N87-24421

THE GROUND EFFECTS OF A POWERED-LIFT STOL AIRCRAFT DURING LANDING APPROACH

Victor C. Stevens

Ames Research Center

SUMMARY

This paper presents the effects of ground proximity on a powered-lift STOL aircraft. The data presented in this paper are from NASA's Quiet Short Haul Research Aircraft (QSRA) flown at landing approach airspeeds of less than 60 knots with an 80 lb/ft^2 wing loading (C_L > 7). These results show that the ground effect change in lift is positive and does significantly reduce the touchdown sink rate. These results are compared to those of the YC-14 and YC-15. The change in drag and pitching moment caused by ground effects is also presented.

NOMENCLATURE

AGL	above ground level, ft
A_x	body-axis acceleration, fwd and aft (+ fwd), g's
A_z	body-axis acceleration vertical (+ up), g's
b	aircraft wing span, ft (b = 73 ft for QSRA)
C_D	measured-drag coefficient
C_{D_∞}	free-air drag coefficient (out of ground effect)
C_L	measured lift coefficient
C_{L_∞}	free-air lift coefficient (out of ground effect)
C_T	thrust coefficient
g	acceleration caused by gravity, 32.2 ft/sec^2
GE	ground effect
h	height above the ground, ft
h/b	wing height above the ground in terms of wing span

PRECEDING PAGE BLANK NOT FILMED

q	dynamic pressure, lb/ft^2
S	aircraft wing area, ft^2 ($S = 600\ ft^2$ QSRA)
TEU	trailing edge up
V	aircraft velocity, ft/sec
α	angle of attack, deg
δ_e	elevator position, deg
ΔV_I	induced velocity caused by image bound vortex, ft/sec
θ	pitch attitude, deg
$\dot{\theta}$	pitch rate, deg/sec
$\ddot{\theta}$	pitch acceleration, deg/sec^2

INTRODUCTION

Ground effects have a strong influence on an aircraft's landing performance. For STOL aircraft designed to use as little runway as possible, this influence of ground effects is even more significant. In the past, there has been a lack of agreement between ground effect data obtained from wind tunnel tests and that of aircraft flight testing, especially at high lift coefficients (refs. 1 and 2). This has created a need for more flight test data to accurately define the actual ground effects of powered-lift STOL aircraft for future designs and flight simulation math models. Other reports have previously presented the ground effects of the YC-15 powered lift STOL aircraft, which landed at lift coefficients slightly over 3 (refs. 3 and 4). This paper presents a technique to derive the ground effects from powered-lift aircraft flight data and then gives the results of using this technique for NASA's Quiet Short Haul Research Aircraft (QSRA) (fig. 1) landing at lift coefficients greater than 7. Comparisons are made between the YC-14, the YC-15, and the QSRA flight data.

TECHNIQUE

Ground effect data are analyzed in terms of aircraft wing height above the ground (h) divided by the wingspan (b). This normalized aircraft height, referred to as "h/b," allows comparison of ground effects among various aircraft configurations. At $h/b = 1$, for the QSRA the wing height above the ground is 73 ft. At touchdown, the QSRA's wing height is 13.9 ft or $h/b = 0.19$. The normal assumption is that at h/b greater than 1, the ground effects have no appreciable influence on the aircraft. The primary problem in determining the magnitude ground effects is to separate the ground effects from the influence of pilot control inputs and atmospheric effects on aircraft dynamics during a landing approach. The flight maneuver used to obtain good ground effect data is a landing approach that minimizes pilot control inputs with the aircraft flown in calm wind conditions (less than 3 knots). The pilot's flight card read as follows:

> "Perform landing approaches to touch down with the following procedures to obtain ground effect data. Stabilize the aircraft 200 feet above ground level (AGL) during landing approach. Below 200 feet AGL do not change flaps or Engine Fan RPM, maintaining a constant airspeed with a minimum of control inputs. As the aircraft nears the ground (less than 40' AGL), use elevator control inputs to hold pitch attitude constant to touchdown (No Flare)."

The goal of these instructions is to force any dominant change in aircraft dynamics during the landing approach to be caused by the ground effects. The pilot must stabilize the aircraft out of ground effects (when $h/b > 1$) for sufficient time to obtain good average values of C_L, α, C_T, C_D, δ_e for each landing approach. These values can then be used as reference values in the small perturbation model equation (eqs. 2, 5, and 6).

Figure 2 is a plot of lift coefficient (C_L) versus normalized height (h/b) for a QSRA landing approach. The aircraft C_L (top curve) is calculated at each data point by:

$$C_L = Wt/qS\,(A_x \sin\alpha + A_z \cos\alpha) \tag{1}$$

where $+A_x$ is fwd (body axis)
$+A_z$ is up

A plot of C_L versus h/b by itself cannot indicate the magnitude of the ground effects, since other quantities such as angle of attack, airspeed, and thrust coefficient may vary during the landing approach and thus change the value of C_L. To determine the magnitude of ground effects on lift coefficient, the measured lift coefficient (C_L) is compared to a small perturbation model for lift coefficient (C_{L_∞}). This small perturbation model of lift coefficient represents what the lift coefficient is for the same flight conditions in free air (out of ground effects) and takes into account changes in C_L due to small variations of angle of attack and thrust coefficient.

$$C_{L_\infty} = C_{L_{ref}} + \frac{\Delta C_L}{\Delta \alpha}(\alpha - \alpha_{ref}) + \frac{\Delta C_L}{\Delta C_T}(C_T - C_{T_{ref}})$$

(Small perturbation model of C_L) (2)

The values of $C_{L_{ref}}$, α_{ref}, and $C_{T_{ref}}$ are the averages of these quantities during each landing approach while the aircraft is stabilized at an altitude above which there is no significant ground effect influence on the aircraft. The change in lift caused by ground effects, $\Delta C_{L_{GE}}$, as shown in figure 2, is the difference between the measured lift coefficient C_L and the calculated equivalent free air lift coefficient C_{L_∞}. The validity of this procedure can be verified by the degree with which measured C_L and modeled C_{L_∞} match out of ground effect (h/b > 1) (see fig. 2). The lift coefficient used in this paper is the total aircraft lift which includes the direct lift caused by the engine exhaust flow turning (ref. 5).

Figure 3 is a time history of a typical QSRA landing approach used to obtain ground effects data. Note the relatively constant pitch attitude (θ) during the approach, the constant engine fan % rpm (constant thrust) and the change in the elevator (δ_e) required to maintain the relatively constant pitch attitude to touch down. The reference values used in this landing approach ($C_{L_{ref}}$, α_{ref}, $C_{T_{ref}}$, etc.) were the average of these quantities from 22 seconds to 31 seconds as shown in figure 3. The α used in equation (2) is true alpha derived from θ and γ, not the noseboom vane alpha, α_V, which is shown in the time history of the landing approach. The flightpath angle, γ, is determined from the true airspeed and the barometric altitude rate of change.

