying suggests the need for further investigation of the problem. Several possible sources of the difference have been suggested. One is the possibility that Reynolds number significantly affects small-scale wind-tunnel measurements of ground effect. Second is the possibility that the pilot cannot make realistic assessments from fixed-base simulations in which motion is lacking and the resolution in the visual display is limited.

Flight-test programs on two low-aspect-ratio delta-wing aircraft were extended to measure the ground effect on each. These aircraft are the F5D-1, equipped with an ogee planform, being flown at the Ames Research Center, and the XB-70A, which is currently undergoing joint Air Force and NASA flight testing at Edwards Air Force Base. In addition, comprehensive tests with both small and full-scale models were conducted in several wind tunnels to document the characteristics of the F5D-1 aircraft.

This paper will present the ground effect data measured on the XB-70A and the F5D-1 aircraft in flight, will compare wind-tunnel and flight data, and will indicate, on the basis of piloted simulator studies, the manner in which various magnitudes of ground effect influence the precision of the landing.

SYMBOLS

C_L	lift coefficient, L/qS
$C_{L_{trim}}$	lift coefficient in trim
C_{L_∞}	lift coefficient out of ground effect
C_D	drag coefficient, D/qS
$\bar{c}$	mean aerodynamic chord, ft
D	drag, lb
g	acceleration due to gravity, ft/sec^2
h	distance from reference point on aircraft to ground, ft
L	lift, lb
q	dynamic pressure, lb/sq ft
S	wing area, sq ft
T	thrust, lb
W	weight, lb
δ_E	elevon deflection, deg
$\delta_{E_{trim}}$	elevon deflection required for trim, deg
γ	flight-path angle, deg

$(\Delta C_L)_{GE}$ change in lift coefficient due to ground effect

$(\Delta C_m)_{GE}$ change in pitching-moment coefficient due to ground effect

TEST AIRCRAFT AND TEST TECHNIQUES

Test Aircraft

Figures 1 and 2 are photographs of the two aircraft for which ground effects were measured in flight. Figure 1 shows the F5D-1 aircraft, constructed by the Douglas Aircraft Company with a wing modified to an Ogee planform. This aircraft has an aspect ratio of 1.70, a wing area of 661 square feet, and a mean aerodynamic chord of 22.6 feet. Figure 2 shows the XB-70A aircraft, a multijet, supersonic bomber built by North American Aviation. This aircraft has an aspect ratio of 1.75, a wing area of 6300 square feet, and mean aerodynamic chord of 78.5 feet. It is apparent that there is a large difference in the size of the two aircraft.

Test Techniques

Ground effect on the XB-70A was measured during the landing approach while the aircraft was making a steady descent at a constant angle of attack and power setting. The increase in lift coefficient was determined from the resultant flare as the aircraft approached the ground. In addition, the change in elevon position determined the pitching moment due to ground effect. The equations for determining the lift changes from the measured quantities are shown in figure 3. In this case, the Askania Tracking System of the Air Force Flight Test Center's take-off and landing facility was used to measure the changes in rate of descent and flight path, while onboard instrumentation recorded angle of attack and elevon position.

The data for the F5D-1 aircraft were obtained during level "fly-by" runs at various heights and at several speeds. Figure 4 shows the aircraft during one of these runs along the runway. (The white shadow across the base of the vertical surface is a condensation trail caused by the strong vortex at the root leading edge of the ogee wing.) This method relied upon the onboard measurements of aircraft accelerations, thrust, attitude, and height to permit the calculation of the parameters significant to ground effect. The methods for reducing these measured quantities to lift and drag coefficients are presented in reference 1. A Lockheed Location Orientation Recording Instrument (LORI) was mounted vertically on the lower surface of the fuselage. This system measured aircraft height above the runway, rate of change in height, ground speed, and pitch angle.

