UTSI ATMOSPHERIC SCIENCE PROGRAM

Walter Frost
Director of Atmospheric Science
University of Tennessee Space Institute

Two areas of research are being carried out in the Tullahoma area which is of interest to a group concerned with meteorological and environmental inputs to aviation systems. One effort deals with the investigation of wind fields about bluff geometries typical of buildings or other man-made obstructions to the surface wind and the behavior of aircraft flying through these disturbed wind fields. The second effort is the definition and mathematical models of atmospheric wind shear associated with thunderstorms, stable boundary layers and synoptic fronts. These mathematical models can be utilized in flight simulators to train pilots and flight crews and to develop instrumentation for landing in adverse wind shear conditions.

The objective of the first project is to enhance the safety of aircraft operations under adverse wind conditions with special emphasis on wind fields around a surface obstruction. The project consists of two parts: (1) definition of the wind environment and (2) computer simulation of aircraft dynamics in variable wind fields. The scope of the wind environment definition portion of the program is presently to (1) survey and define the problem (2) analytically model winds about bluff building-like geometries, (3) conduct experimental field studies of winds over simulated block buildings, (4) develop turbulence simulation techniques and (5) conduct analytical studies of the secondary wave structure in the planetary boundary layer.

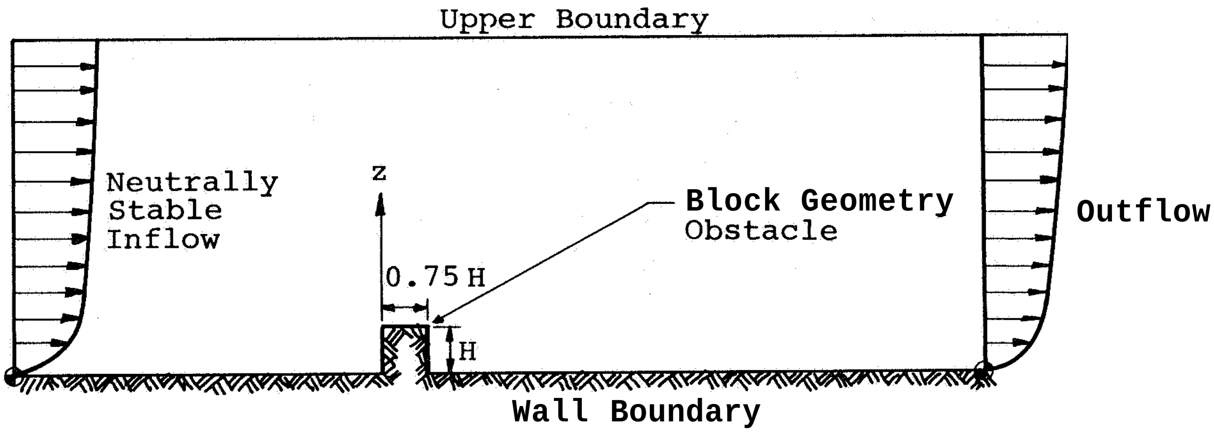
a

The work conducted to date in the wind environment definition is listed in Tables 1 through 4. References to detailed reports on the research are also listed in the tables.

The scope of the computer simulation of aircraft dynamics in variable wind fields includes computer simulation of flight paths through the wind fields which are computed under the wind environment definition portion of the study. The two-dimensional equations of motion with variable wind inputs are utilized with both fixed control and digital automatic control simulation. Some work on the influence of variable winds on aerodynamic coefficients is also being carried out. Table 5 lists the areas of completed work and reference reports of the research conducted to date. A brief description of this aspect of the work is given in the following.

Operations of V/STOL aircraft in the vicinity of buildings may became hazardous due to the complex flow fields created by surface winds passing over the buildings [1]. The research investigates the behavior of winds about block geometries characteristic of building shapes and of the flight performance of an airplane passing through the wind fields. For illustrative purposes an aircraft having the characteristics of a DHC-6 or DC-8 is utilized. The two-dimensional equations of motion for the aircraft are written to include variable winds and wind shear components. The influence of those terms in the, equations of motion which explicitly contain effects due to wind shear have been assessed as part of the research effort.

Two characteristic building geometries considered to date are a long, low two-dimensional building which is simulated as a forward facing step and a long, rectangular cross section block geometry. Both geometries are illustrated in Figure 1.



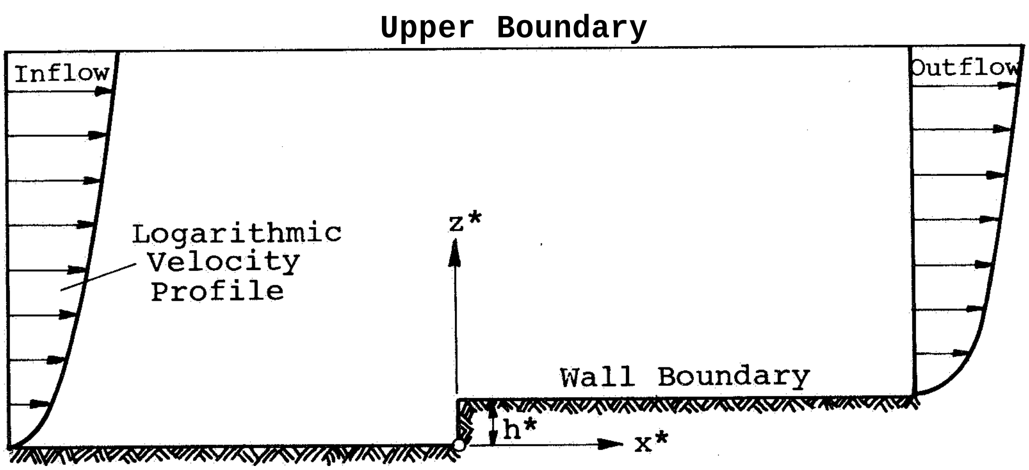


Figure 1. Illustrates typical bluff geometries considered to simulate buildings.

Wind fields about bluff geometries. Wind fields about the bluff geometries illustrated in Figure 1 have been computed by solving the two-dimensional incompressible Navier-Stokes equations. Turbulence was modelled in the solution with the two equation model that includes a transport equation for the turbulence kinetic energy and a transport equation for the turbulence length scale. Details of these solutions are given in Bitte and Frost [2] and Shieh, Frost and Bitte [3] . Figure 2 shows typical wind fields over the forward facing step and over the block geometry, respectively.

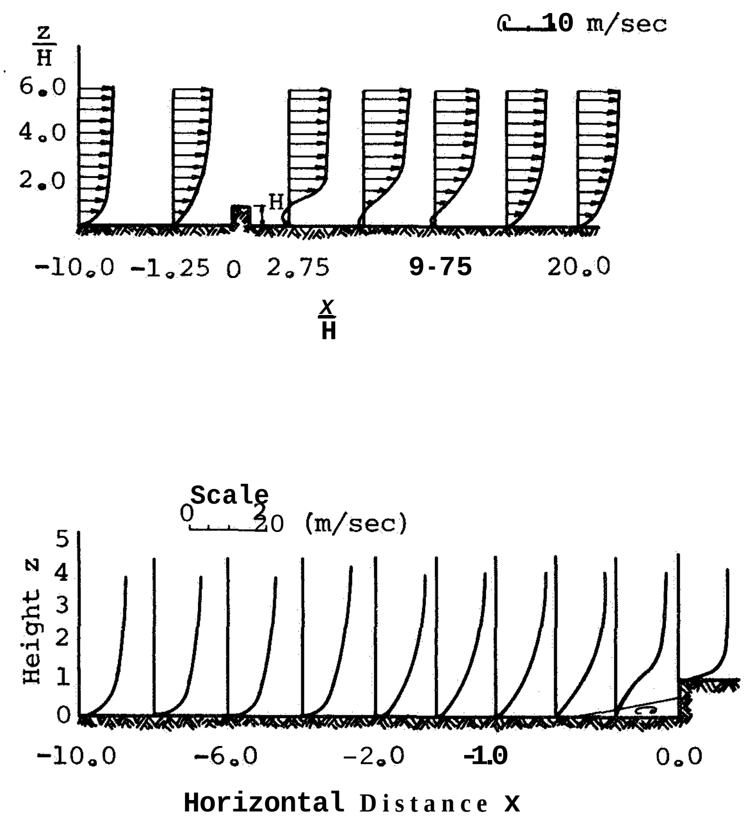


Figure 2 Typical Wind Fields About Simulated Buildings.

The influence of these wind fields on a STOL aircraft passing over the building or landing upon the top of the building are investigated by solving the two-dimensional equations of motion for the aircraft with the computed wind fields as inputs.

Governing equations of motion. The aircraft is modelled as a point mass and a force balance perpendicular and parallel to the ground speed velocity vector, Figure 3, is employed to derive the following equations:

$$V = -D_1 \, (C_D \cos \delta + C_L \sin 6) \, V_a^2 - D_2 \sin\gamma + D_6 F_T \cos(\delta_T + \alpha) \qquad (1)$$

$$\dot\gamma = (D_1 V_a^2 \, (C_L \cos \delta = C_D \sin \delta) - D_2 \cos\gamma + D_6 F_T \sin(\delta_T + \alpha))/V \qquad (2)$$

where Figure 3 defines the nomenclature. A momentum balance gives:

$$q = D_7 F_T + D_5 V_a^2 C_m \qquad (3)$$

with the remaining equations making up the complete set being:

$$V_a = [(is - W_x)^2 + (\dot z - W_z)^2] \qquad (4)$$

$$V = W_x \cos \delta - W_z \sin\gamma + ((W_z \sin\gamma - W_x \cos\gamma)^2 + V_a^2 - (W_x^2 + W_z^2))^{1/2} \qquad (5)$$