AIRSPEED MEASUREMENT

Valid ground effect measurements require accurate airspeed measurements. Airspeed measurement for ground effects analysis is complicated since the ground effect itself causes errors in the aircraft's pitot-static system. One technique that can be used to evaluate the ground effect influence on the pitot-static system is to measure the difference between the barometric altitude above ground level and the radar altitude as the aircraft approaches the ground. Figure 4 shows this pressure altitude error for the Boeing YC-14 which has its static pressure source located just below the pilot's side cockpit window. Figure 5 shows the same error in pressure altitude due to ground effects for the QSRA with a noseboom static source. Since the QSRA's static source on the noseboom is 0.6 of a wingspan in front of the wing, the influence of ground effect is much less. Since the ground effect data are determined by taking a small difference between two relatively large values, this small correction to the noseboom airspeed must be made. At 60 knots airspeed, a 3 ft pressure altitude error is equal to a 1.6 knot airspeed error, which results in a 5% error in determining C_L. The equation to correct airspeed using the measured pressure altitude error is given by:

$$\Delta V_I = \frac{g\ \Delta h}{V} \tag{3}$$

where

g = 32.2 ft/sec (acceleration of gravity)
Δh = pressure altitude error, ft ($= h_{baro_{AGL}} - h_{radar}$)

This airspeed error that is induced at the noseboom results from the image of the bound vortex as shown in figure 6. As the aircraft descends to touchdown, the angle ψ between the induced velocity ΔV_I vector and the aircraft velocity vector increases. Thus, the ΔV_I component on the aircraft velocity is needed to correct airspeed error caused by ground effects. These airspeed corrections have been applied to the QSRA ground effects data of this study (and to the YC-14 data) to derive the correct values of lift coefficient.

Lift

Figure 7 shows the percent increase of lift, due to ground effect as a function of h/b for five QSRA landing approaches. This clearly illustrates that the influence of ground effect is increasing lift even while landing at high lift coefficients. The QSRA's percent change in lift due to ground effect is very similar in shape and magnitude to the plots of YC-15 flight data in figure 8 and to the YC-14 flight data in figure 9 landing at lower lift coefficients.

Drag

The change in drag caused by ground effects was determined by the same method as that used for lift. The change in drag due to ground effect was determined from the difference between the measured drag coefficient (C_D) and the expected modeled free air drag coefficient (C_{D_∞}).

$$C_D = Wt/qS\,(-A_x \cos \alpha + A_z \sin \alpha) \qquad \text{(measured)} \qquad (4)$$

where $+A_x$ is fwd (body axis)
$+A_z$ is up

$$C_{D_\infty} = C_{D_{ref}} + \frac{\Delta C_D}{\Delta C_T}(C_T - C_{T_{ref}}) + \frac{\Delta C_D}{\Delta C_L}(C_{L_\infty} - C_{L_{ref}}) \qquad \text{(Free Air)} \qquad (5)$$

The change in drag coefficient caused by ground effects is shown in figure 10. The data for the five QSRA landing approaches show a large variation in the change in drag coefficient caused by ground effect at $h/b \approx 0.2$. Also, this reduction in drag coefficient for the QSRA is much larger than that obtained by Dr. Parks for the YC-15 (ref. 4) as shown by the solid symbols in figure 10. If the $\Delta C_{D_{GE}}$ data are divided by the square of the lift coefficients to normalize the curves, this data coalesce as shown in figure 11. This normalization by C_L^2 is logical since the ground effect is expected to cause a reduction in the induced drag which is proportional to C_L^2. This normalization not only causes the coalescence of the QSRA data, but brings the YC-15 data into much closer agreement with the QSRA data.

Pitching Moments

The change in aircraft pitching moment resulting from ground proximity can be evaluated by the amount of elevator required to maintain constant aircraft pitch attitude (θ) near the ground. Again, the measured elevator position (δ_e) is compared to the elevator (δ_{e_∞}) position of the model expected for the same flight conditions in free air (eq. 7).

$$\delta_{e_\infty} = \delta_{e_{ref}} + \frac{\Delta\delta_e}{\Delta C_T}(C_T - C_{T_{ref}}) + \frac{\Delta\delta_e}{\Delta C_L}(C_{L_\infty} - C_{L_{ref}}) + \frac{\Delta\delta_e}{\Delta\dot{\theta}}(\dot{\theta}) + \frac{\Delta\delta_e}{\Delta\ddot{\theta}}(\ddot{\theta}) \qquad (6)$$

$$\delta_{e_{GE}} = \delta_e - \delta_{e_\infty} \qquad (7)$$

Figure 12 shows the change in elevator position required to maintain constant aircraft pitch attitude for nine landing approaches. There is considerable scatter in the data at $h/b = 0.2$ (just before touchdown). Figure 13 shows the elevator position at $h/b = 0.2$ as a function of landing approach airspeed. This figure clearly shows the strong influence that airspeed has on the amount of elevator required to maintain constant pitch attitude. Since the ground effects are so dominant for the amount of elevator required, the simpler equation $\delta_{e_{GE}} = \delta_e - \delta_{e_{ref}}$ for relatively constant pitch attitude landing approaches will give a good first order indication of the elevator inputs required to compensate for ground effects.

DISCUSSION AND SIGNIFICANCE OF THE RESULTS

The most significant result of the increase in lift caused by ground effects is the reduction in touchdown sink rate which is a minimum of 2 ft/sec for the QSRA. This sink rate reduction data in figure 14 is the comparison of steady state sink rate and aircraft pitch attitude at $h/b = 1$ to the sink rate at touchdown.

The positive ground effects influenced the technique used in the QSRA carrier landing program (ref. 6). A sink rate was chosen for the carrier landings that would allow the QSRA to "punch" through the ground effect, but not exceed the landing gear sink rate limits. If a landing approach was made too shallow, at a glideslope angle less than 3°, the QSRA would float as shown in the time history in figure 15. This float increases the touchdown dispersion significantly. Note in this time history the airspeed increase caused by the reduction in drag in ground effect. Note that the aircraft did not land until the engine thrust (engine fan rpm) was reduced.

The elevator position change required when $h/b < 1$ to counter the pitching moment change is very significant, especially considering the QSRA has a T tail. The elevator authority required to maintain constant pitch attitude with ground effects would increase significantly for a conventional, low-mounted tail. Figure 13 shows the strong influence of landing approach speed on the elevator authority requirement. Pilots are not generally aware of the large amount of elevator required to compensate for ground effects since most STOL approaches are flown with stability augmentation systems that input the delta elevator required to maintain constant pitch attitude.