The wind-tunnel program conducted in conjunction with the flight tests of the ogee wing F5D-1 aircraft included tests in three wind tunnels and afforded the opportunity to evaluate scale effects as well as to compare tunnel and flight measured results. For the full-scale data the actual aircraft was used as a model in the Ames 40- by 80-foot wind tunnel and for the small-scale data a properly modified 0.15-scale model of the F5D-1 aircraft was tested in the Lockheed 8- by 12-foot wind tunnel and the Langley 7- by 10-foot wind tunnel. Tests in the Langley tunnel were conducted with both a moving and stationary ground plane.

RESULTS AND DISCUSSION

Figure 5 shows a set of data measured on the XB-70A aircraft. Briefly, the measured data, in the form of the rate of descent and elevon angle to trim, are plotted as a function of the height parameter or the height divided by the mean aerodynamic chord. The change in the rate of descent as the vehicle nears the ground is used to calculate the resultant increase in lift coefficient. During this flight maneuver, elevon motion is used to maintain the prescribed flight path. Thus, to obtain the actual lift coefficient increase due to ground effect, it is necessary to correct the measured lift increment to zero elevon angle as shown on this figure. For this particular aircraft the elevon movement nearly cancels the increase in lift due to the ground effect. Also on this figure two symbols indicate the amount of ground effect measured in a wind tunnel. The wind-tunnel data are too limited for definitive conclusions as to agreement, but testing is continuing.

The effect of the ground proximity on the aerodynamic properties of the F5D-1 aircraft is presented on figure 6, which shows the variations of angle of attack, drag coefficient, and elevon angle for trim as a function of lift coefficient. The shaded area on each curve shows the ranges covered during the flight tests. One boundary curve represents the characteristics out of ground effect while the other boundary represents the characteristics at touchdown and there are progressive variations with height between these curves. Thus, the difference between these two curves is the magnitude of the ground effect for each quantity.

Comparisons of the flight and wind-tunnel measured ground effect on the F5D-1 ogee configuration are presented on figures 7 and 8. Figure 7 presents the lift data and figure 8 the moment data in terms of the elevon angle required for trim. For simplicity of presentation, only the lift and moment comparisons are presented, and they are presented at only the highest and lowest height for which comparative data are available. The aircraft touchdown occurs at an $h/\bar{c}$ of 0.28. A more complete comparison is presented in reference 2. The curves are identified with each wind tunnel, while the data points are the flight data. The Langley tests in the 7- by 10-foot wind tunnel showed no difference between the data for the ground plane moving or stationary and the lift data from all sources agree well. The moment data show a difference between the flight and wind-tunnel data equivalent to about 2-percent mean aerodynamic chord uncertainty in the location of the centers of rotation or a shift in the moment at zero lift equal to about 1° of elevon angle. The cause of these discrepancies has not been established, but in any case they are small enough to be of little concern. In general, it appears from this limited comparison that scale effect is not of first-order importance in defining ground effect, and that wind-tunnel tests provide reasonable agreement with values determined in flight.

The measured effects of the ground proximity on the aerodynamic characteristics of the aircraft were used to calculate the landing characteristics illustrated in figure 9. These data from analog computed landings show the rate of descent at various heights and indicate that the ground effect depends on how the pilot controls the aircraft. The data on the left side of the figure are for a constant pitch attitude approach and illustrate that there is a large reduction in the rate of descent at touchdown. In essence, the data indicate what the response would be if the pilot were completely successful in counteracting the effect of the pitching-moment change on the aircraft's attitude, thus permitting the lift increment to assist in arresting the rate of descent. The required elevon angle variation does, however, reduce the ground effect lift increment as was noted in the case of the XB-70A. The right side of the figure shows the approach with constant elevon control. Here, the pitching moment has a predominant effect on the rate of descent near the ground as evidenced by the increase in rate of descent at touchdown. Also these figures show that the low approach angle is generally beneficial except that for the constant attitude case the aircraft actually did not touch down, but ballooned.