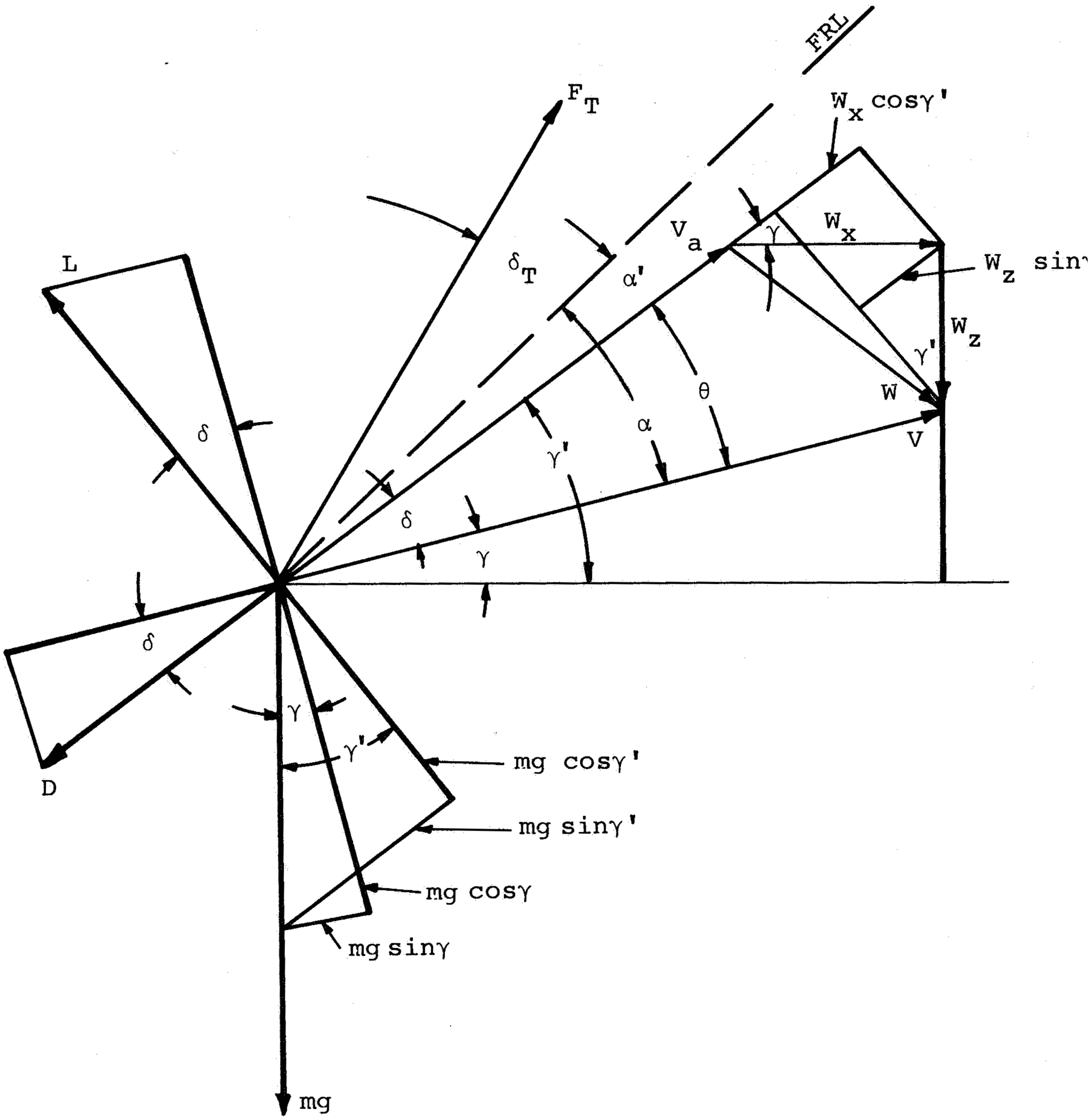


Figure 3 Point Mass Aircraft Model and Nomenclature.

$$\sin \delta = (W_x \sin \gamma + W_z \cos \gamma)/V_a \qquad (6)$$

$$\dot{\alpha}' = q - D_1 C_L V_a - (D_2 \cos \gamma' + D_6 F_T \sin (\delta_T + \alpha')$$

$$+ (\dot{W}_x \sin \gamma' + \dot{W}_z \cos \gamma'))/V \qquad (7)$$

$$\dot{W}_x = \frac{\partial W_x}{\partial t} + V \left[\frac{\partial W_x}{\partial x} \cos \gamma - \frac{\partial W_x}{\partial z} \sin \gamma \right] \qquad (8)$$

$$\dot{W}_z = \frac{\partial W_z}{\partial t} + V \left[\frac{\partial W_z}{\partial x} \cos \gamma - \frac{\partial W_z}{\partial x} \sin \gamma \right] \qquad (9)$$

Inspection of the equations show that wind shear enters explicitly only in Equation(7). The term $\dot{W}_x \sin \gamma' + \dot{W}_z \cos \gamma'$ in this equation demonstrates that passing through a varying wind field results in a contribution to the rate of change in angle of attack. Of course, variation in wind enters Equations(1)and(2) indirectly through V_a and δ, see Equations *(4)*and(6). Characteristic aerodynamic coefficients C_L, C_D and C_M are used in the analysis as pertain to the aircraft of interest.

If the equations of motion are written in terms of airspeed V_a and pitch angle relative to the direction of V_a for a coordinate system with **x** aligned along V_a, one obtains:

$$\dot{V}_a = - D_1 V_a^2 C_D - D_2 \sin \gamma' + D_6 \cos (\delta_T + \alpha')$$

$$- \dot{W}_x \cos \gamma' - \dot{W}_z \sin \gamma') \qquad (10)$$

$$\dot{\gamma}' = - D_1 V_a^2 C_D - D_2 \sin \gamma' + D_6 \cos (\delta_T + \alpha')$$

$$- (\dot{W}_x \cos \gamma' - \dot{W}_z \sin \gamma') \qquad (11)$$

In these equations wind shear appears explicitly when $\dot{W}_x$ and $\dot{W}_z$ are introduced through Equations (8) and (9).

Discussion of the equations of motion. It is frequently reported that the influence of wind shear will have particularly strong effects on STOL aircraft due to their slow landing speed and steep flight paths. To investigate the significance of this statement, the various terms which explicitly contain wind effects in the equation of motion are examined for the conventional take-off and landing aircraft (CTOL) and for the short take-off and landing aircraft (STOL). Aerodynamic coefficients characteristic of a **DC-8** and of a DHC-6 are used in the investigation. Examination of Equations (10) and **(11)** indicate that there is a contribution to the acceleration of relative air speed of the aircraft and of pitch rate due to the direct entrance of wind shear into the last term on the right-hand side of the equations.

One can isolate these terms and compare their relative magnitudes for different types of airplanes under different glide slopes and landing speeds. The contribution to $\dot{V}_a$ and γ' of the wind shear terms thus isolated are given in Equations (12) and **(13)** below:

$$\Delta V_a = - \frac{\partial W_x}{\partial z} V_a \left| \frac{V}{V_a} \sin\gamma \left| \frac{V}{V_a} \cos\gamma - \frac{W_x}{V_a} \right| \right| \qquad (12)$$

$$\Delta\dot{\gamma}' = \frac{\partial W_x}{\partial z} \left[\frac{V}{V_a} \right]^2 \sin 2\gamma \qquad (13)$$

Equation (12) shows the contribution to the acceleration of relative velocity resulting in Equation (10) from the wind shear contribution. Figure *4* illustrates the variation of this contribution to the acceleration as a function of altitude. The wind shear considered in Figure *4* is taken as a conventional logarithmic wind profile having a friction velocity $u^* = 1$ m/s and a surface roughness $z_o = 10^{-3}$ meters.