Following the QSRA carrier landings, pilots reported that one of the few differences between the land-based carrier landing practice and the actual carrier landings was some "suck down" experienced just before touchdown on the carrier. The carrier landings were not preceded by steady state type approaches needed to get good ground effect data. The average change in flight data as the QSRA flew over the carrier ramp to touchdown in 46 landing approaches indicates the nature of the ground effects:

QSRA Carrier Landings Data
(Average Data for 46 Landing Approaches)

	At the Ramp	At Touch-down	Change	
Sink rate, ft/sec	8.36	6.9	-1.46	(reduction in sink rate)
Engine fan, % rpm	77.4	75.0	-2.4	(reduction in thrust)
Elevator, deg	-0.01	-8.12	-8.11	elev.(-TEU)
Pitch attitude, deg	2.18	1.38	-0.80	(nose-down pitch)

It appears that the 2-sec time period that it took the QSRA to fly from the aft ramp to touch down was enough time for the ground effect from the carrier deck to cause a nose-down aircraft pitch change which the pilots bring forward of the c.g. interpreted as suck down. Note also that for the carrier landings the sink rate is reduced (opposite of suck down). The pilot probably did not notice this during land based operations since the influence of ground effects was gradual, not abrupt as when he flew over the ramp of the carrier. This phenomenon is not unique to QSRA carrier landings. A similar experience occurred with the XV-15 Tilt Rotor simulator. After the XV-15 Tilt Rotor simulation math model was modified to include ground effects, the pilot stated, "Great, you've got the slight suck down we've experienced just before touch down." The only modification made to the simulation model was the addition of the nose down pitching moment from ground effect, which again, the pilot being forward of the C.G. had interpreted a nose-down pitch change as suck down.

This tendency for powered-lift STOL aircraft to have a nose-down pitching moment at reduced landing approach speeds strongly suggests that future powered-lift STOL Aircraft be designed so they can tolerate nose-gear first touchdowns.

CONCLUSIONS

For the QSRA landing at C_L greater than 7, the change in lift due to ground effect is still positive. The percent increase in lift for the QSRA landing at high C_L is similar to that of other aircraft landing at much lower C_L. The ground effects reduced the sink rate for the QSRA by 2 ft/sec for no flare landings.

The reduction in drag due to ground effects for the QSRA is comparable to the drag reduction for the YC-15 when the change in drag coefficient is normalized with division by C_L^2. This reduction in drag along with the increase in lift caused by ground effects will tend to make the QSRA "float" for shallow glide slope (<3°) landing approaches.

A significant amount of elevator input is required to maintain constant aircraft pitch attitude upon entry into ground effect. The magnitude of elevator required to maintain a constant pitch attitude increases as the landing approach airspeed is reduced.

REFERENCES

1. Haak, D. E.; and Finch, R. D.: USAF Stability and Control DATCOM-AFFDL Wright-Patterson AFB, 1960 (revised 1975).

2. Gratzer, L. B.; and Mahal, A. S.: Ground Effects in STOL Operations. J. Aircraft, Vol. 9, No. 33, March 1972.

3. Stevens, V. C.; and Wingrove, R. C.: STOL Ground Effects determined from Flight Data. AIAA Paper 77-576, June 1977.

4. Parks, E. K.; and Wingrove, R. C.: Flight Test Measurements of Ground Effects - STOL Airplanes. 8th Annual Symposium of Society of Flight Test Engineers, August 1977.

5. Stevens, V. C.: A Technique for Determining Powered-Lift STOL Aircraft Performance at Sea Level from Flight Data Taken at Altitude. 13th Annual Symposium, Society of Flight Test Engineers, 1983.

6. Stevens, V. C.; Riddle, D. W.; Martin, J. L.; and Innis, R. C.: Powered-Lift STOL Aircraft Shipboard Operations; A Comparison of Simulation, Land-Based and Sea Trial Results for the QSRA. AIAA Paper 81-2480, 1981.

7. Vincent, J. H.; and Mowley, A. C.: Quiet Short Haul Research Aircraft Phase I: Flight Simulation Investigations, Vol. II. NASA CR 151965, March 1977.

Figure 1.- NASA Quiet Short Haul Research Aircraft.

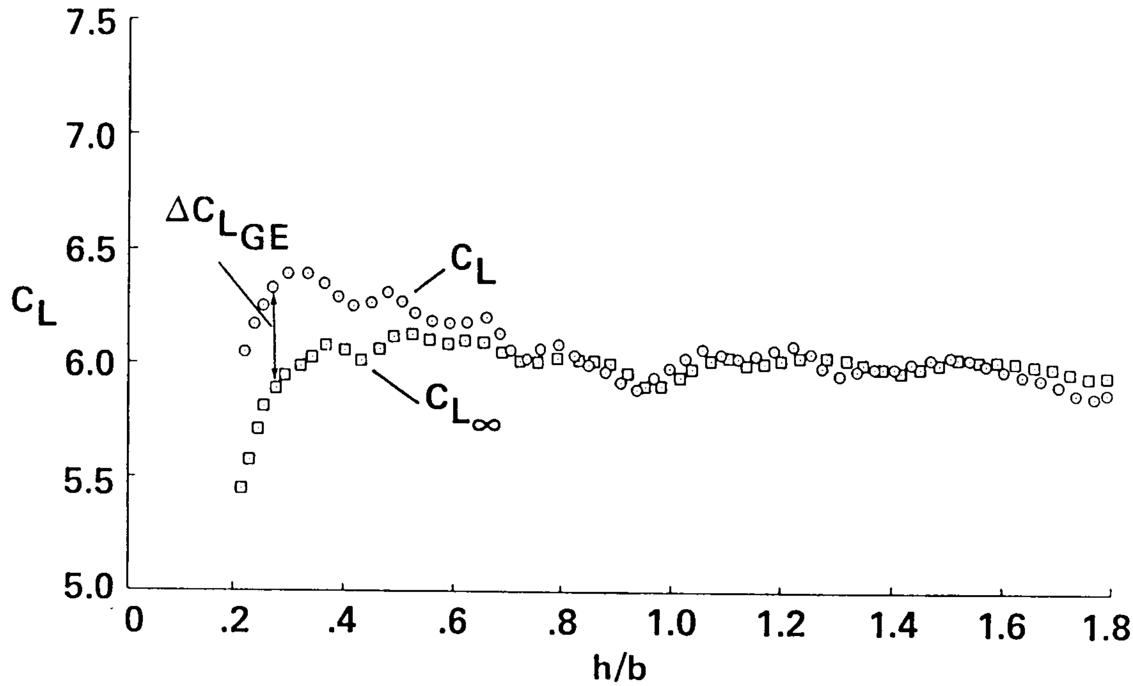

Figure 2.- Lift coefficient during a landing approach, for QSRA flight data.