While it is beyond the scope of this paper to go into detail regarding the simulator study, it is considered apropos to make some mention of these results. To provide some confidence to the simulation, a considerable amount of time was spent in simulating characteristics of aircraft (the F5D-1 and the DC-8) with which the pilots had some flight experience or knowledge. After the pilots gained confidence in the simulation, they rated the landing characteristics of a large low-aspect-ratio delta-wing aircraft with various combinations of lift and moment changes due to ground effect. Their ratings are summarized on figure 10. It should be emphasized that these data are preliminary and are presented simply to indicate trends -- not to establish boundaries. The ordinate is the change in lift coefficient due to ground effect divided by the lift coefficient out of ground effect and the abscissa is the change in pitching moment due to ground effect divided by the lift coefficient out of ground effect. The combinations of lift and moment changes due to ground effect which were investigated on the simulator fall within the shaded areas. The adjective pilot rating is listed beside each test configuration. The pilots rated the conditions on the right side of the figure as unsatisfactory because of the difficulty in controlling the large pitch-down tendencies; they rated those in the upper region as only marginally satisfactory because of the additional effort necessary to control the floating tendencies; and they rated those in the lower left area as satisfactory. These tests also indicated the pilots reacted more to small changes in the pitching moment than to small changes in the lift. An incidental point of interest is that these simulator studies indicated an improvement in the pilots' ratings if the lift increment "leads" the pitching-moment change (i.e., starts to increase at heights higher than those where the pitching moment starts to change). It was also observed generally that if the moment change occurs after the pilot has started his flare maneuver, the effect of the pitching moment tends to be obscured; this suggests one reason why the unfavorable pitching-moment changes have not been significant for the smaller aircraft. The moment and lift changes for the F5D-1 and the XB-70A aircraft fall in the area considered satisfactory by the pilot.

CONCLUDING REMARKS

Flight tests on two low-aspect-ratio delta-wing aircraft indicated that the ground effect was not a problem in landing either vehicle. A limited wind-tunnel program indicated that scale effects were not of first-order importance in defining ground effect, and that wind-tunnel tests provide reasonable agreement with values in flight. Simulator studies indicated the levels of moment and lift changes due to ground effect which would be unsatisfactory from the pilot's standpoint; however, some possible alleviating features were noted.

REFERENCES

1. Rolls, L. Stewart; and Wingrove, Rodney C.: An Investigation of the Drag Characteristics of a Tailless Delta-Wing Airplane in Flight, Including Comparison With Wind-Tunnel Data. NASA MEMO 10-8-58A, 1958.

2. Rolls, L. Stewart; and Koenig, David G.: Flight Measured Ground Effect on a Low-Aspect-Ratio Ogee Wing Including a Comparison With Wind-Tunnel Results. NASA TN D-3431, 1966.