$$W_x = \frac{u^*}{\kappa} \ln \frac{z + z_o}{z_o} \qquad (14)$$

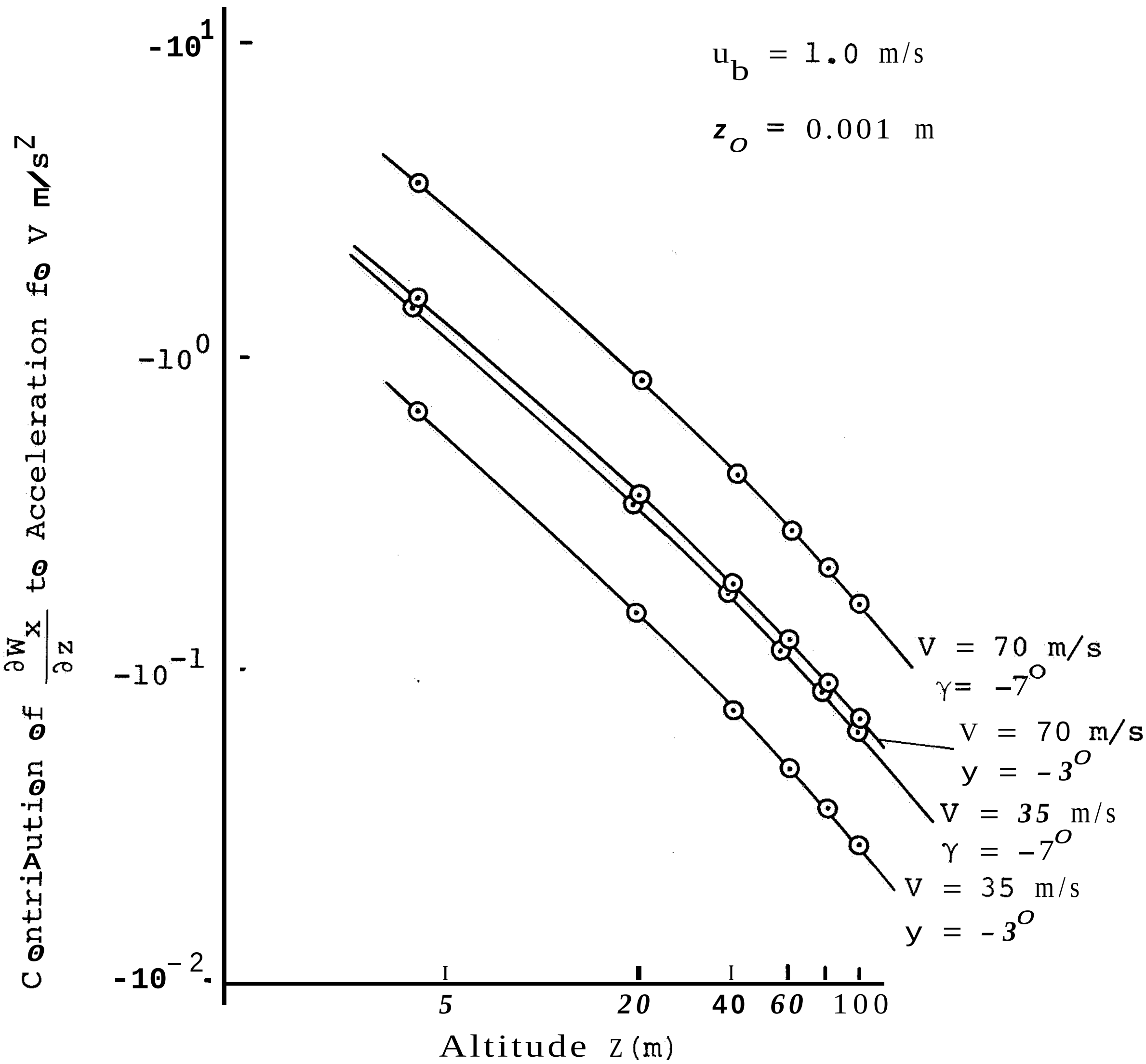


Figure 4 Contribution of Wind Shear Term to the Relative Acceleration

It is interesting to observe that the curves for the landing speed of 70 m/s at an angle of 3" lies almost on top of the curve for a slower landing speed of 35 m/s and a steeper glide path of 7". The former values are typical of the landing speed and glide path of a CTOL aircraft whereas the latter values are typical of those of a STOL aircraft. The figure illustrates that the strong influence of wind shear suspected to occur on STOL aircraft is no worse than the CTOL due to the compensating effects of the steeper glide path. The reason is that even though the STOL has a slower landing speed it "cuts" through velocity gradients at an equal rate to that of the CTOL aircraft because of the steeper glide slope.

Figure 5 shows the contribution to the change of pitch angle caused by wind shear. Again one sees that the compensating effects of higher landing speed coupled with smaller glide slope and slower landing speed coupled with steeper glide slope tends to bring the curves for the rate of change of pitch rate closer' to one another.

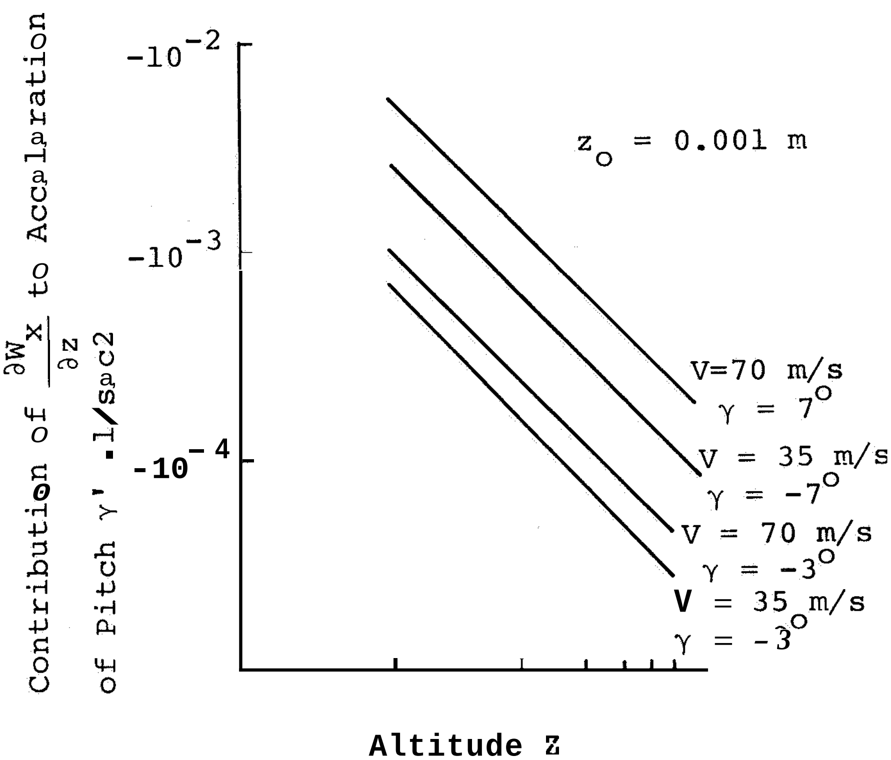


Figure 5 Contribution of Wind Shear to Change in γ'.

It is also interesting to compare the contribution to the change of relative velocity caused by wind shear to that caused by drag. Taking the ratio of those two terms appearing in Equation (8) andcomputingtheir effects for an atmospheric boundary layer, one obtains the results shown in Figure 6. Once again, due to the variation in landing speed and glide slope, this ratio remains almost identical for the two different aircraft. Thus one is led to believe that the suspected influence of wind shear on the STOL aircraft will not be as pronounced as originally suggested [4,5]. Similar conclusions regarding the influence of wind shear on **STOL** aircraft are reported by Ramsdell[6]. Further examination of the various terms and their comparison with terms contributed due to wind shear are being investigated under the current contract effort.

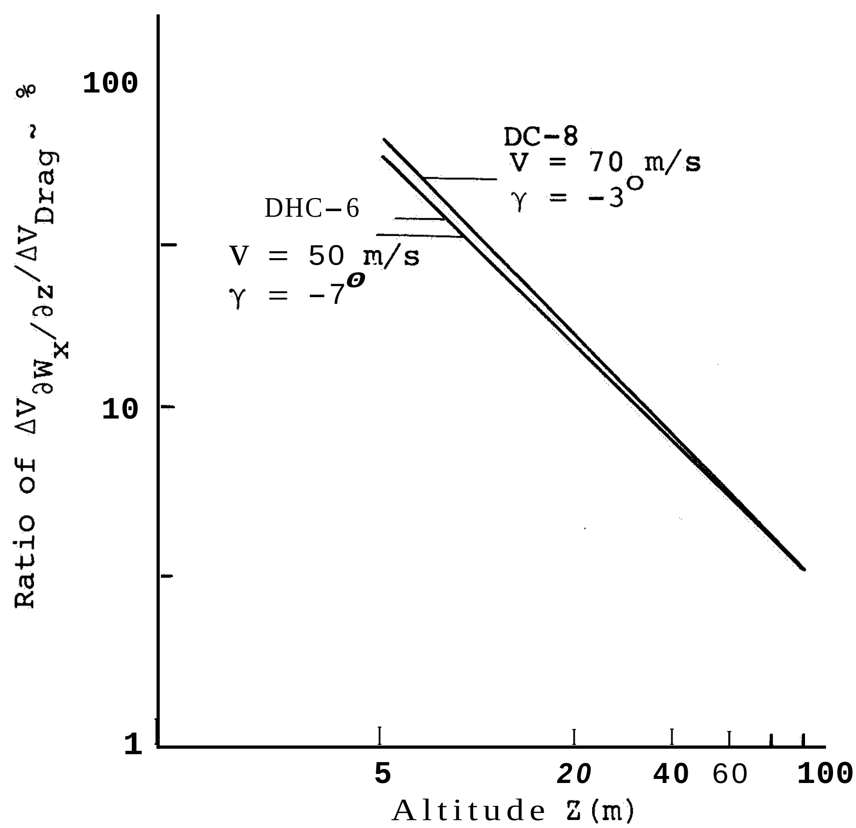


Figure 6 Ratio of Change in V_a due to Wind Shear to that due to Drag

Flight through building; disturbed winds. Having introduced the effects of wind shear into the governing equations of motion for the airplane, the performance of aircraft in the wind fields created by atmospheric flow over simulated buildings is investigated. Figure (7) shows the flight path of an aircraft taking off and landing into the wind flowing over a two-dimensional bluff type body similar to a long building. Figures (8) and (9) show typical wind fields that would be encountered by the aircraft if it remained on the prescribed flight path. One observes for landing into a flow over a building a sudden drop in longitudinal wind speed just as the aircraft passes over the building and a sudden increase in vertical updraft. Figure (9) shows the wind encountered by an airplane on the fixed take-off path. Again one observes a rather severe increase in head-wind as the airplane passes over the building. These wind fields