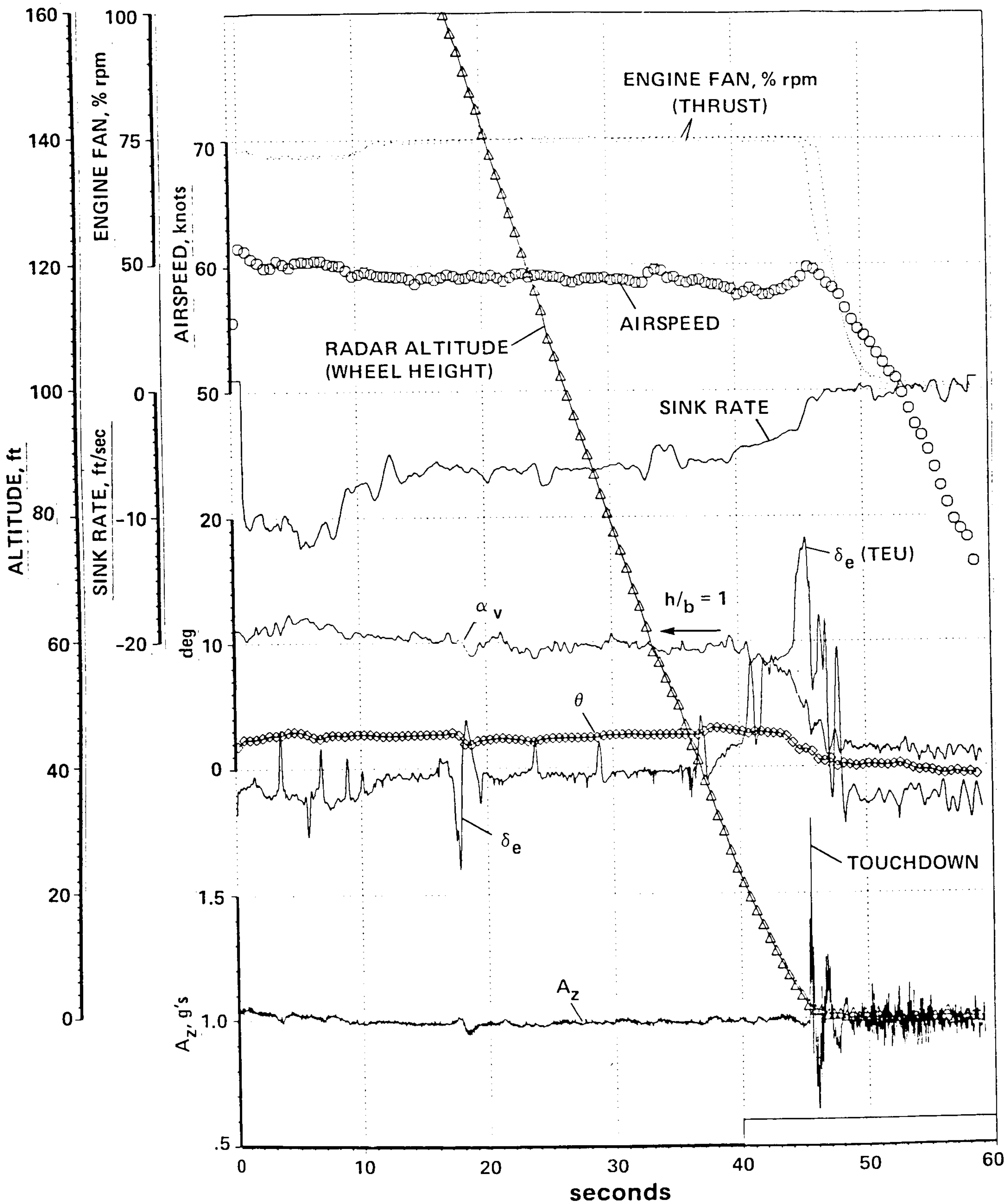

Figure 3.- Time history for a QSRA landing approach.

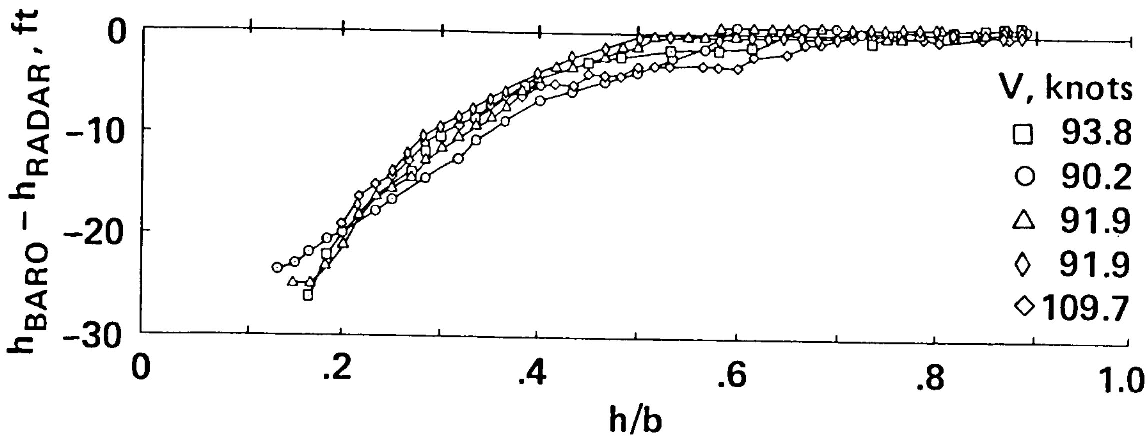

Figure 4.- Difference between barometric altimeter and radar altimeter for YC-14 data.