F5D-I AIRCRAFT

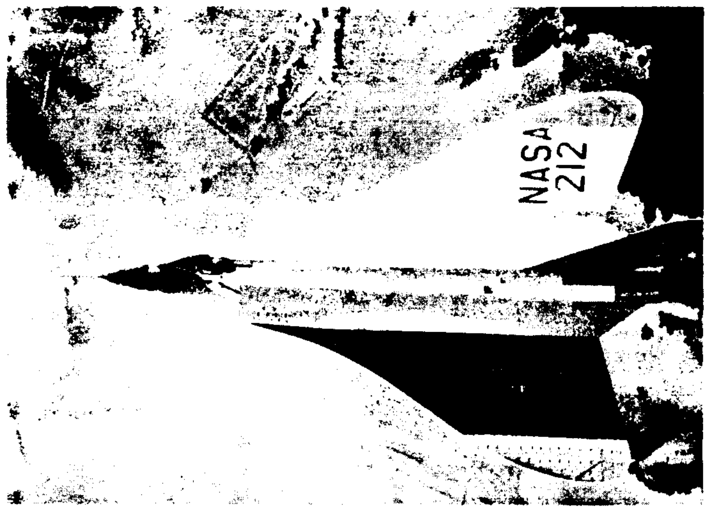


Figure 1 A-33500-3

XB-70A AIRCRAFT

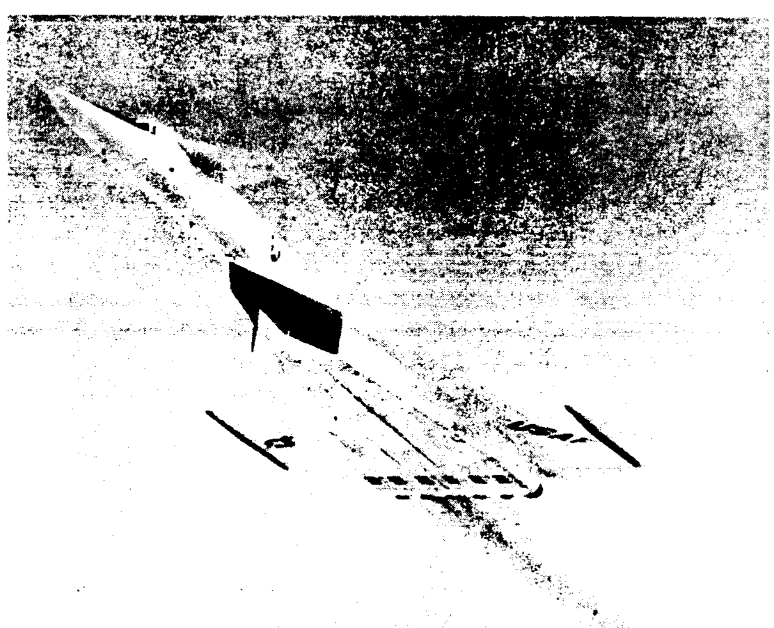
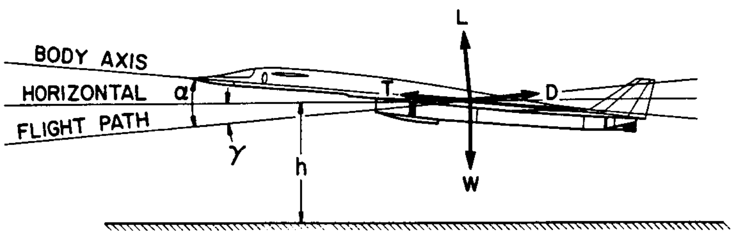


Figure 2 A-36987

LIFT EQUATION, XB-70A METHOD



EQUATING VERTICAL FORCES

$$L \cos \gamma + D \sin \gamma - W + T \sin(\alpha - \gamma) = \frac{W}{g}\frac{d^2h}{dt^2}$$