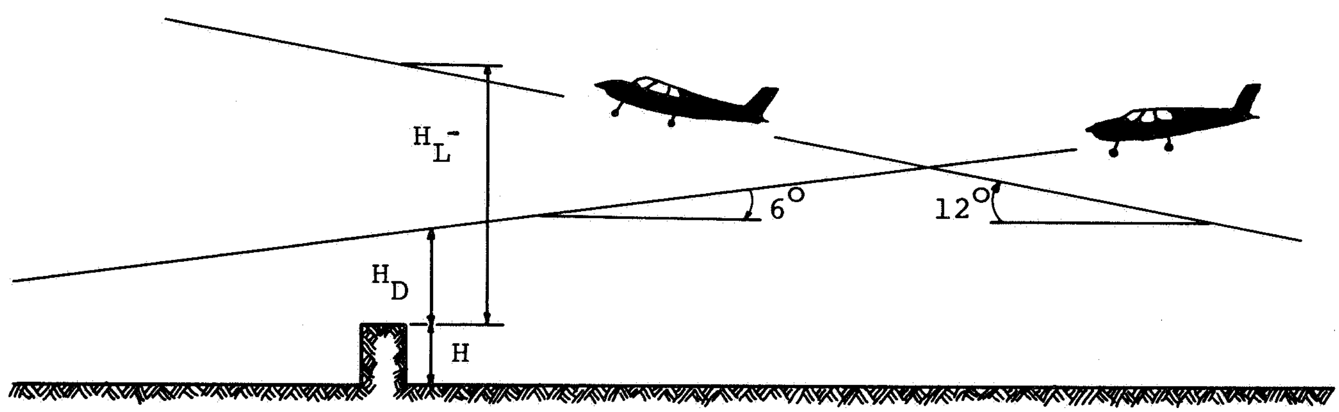


Figure 7 Illustrates Flight Path of Aircraft over Building

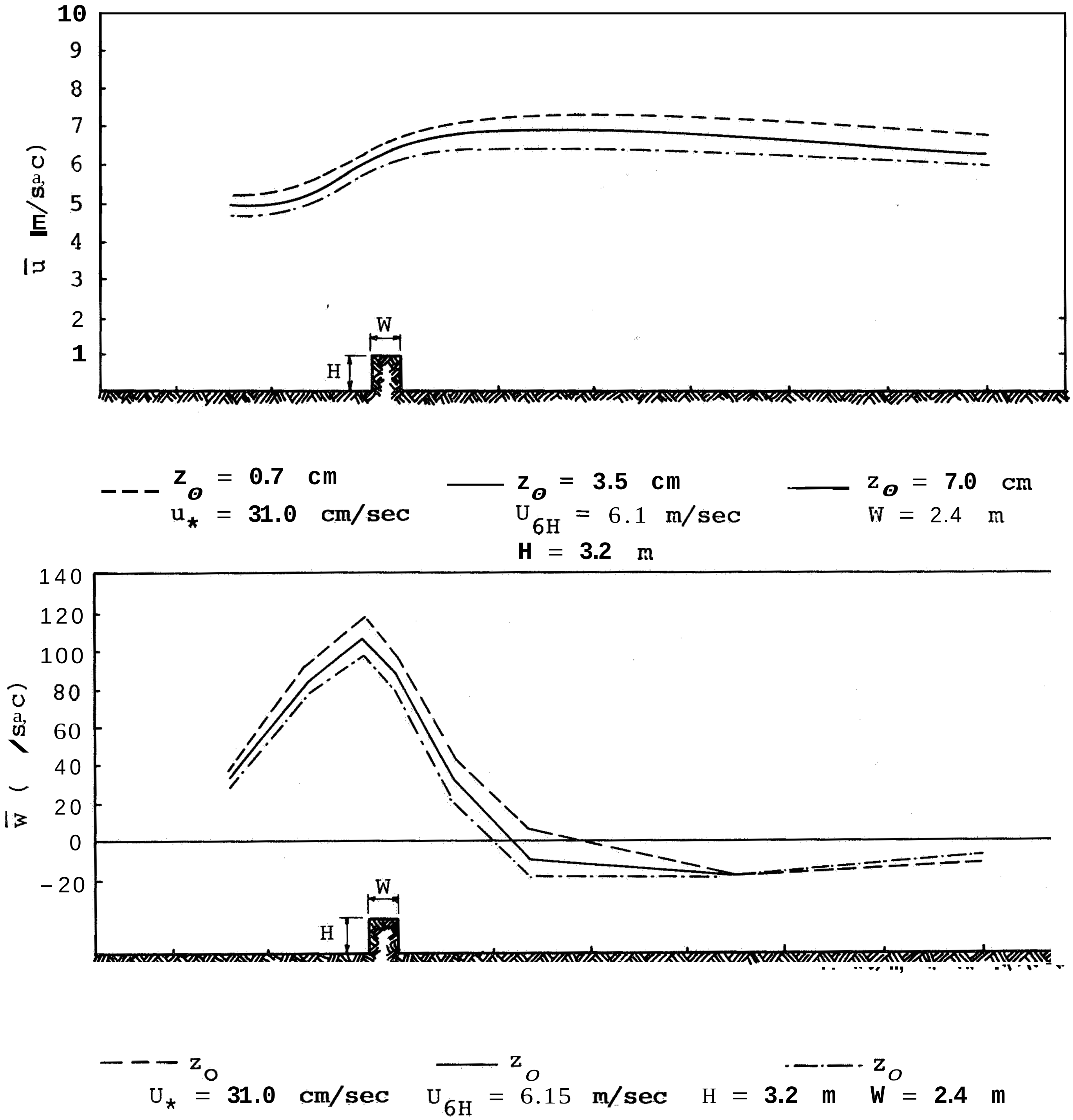
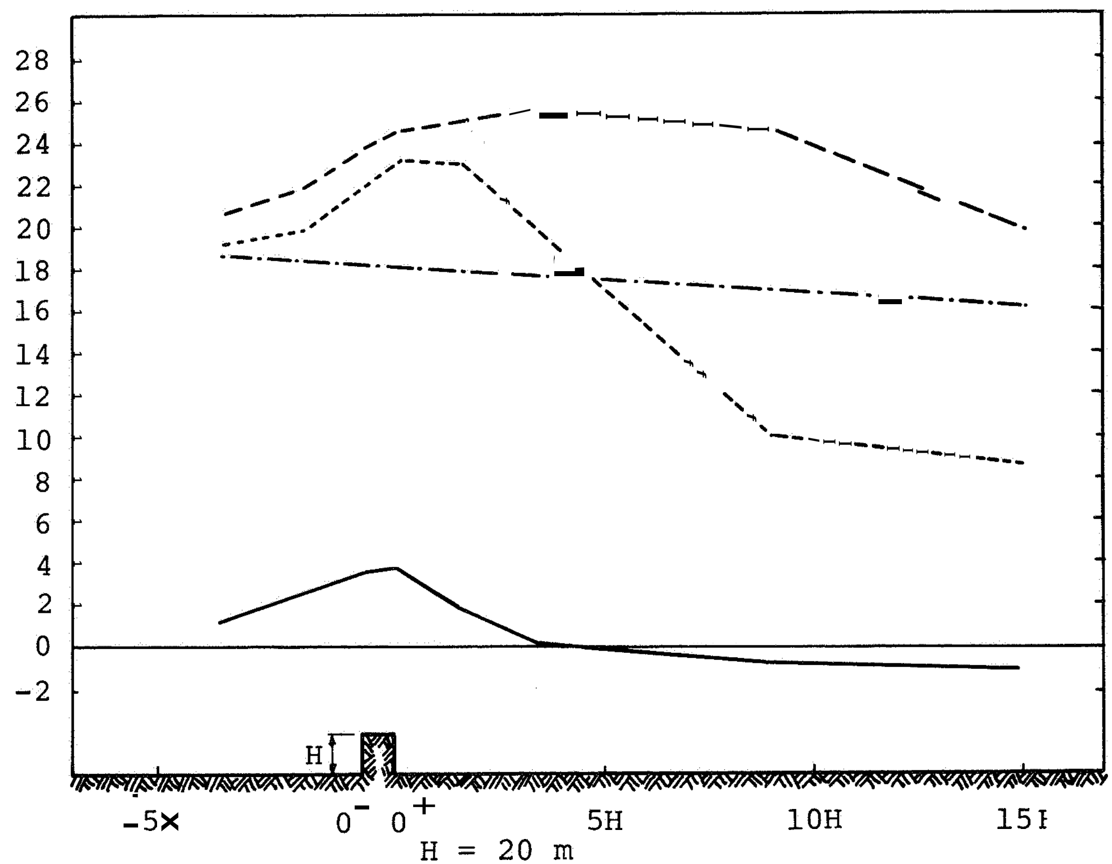


Figure 8 Wind "Seen" by Aircraft Landing over Block Building.



u-component velocity distribution along 6° take-off path (no building presence).
u-component velocity distribution along 9° take-off path (building presence).
u-component velocity distribution along 12° take-off path (building presence).
v-component velocity distribution along 9° take-off path (building presence).

Figure 9 Wind Speed 'Seen' by Aircraft Taking off over Block Building.

are being introduced into the equations of motion and results describing the computed flight paths of the airplane through the wind fields with both fixed and automatic controls will be provided.

Figures 10 and 11 show the flight path of a STOL aircraft landing with fixed controls over a long, very wide, low building. Additionally, the flight path and the aircraft trajectory if landing in an atmospheric boundary layer undisturbed by the presence of the building are illustrated. The sudden decrease in headwind encountered just at the leading edge of the building causes the airplane with fixed controls to land short. With a 10 m/s wind the airplane lands approximately 30 m short of the glide path touchdown point and with a 50 m/sec wind and the aircraft lands approximately 70 m short. Thus under strong wind conditions, the aircraft encountering a strong shear caused by the edge of the building, is drawn in toward the building. This illustrates the potential hazard of the presence of large bluff objects which create complex wind patterns in approach paths.

Many other flight paths with both fixed and automatic controls and the control inputs required to remain on the glide slope will be investigated during the study. Results of the program will provide an envelope of wind speeds and building geometries for parametric variations in surface roughness of the surroundings which create hazardous landing conditions for STOL type aircraft operating in the vicinity of buildings.

Flight through Wind Shear. The second phase of the work has the objectives of studying and analyzing available wind shear information for synthesizing wind shear models for aircraft hazard definition. From this information a comprehensive set of wind profiles and associated wind shear characteristics which incompass the full range wind shear environment potentially encounterable by an aircraft in the terminal area will be developed. The mathematical wind shear scenario will be provided in format for direct engineering applications.

A supplementary effort to this program is to develop the necessary two-dimensional computer code for aircraft motion which will allow analysis of the flight through the thunderstorm wind shear profiles to be carried out.