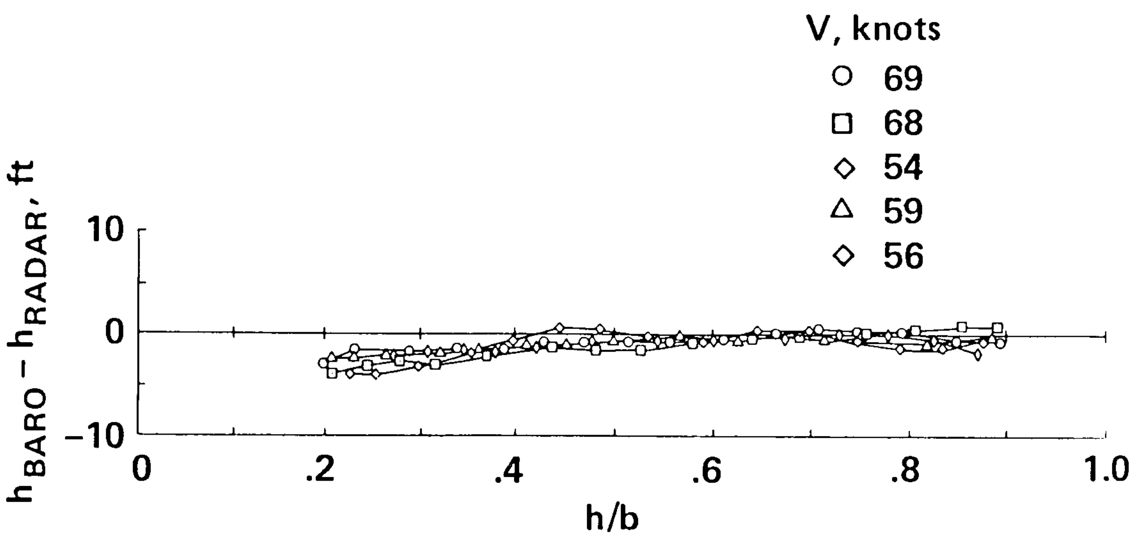

Figure 5.- Difference between barometric altimeter and radar altitude due to ground proximity; nose boom, QSRA flight data.

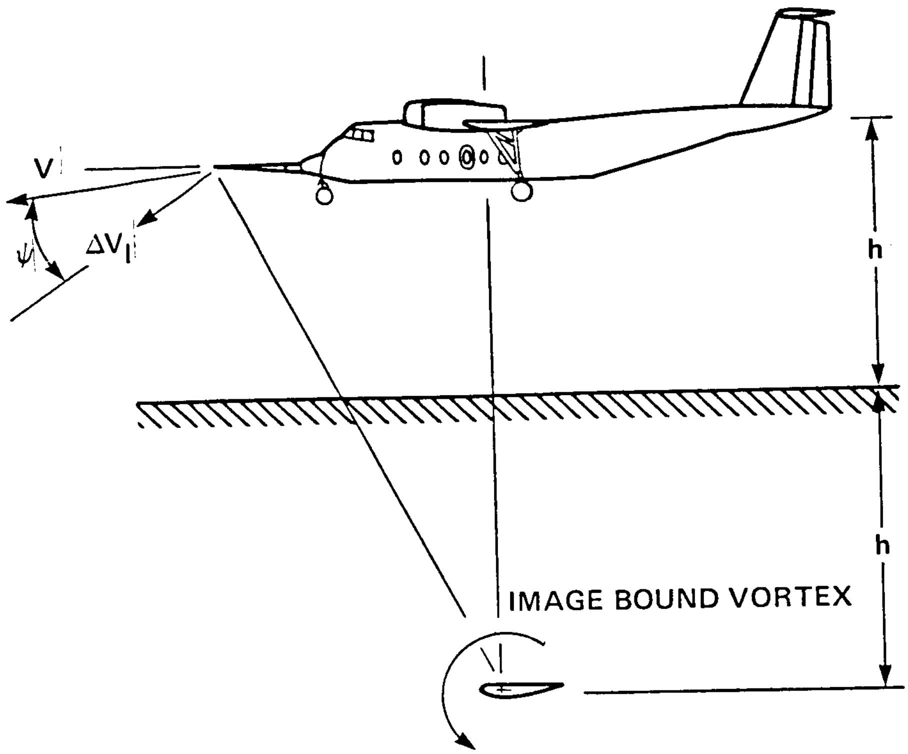

Figure 6.- Image-bound vortex influence on the nose-boom airspeed sensor.

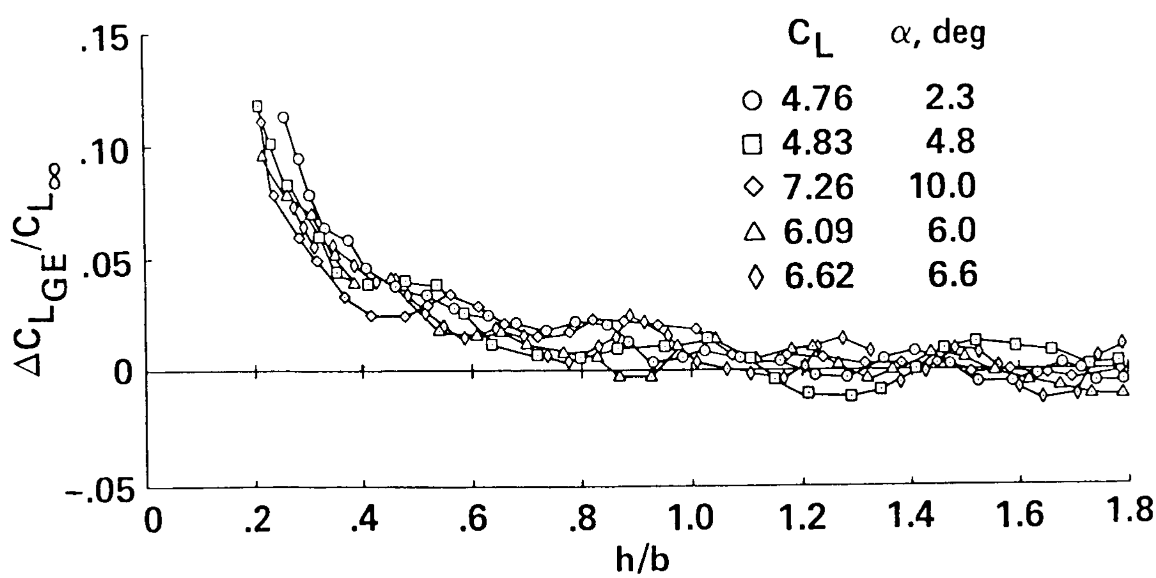

Figure 7.- Change in lift due to ground proximity, QSRA flight data.