ASSUMING: γ IS SMALL (3° OR LESS) & $T \sin(\alpha - \gamma)$ IS SMALL

THEN: $$L \cos \gamma - W = \frac{W}{g}\frac{d^2h}{dt^2}$$

Figure 3

F5D-I DURING LEVEL RUN ALONG RUNWAY

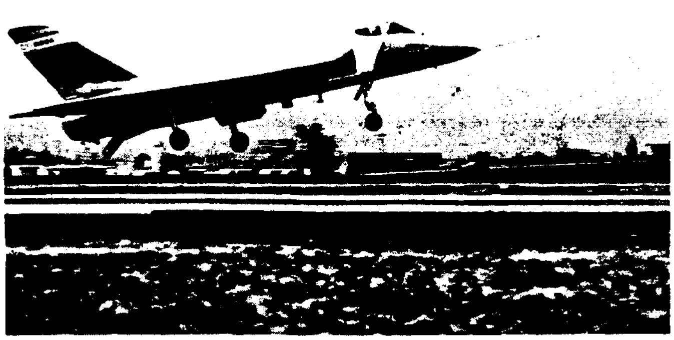


Figure 4 A-35650-2

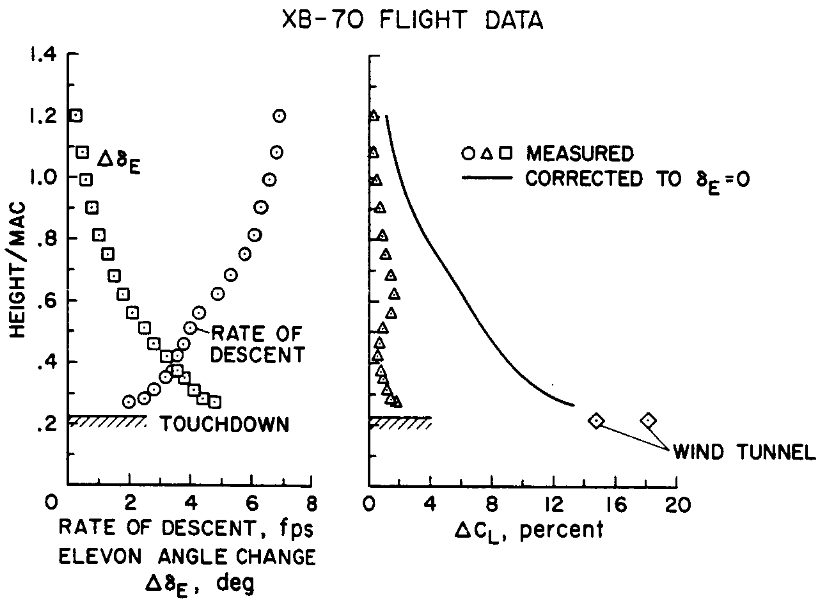


Figure 5

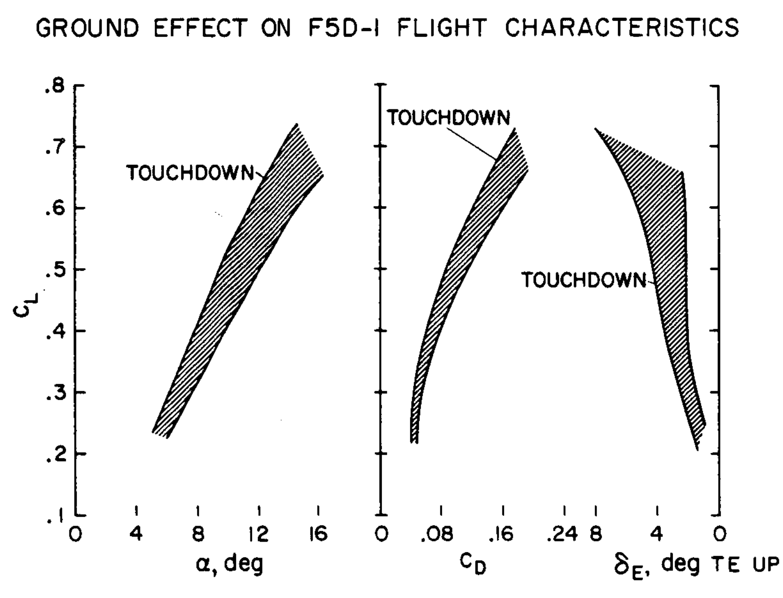


Figure 6