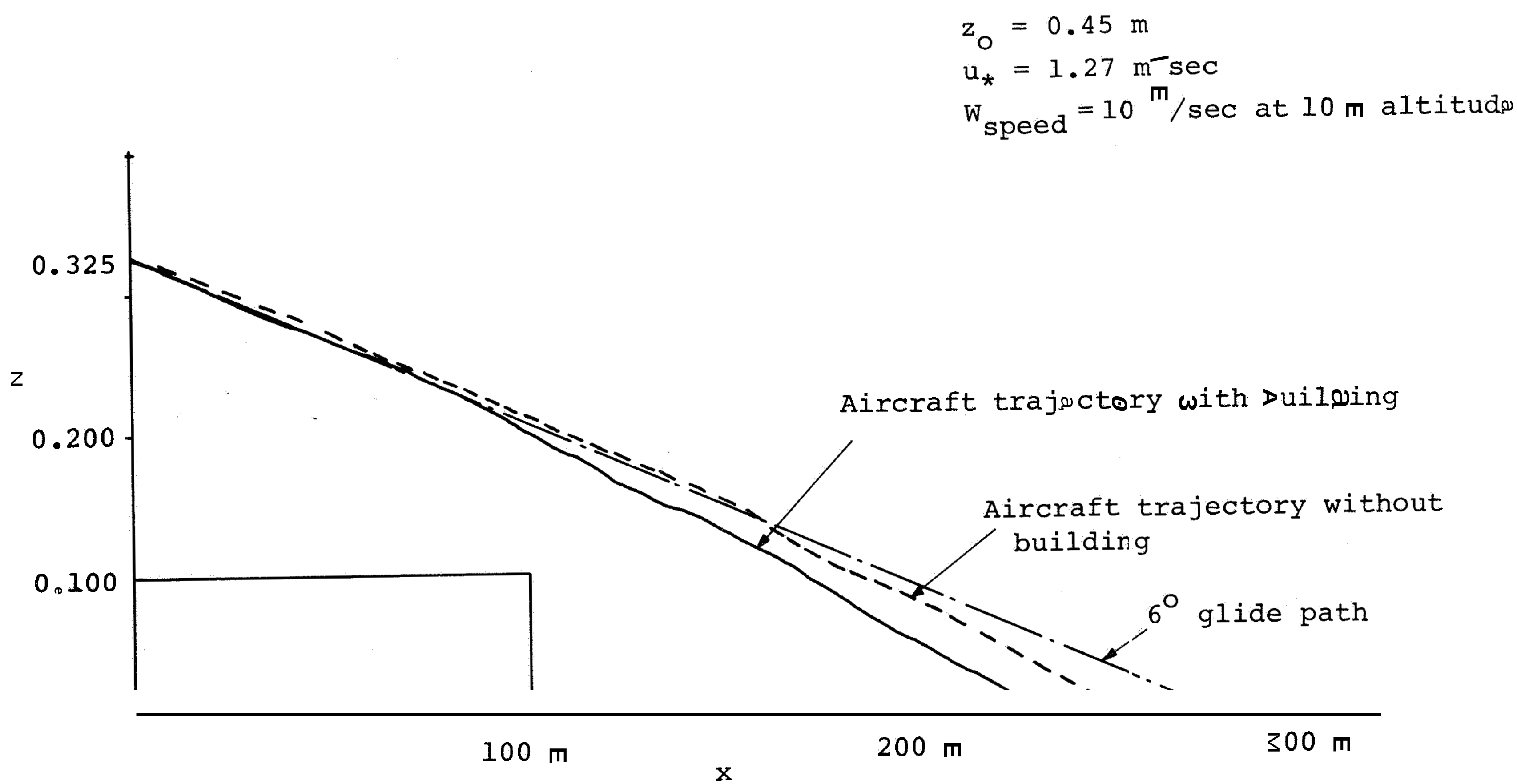


Figure 10 Landing Flight Path over Long, Very Wide, Low Building in a 10 m/s Headwind.

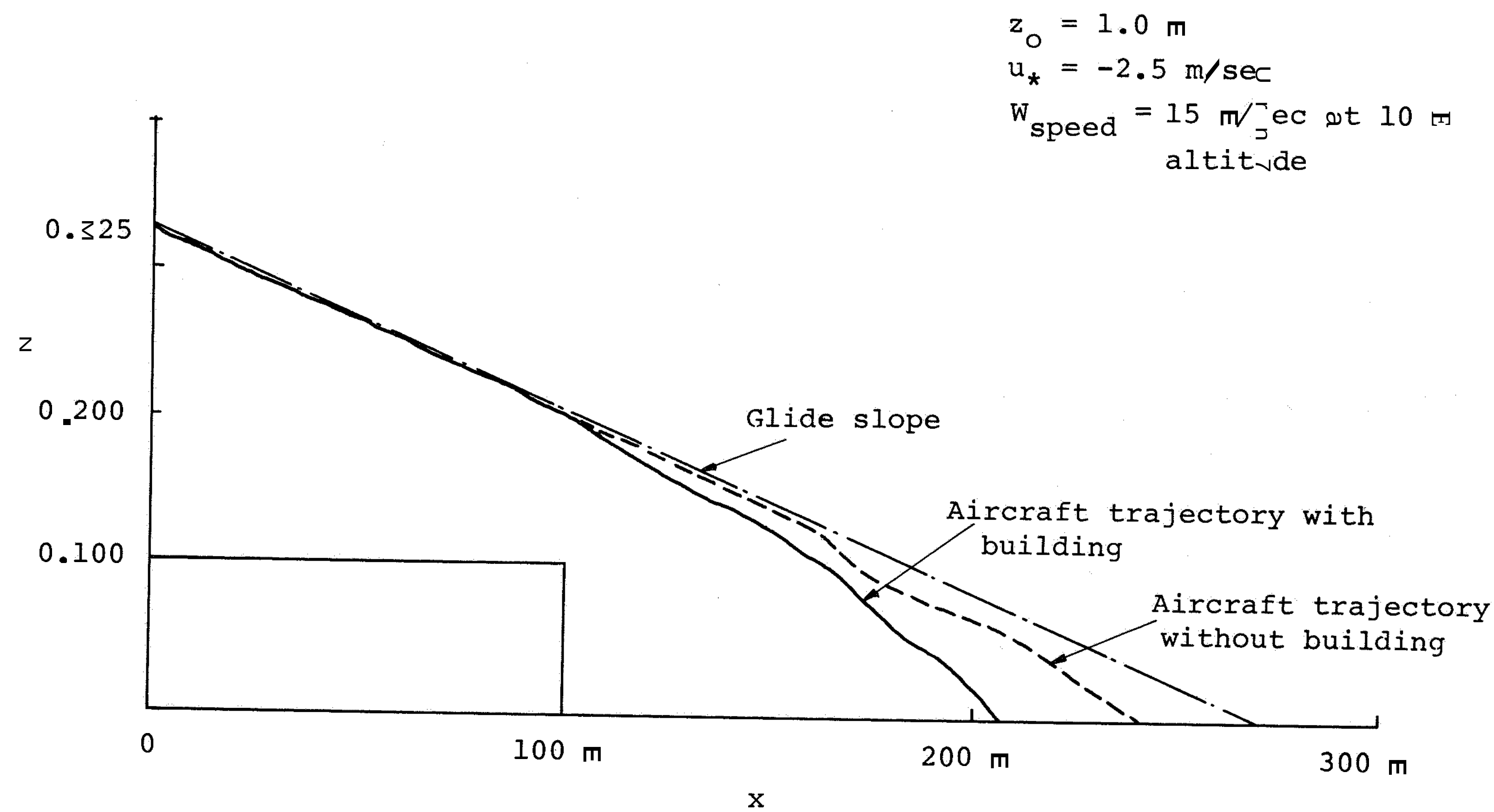


Figure 11 Landing Flight Path over a Long, Very Wide, Low Building in a 15 m/s Headwind

The wind shear profiles considered are the stable and neutral boundary layer, thunderstorms and frontal winds. The wind shear models developed will be briefly summarized and then a more detailed discussion of the flight paths through the thunderstorms will be given in view of the fact that this is probably of more interest to this particular group.

Mathematical models of the neutral and stable boundary layers consist of a table look up computer code based on the experimental data from Clarke and Hess [7] . These authors measured hourly wind profiles over flat homogeneous terrain for forty days. They expressed their data in terms of contour maps of dimensionless height versus dimensionless stability criteria. These data have been tabulated in a computer program look up routine developed which will permit the wind profile in the vertical direction for both the longitudinal and lateral wind fields to be computed for any given stability condition within the range of $\mu > -200$ < -300. A discussion of the program is given in Reference 1. The mathematical models for the thunderstorm gust fronts also utilize a table look up computer code based on the data of Goff from the National Severe Storms Laboratory [8]. Goff [8] has measured the wind profile's variation with height and with horizontal spatial coordinate based on Taylor's hypothesis for some twenty thunderstorms. These data were measured with a 500 meter tower over varying periods of time. Typical streamline patterns developed by Goff [8] were shown in Figure 12. Corresponding velocity contour maps for the longitudinal, lateral and vertical components of the wind have been given in this reference. All these data have been tabulated on cards and a prescribed grid format with computer table look up routine developed which allows these data to be extrapolated for any position in the x and z coordinates,

Data for major frontal velocity profiles is still being developed.

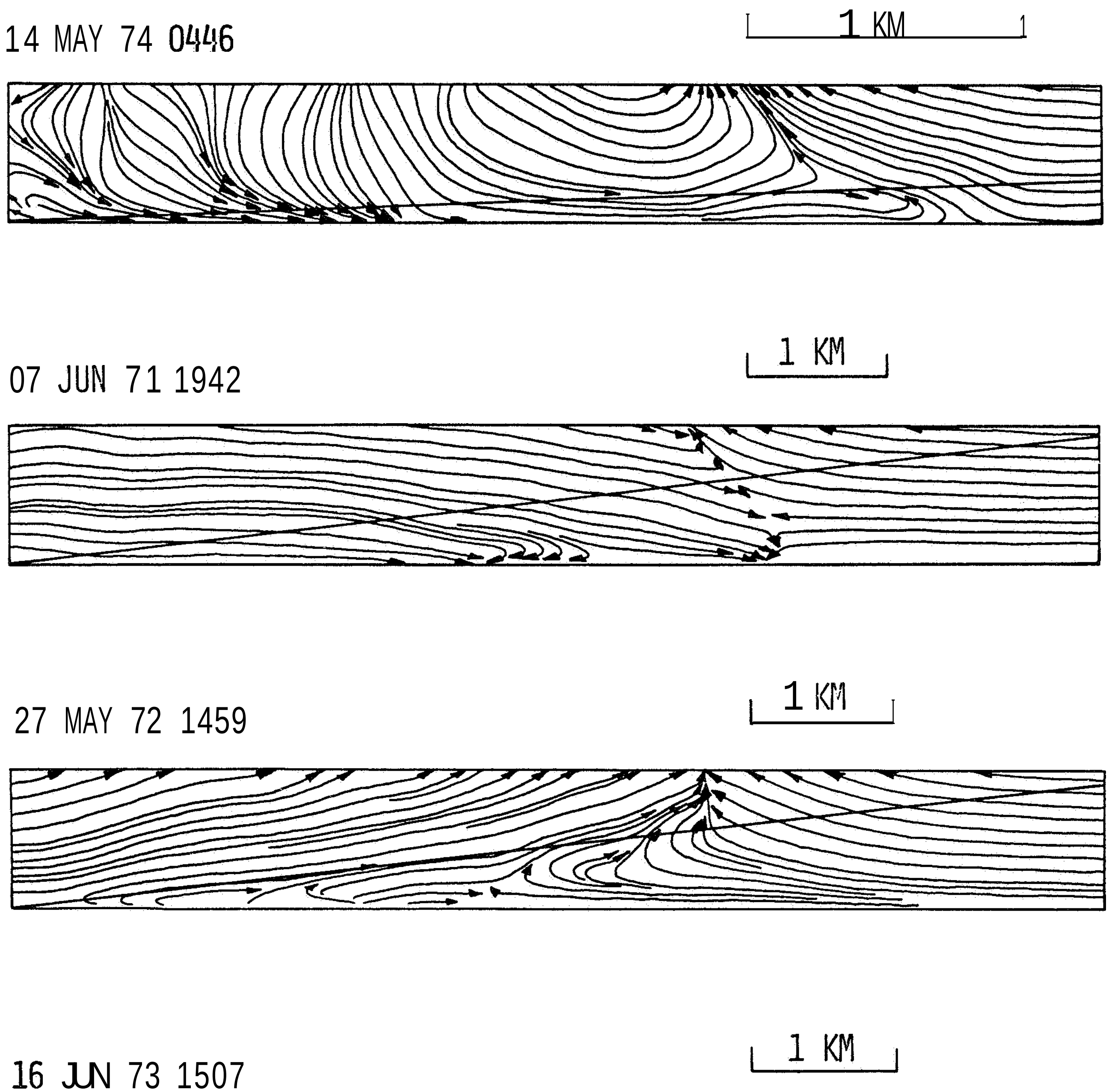


Figure 12 Typical Gust Front Streamline Patterns by Goff [8]

a

Attention is now directed to the behavior of aircraft passing through the thunderstorm gust fronts developed as described in the preceding paragraph.