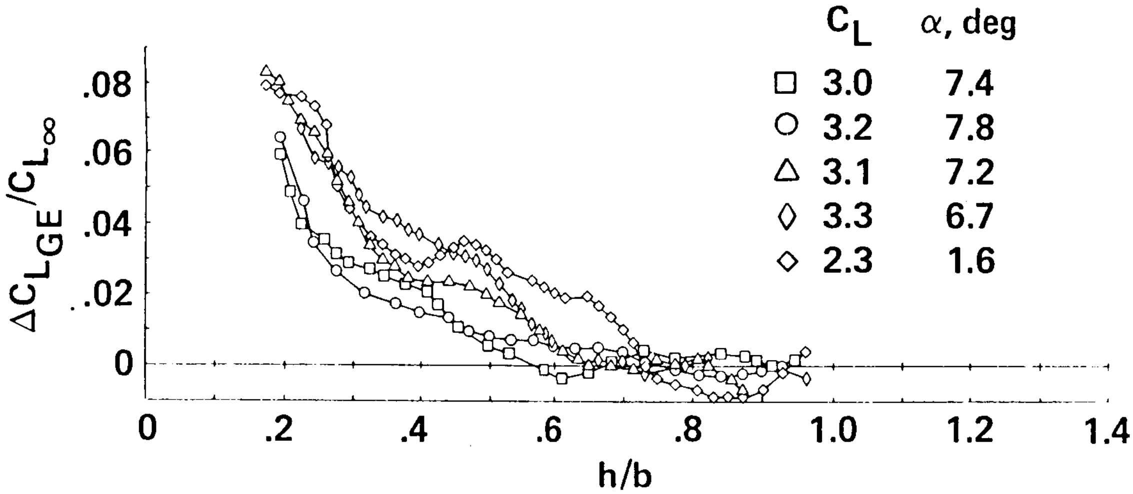

Figure 8.- Change in lift due to ground proximity, YC-15 flight data.

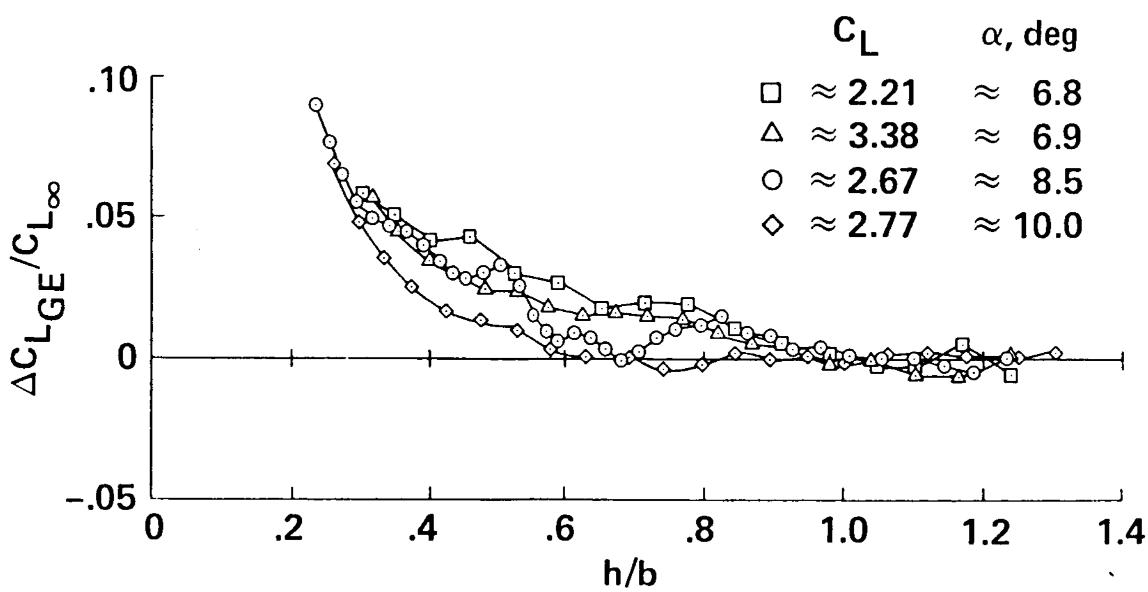

Figure 9.- Change in lift due to ground proximity, YC-14 flight data.

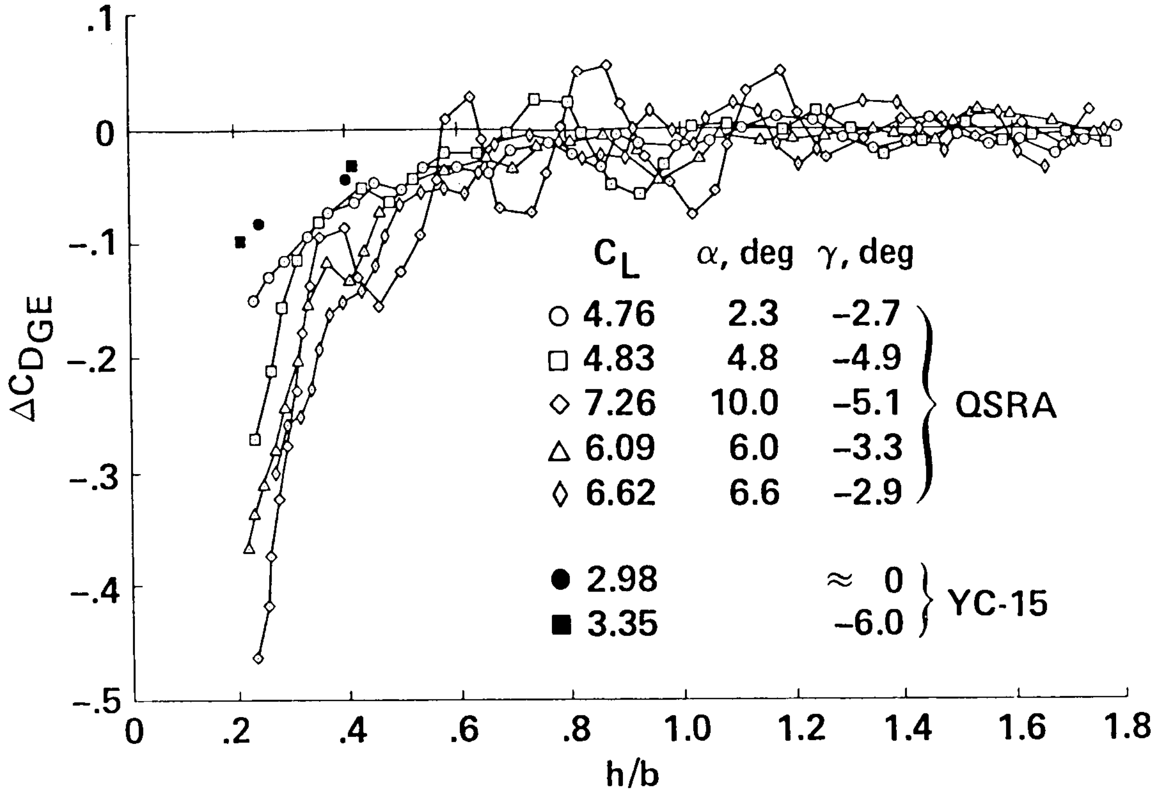

Figure 10.- Change in drag due to ground proximity for QSRA and YC-15 flight data.