COMPARISON OF FLIGHT AND WIND TUNNEL DATA
LIFT CHARACTERISTIC

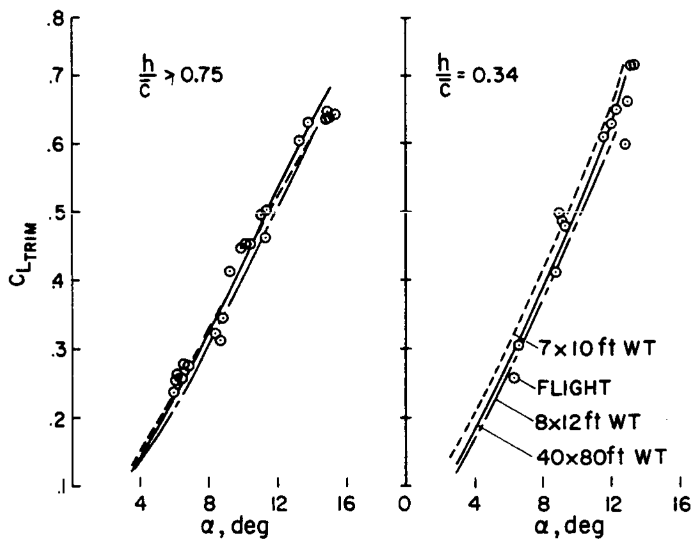


Figure 7

COMPARISON OF FLIGHT AND WIND TUNNEL DATA
ELEVON ANGLE FOR TRIM

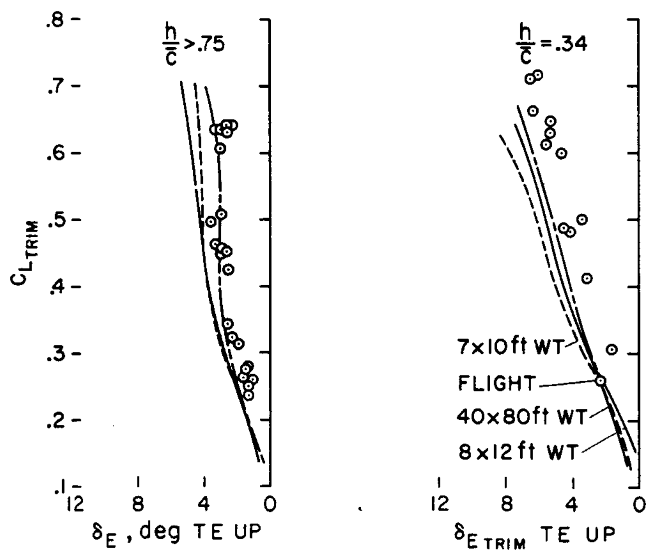


Figure 8

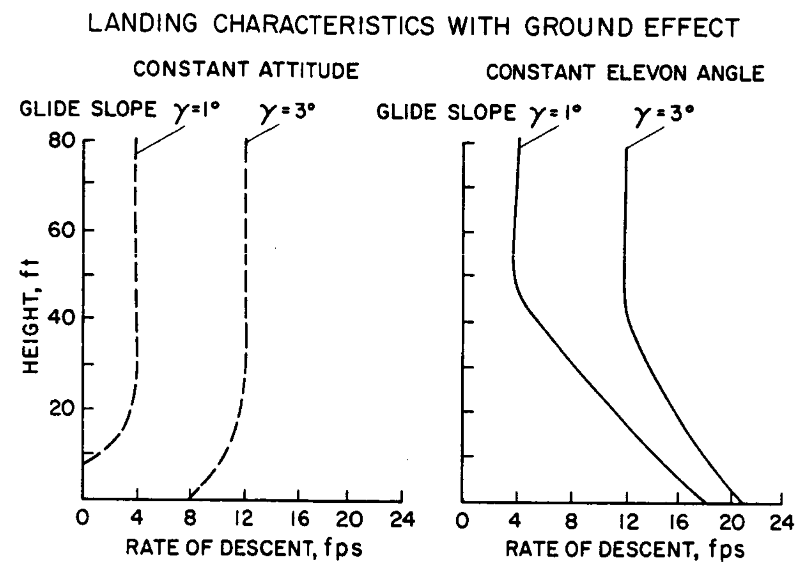


Figure 9

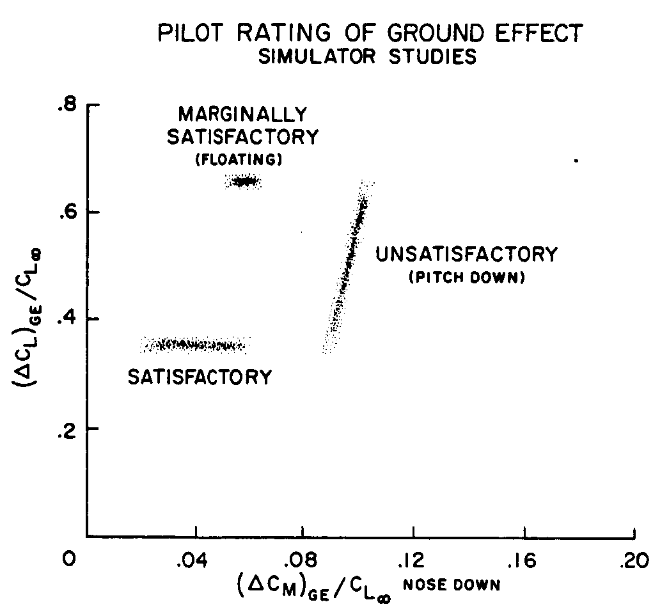


Figure 10