Wind shear associated with thunderstorm gust fronts is a serious hazard to aircraft operations in the terminal areas. Accidents in which wind shear has been identified as a contributing factor have occurred at Kennedy International Airport, Eastern Airlines [9] , at Stapleton Airport, Continental Airlines [10], at Logan International Airport, Iberian Airlines [11] , to mention only a few recent events.

One phase of the research investigates computer simulated flight characteristics of a large jet commercial type airliner landing through 11 separate mathematical models of wind fields associated with thunderstorm outflows. The influence of the wind field and of the separate wind components individually on the aircraft flight path, pitch, ground speed and other aerodynamic parameters is investigated. The analysis is carried out first, with the aircraft controls fixed in the trimmed condition at entry into the flow field and, second, with individual parameters such as ground speed, pitch and relative airspeed held constant throughout the approach. The parameters held constant are those being investigated as the most suitable visual displays for pilot monitoring during landing in severe wind shear in the FAA wind shear manned flight simulation program currently in progress. The results of the study will isolate and identify the influence of individual wind components and of individual control input on landing through wind shears characteristic of thunderstorm outflows.

Wind Shear. Eleven thunderstorm outflows measured with the 500 m tower at the National Severe Storms Laboratory in Norman, Oklahoma [8], as previously described provide two-dimensional wind field where z designates the vertical dimension and x the horizontal dimension. These are tabulated on a grid system as illustrated in Figure 13. The data are punched on computer cards and a computer look up subroutine is programmed. The subroutine when called with the position (x,z) return the horizontal wind speed, W_x, the vertical wind speed, W_z, and the spatial wind gradients W_{xx}, W_{xz}, W_{zx} and W_{zz} at that position. The programmed wind fields combined with the two-dimensional equations of motion governing aircraft flight allows the aircraft behavior in severe wind shear to be evaluated. The governing equations of motion have been described previously.

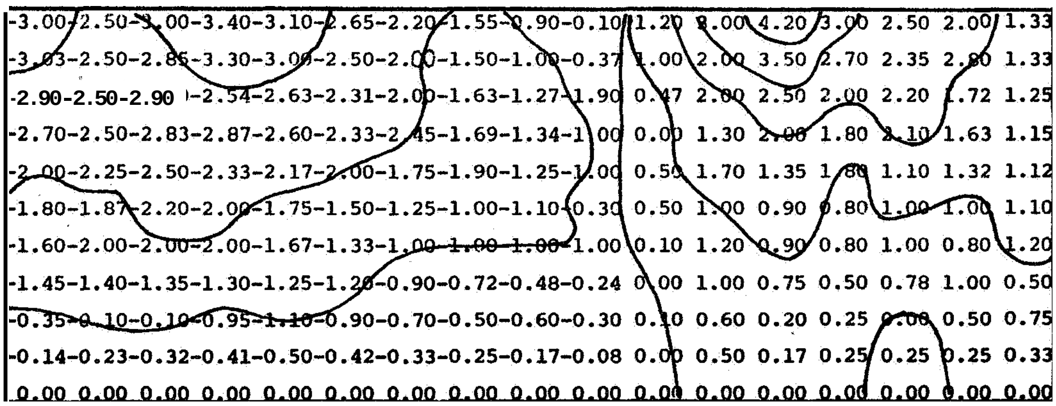


Figure 13 Vertical Velocity Contour Given by Goff [4] Compared with Tabulated Values for Computer Look-up Grid System

The governing equations are solved with a variable step size, multiple equation Runge-Kutta numerical integration scheme. The initial conditions for all analyses are trimmed conditions at the point at which the aircraft is assumed to enter the wind field. Typically the point of entry is either at z=91 m (300 ft) or at z = 305 m (1000 ft) and at the right-hand side of the wind field. This results in the aircraft being normally trimmed for a light tail wind and updraft with subsequent flight into strong headwinds and fluctuating up and downdrafts.

Typical Results. Figure 14 shows the flight path of an aircraft characteristic of a DC-8 with fixed thrust and elevator setting through four representative gust front wind fields. Three of the wind fields excite the phugoid mode of the aircraft causing severe overshooting of the touch down point. Note the approximate phugoid period for the assumed landing speed of 150 mph given by $T = \sqrt{2}\pi V_a/g$ is 32 sec. giving a horizontal wave length $\lambda = TV$ of 1907 m (6256 ft). The non-dimensional $\hat{\lambda} = \lambda/h_a$ is 20 corresponding closely to the typical wave length observed in Figure 14.

For Case #9, the ground speed and pitch angle during approach are shown in Figure 15. The ground speed twice reaches a low of 91 kts at a pitch angle of zero degrees. This ground speed is below the stall speed and represents a very hazardous situation.

In Case #11 wind field, the aircraft does not depart substantially from the 2.7 glide slope for which it is initially trimmed. Inspection of the wind speeds actually "seen" by the aircraft (Figure 16) during landing for Case #9 and Case #11 wind fields reveals that for Case #11 headwinds increase at approximately the same rate as for Case #9, but updrafts were not as severe. In Case #11 a strong downdraft was encountered at the end of the horizontal shear whereas for Case #9, a strong updraft was encountered which forced the aircraft through a second oscillation. To separate the influence of

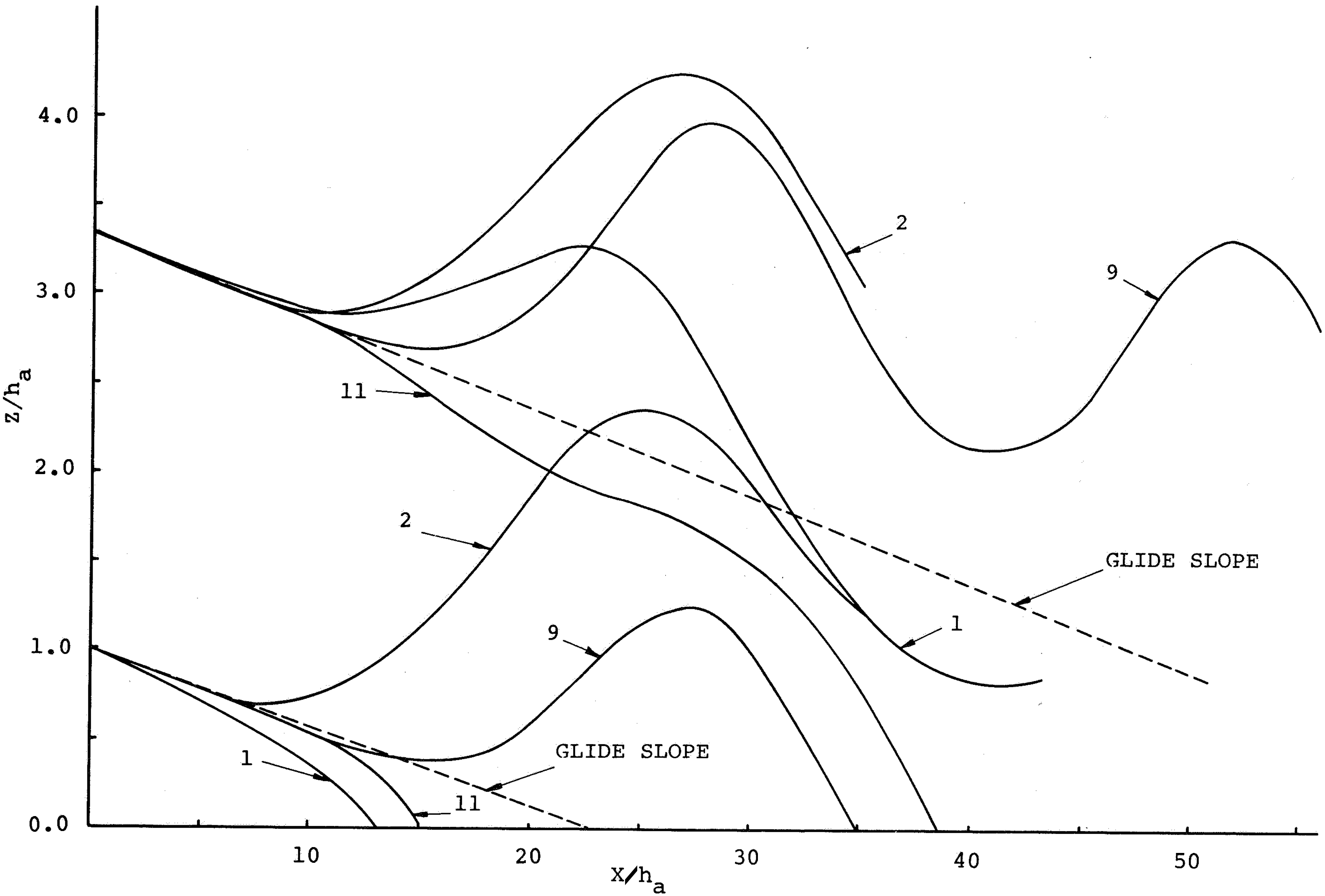


Figure 14 Flight Path of an Aircraft Having Characteristics of a DC-8 Landing with Fixed Controls through Four Different Thunderstorms