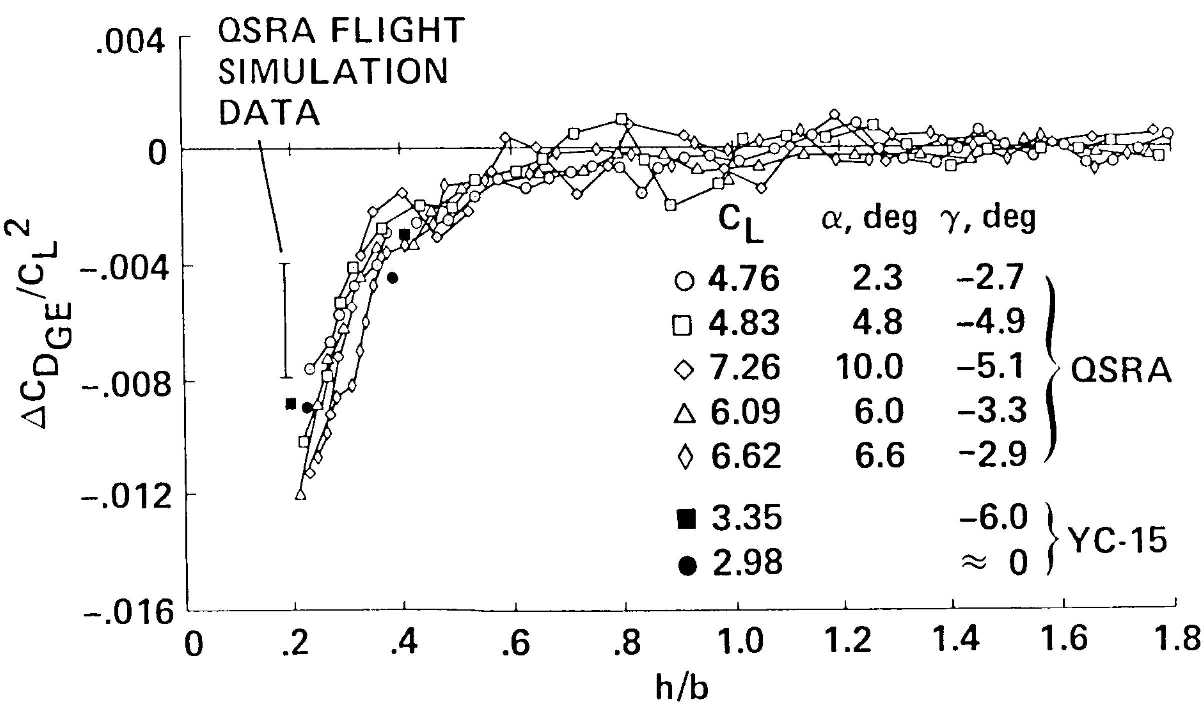

Figure 11.- Change in drag due to ground proximity for QSRA and YC-15 flight data.

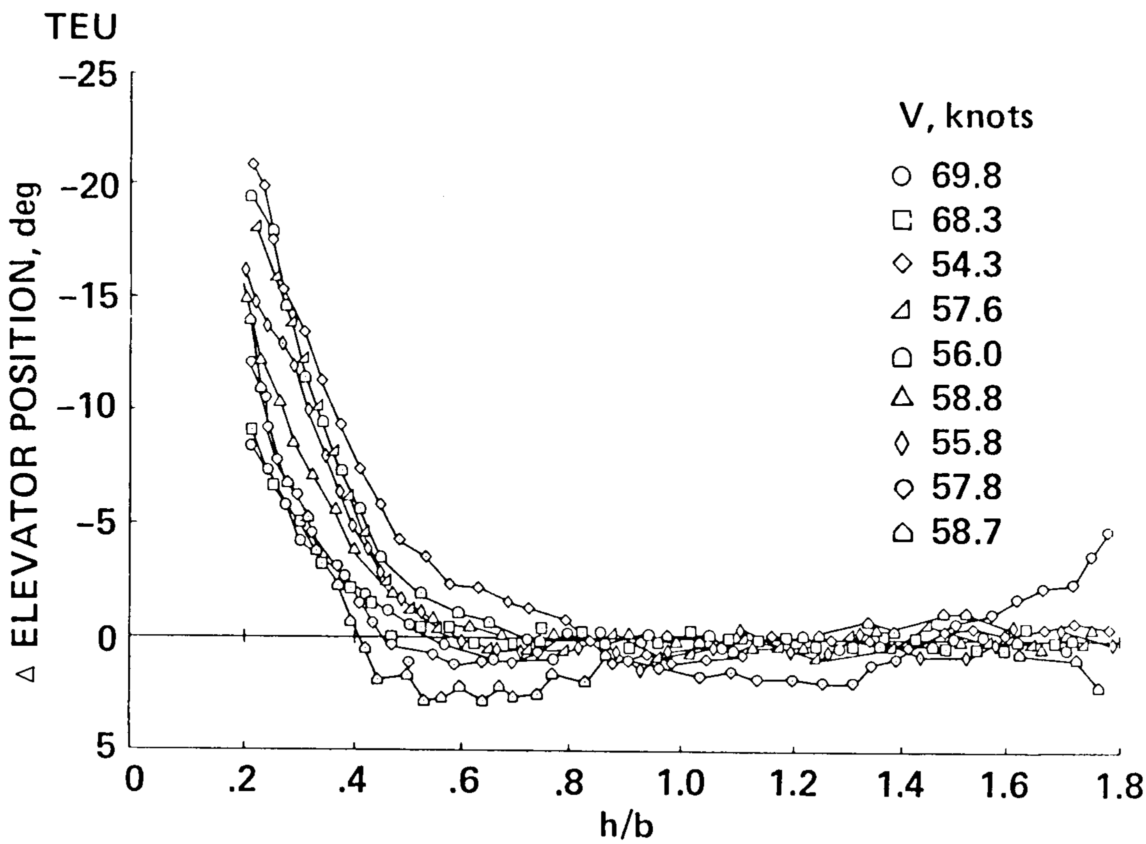

Figure 12.- Change in elevator position due to ground proximity, QSRA flight data.