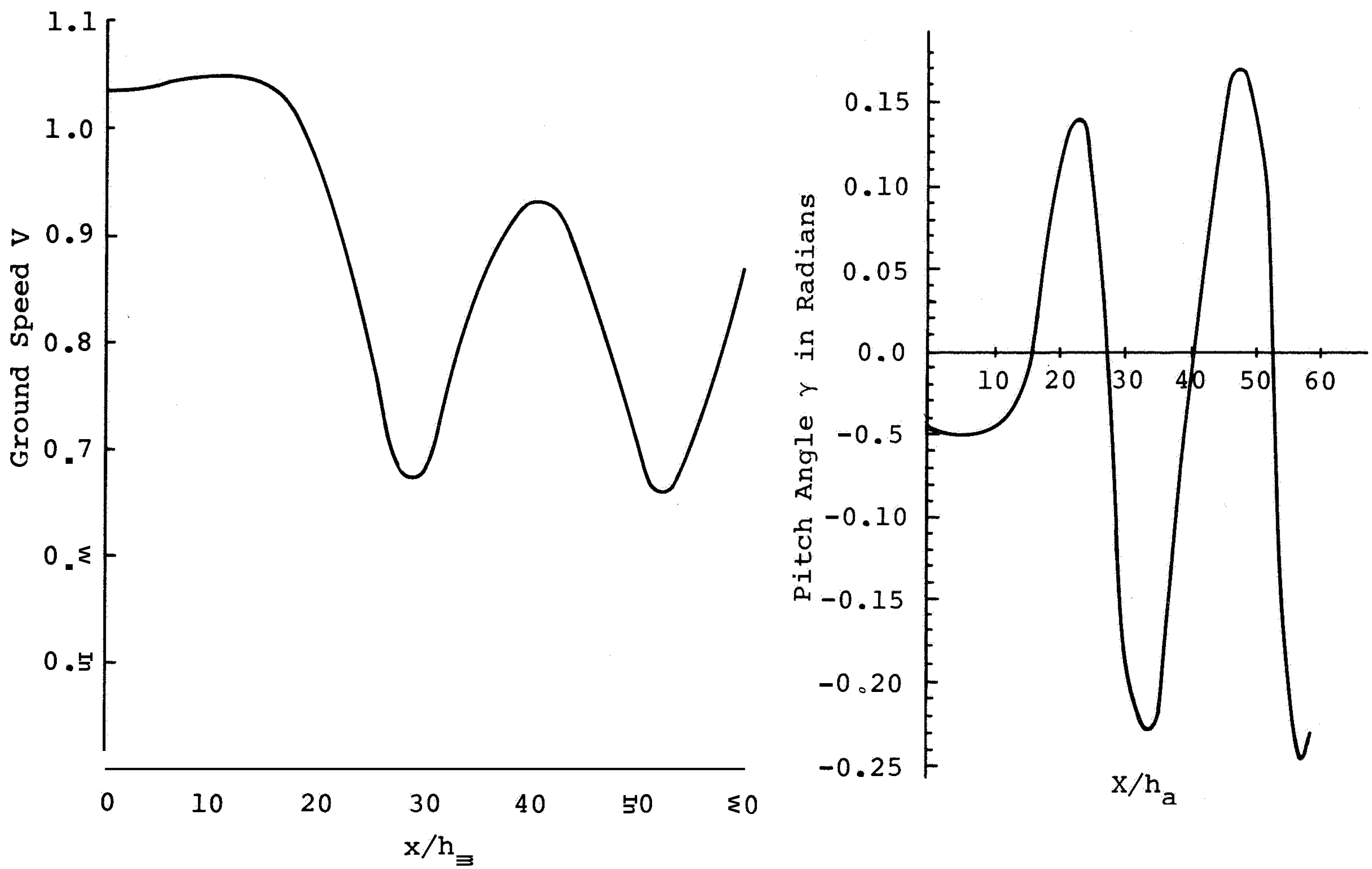


Figure 15 Ground Speed and Pitch Angle During Approach through Thunderstorm
Case 9

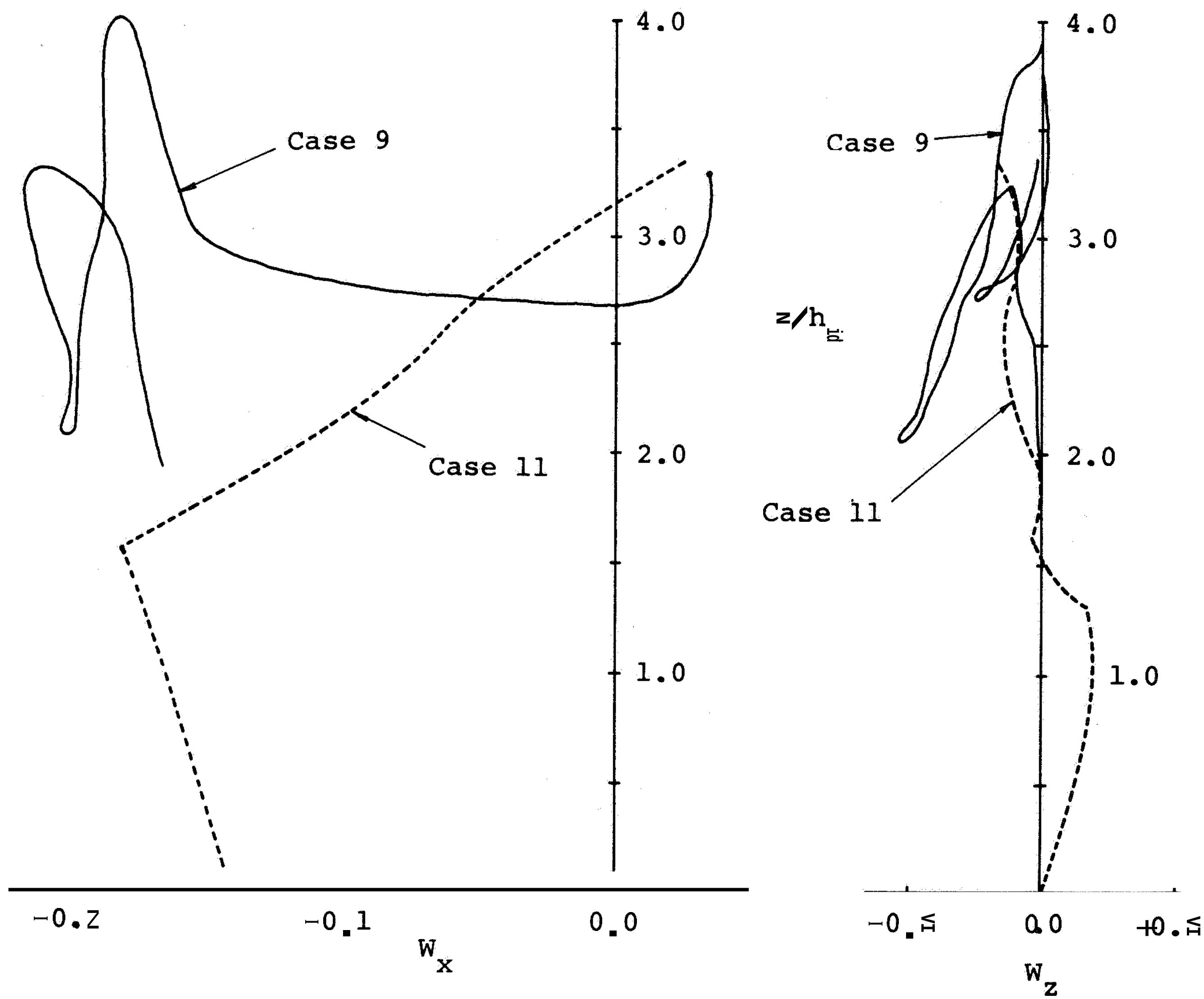


Figure 16 Wind Field "Seen" by Aircraft During Landing through a Thunderstorm Gust Front

variation in up and downdrafts from the influence of variations in horizontal wind speed, the solution for Case #9 was repeated first with $W_z = 0$ and second with $W_x = 0$. The resulting flight paths are shown in Figure 17, respectively.

Figure 17 illustrates that the phugoid mode is excited by the horizontal wind shear from $15 < x/h_a < 40$ but is considerably less strongly influenced by the horizontal wind when the vertical component is absent as in the region of $x/h_a > 40$. Recall, however, from Figure 14 that the wind shear in the horizontal direction is essentially gone when the airplane is beyond $x/h_a > 40$. The curve for the case $W_z = 0$ has only a very small excitation of the phugoid mode and, although causing an over-riding of the glide slope and a long landing, does not cause the extreme oscillations with associated loss of ground speed and severe pitch angles found for Case #9. This observation tends to support the conclusion of McCarthy and Blick [12] that the characteristic wind speed wavelength of thunderstorms can cause instability in the phugoid mode. The results, on the other hand, do not support the conclusions of Fujita [13] who attributes the strong downbursts associated with thunderstorms as being the positive factor in accidents related to flight through thunderstorms. The continuing research will draw further conclusion in this regard and will discuss this aspect of flight in thunderstorms in much greater detail for all 11 thunderstorm cases investigated in further reports.