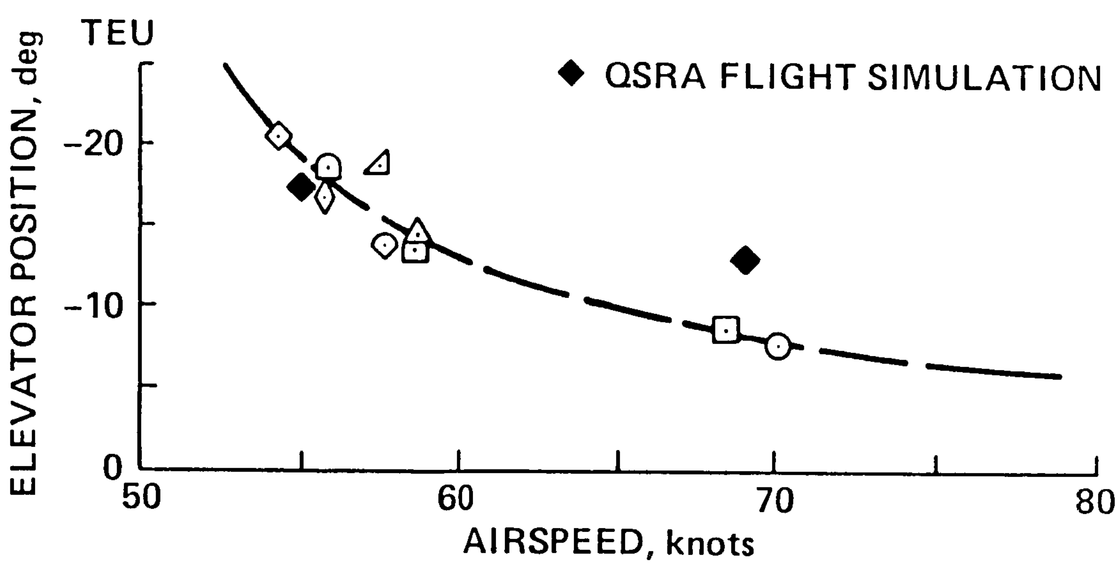

Figure 13.- Elevator position at touchdown required to maintain constant pitch attitude.

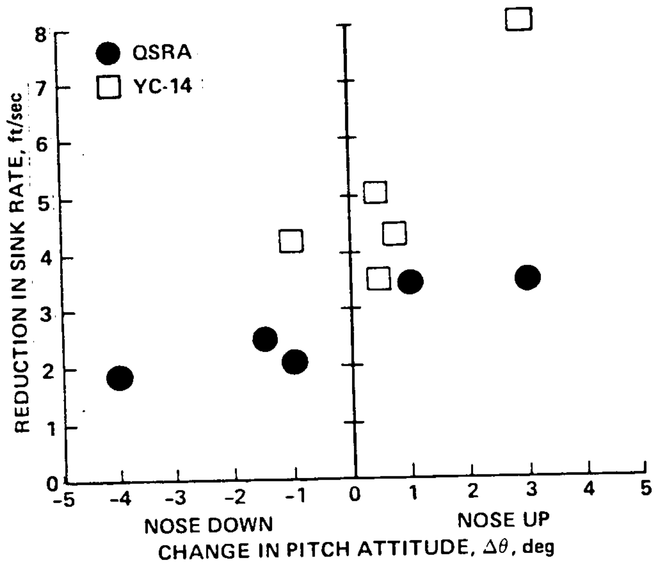

Figure 14.- Reduction of landing sink rate due to ground proximity.

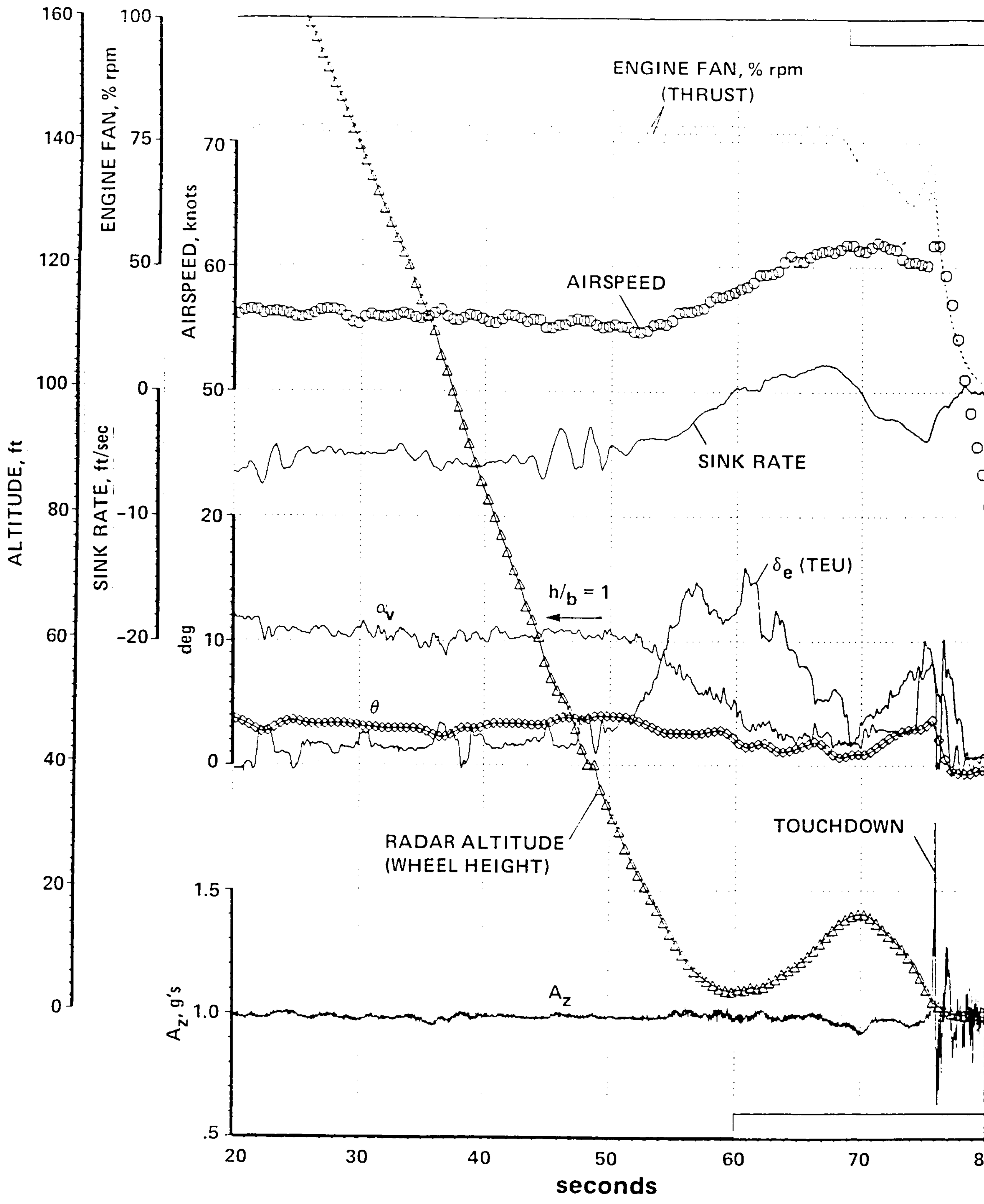

Figure 15.- Time history for a QSRA landing approach.