The preceeding discussion relates to the case where the airplane's controls are fixed at trim condition at the point of entry into the thunderstorm wind field and are then held constant while the airplane makes the approach. Thus, these flight paths represent the one extreme of no control inputs. The opposite of this extreme would be the case where the airplane remains on the 2.7° glide slope and the control inputs required to maintain trimmed conditon all the way along the flight path computed. This case is referred to as the quasi-equilibrium case and has also been computed. Figure 18 shows the thrust requirement of

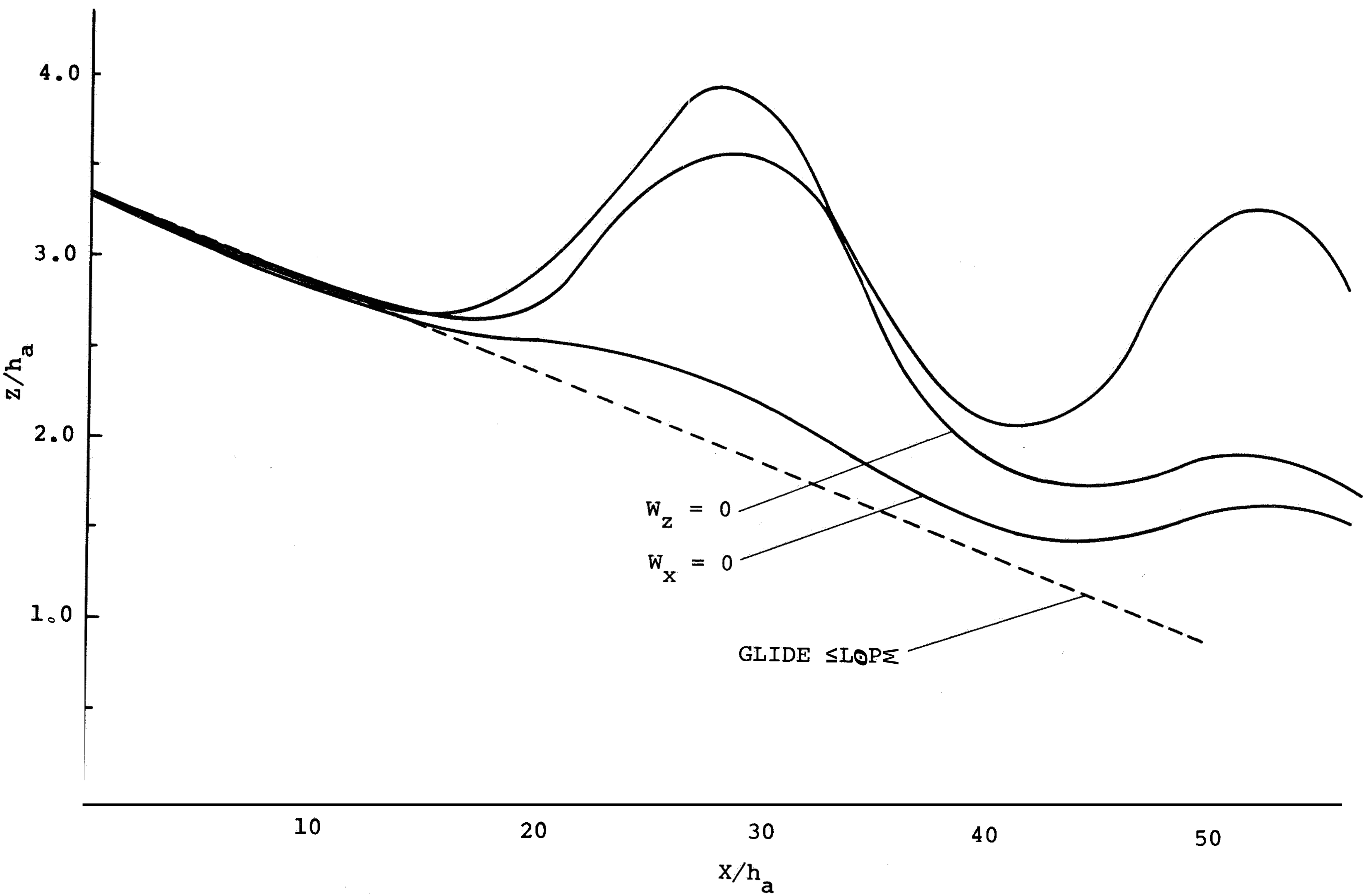


Figure 17 Comparison of Flight Paths through Thunderstorm Case #9 with both Wind Speed Components and with Individual Wind Speed Components: with Neither W_x nor W_z Equal Zero: with W_z Equal Zero: and with W_x Equal Zero

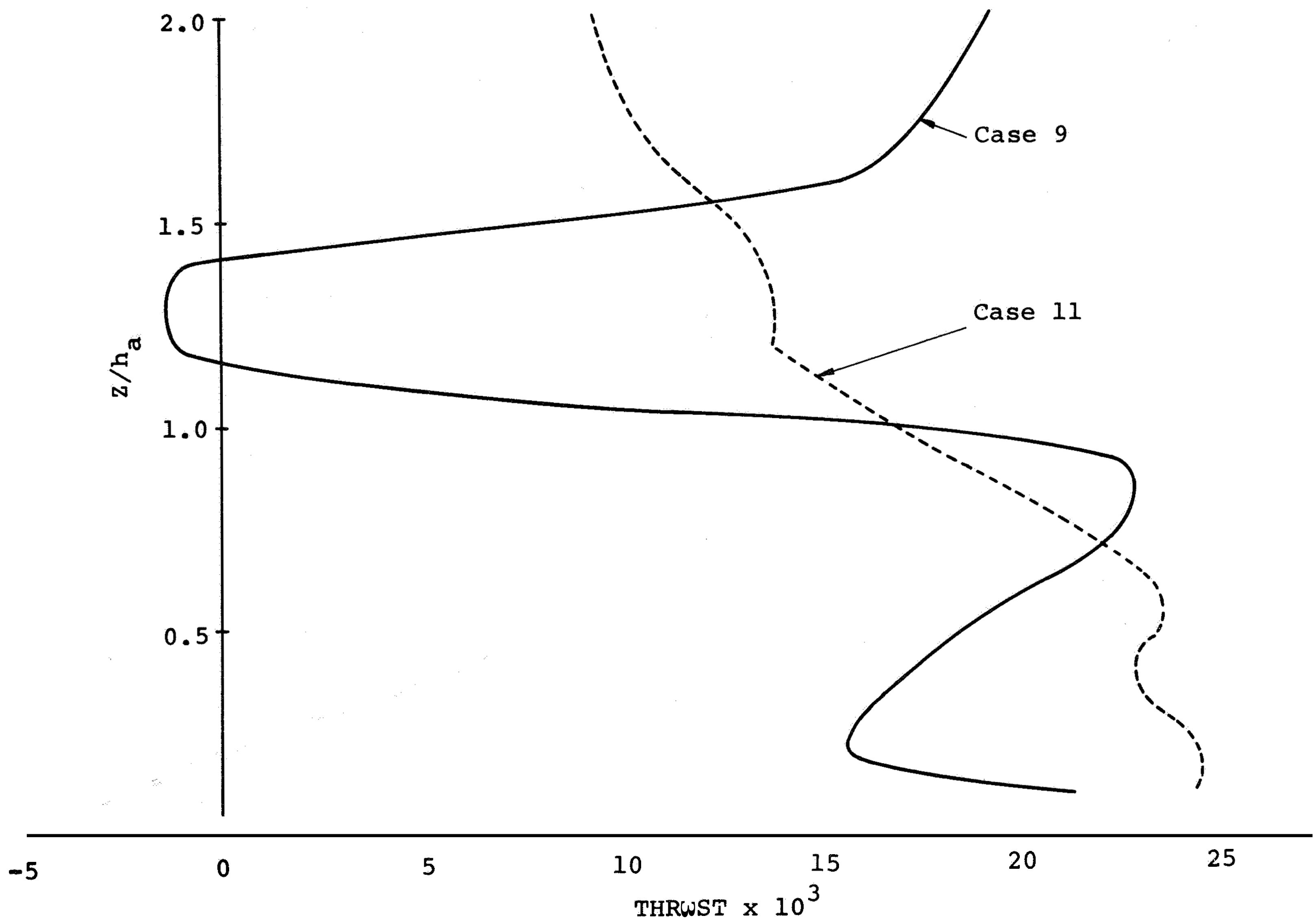


Figure 18 Thrust Required to Maintain Trimmed Conditions along a 2.7° Glide Slope through Thunderstorm Case 9

the airplane with DC-8 characteristics if it is to remain on a glide path during an approach through the Case #9 and Case #11 thunderstorms. In Case #9 maintaining constant relative air speed, one sees that the pilot must draw the thrust control well back and in this extreme ase even negative thrust results. As the horizontal shear diminishes the pilot must quickly restore the thrust if he is to remain on the glide slope. The approximate time required to reduce the thrust to practically zero and return to approximately the original value is on the order of 22 seconds. This is less than the spool up time of most jet engines and thus illustrates that it is essentially impossible to maintain glide slope through thunderstorms as intense as thunderstorm Case #9. For Case #11 where the phugoid mode is not excited, the pilot slowly increases thrust and maintains the glide slope without any extreme variation in thrust taking place.

The nature of the thunderstorm is thus observed to be an important factor in the behavior of the aircraft entering a thunderstorm gust front. The research will investigate the intensity of storms which create hazardous situations such as illustrated for Case #9. Examination of the response of the aircraft in all 11 thunderstorms gives insight into the possibility of aircraft encountering hazardous situations when flying through thunderstorms.

Other results from the study will include landings through the same wind fields with constant ground speed, with constant relative velocity and with constant pitch angle, respectively. The controlled variable which provides for the most stable flight through the strong wind shears will be delineated.

Acknowledgement. This work is being carried out under NASA Contracts NAS8-29584 and NAS8-31718 sponsored by the NASA Marshall Space Flight Center, Atmospheric Science Division. The author is greatful for the assistance of Dennis W. Camp and George H. Fichtl. Also, the financial support of Kenneth Hodge and William Gowan, Office of Aviation Safety Technology, NASA Headquarters, Washington, D.C., are most appreciated.

REFERENCES

1. "Sources of Low-Level Wind Shear Around Airports," George H. Fichtl, Dennis W. Camp, NASA Marshall Space Flight Center, Huntsville, Ala., and Walter Frost, University of Tennessee Space Institute, Tullahoma, TN; J. Aircraft, Vol. 14, No. 1, January 1977.

2. "Atmospheric Flow over Two-Dimensional Bluff Surface Obstructions," Juergen Bitte and Walter Frost, NASA CR-2750, October, 1976.

3. "Neutrally Stable Atmospheric Flow Over a Two-Dimensional Rectangular Block," Chih Fang Shieh, Walter Frost and Juergen Bitte, Contract report prepared under Contract No. NAS8-29584, Atmospheric Science Division, The University of Tennessee Space Institute, Tullahoma, TN 37388.

4. "STOL Technology," NASA SP-320, a conference held at Ames Research Center, Moffett Field, California, October 17-19, 1972.

5. "Flight in Turbulence," AGARD-CP-140. Symposium of the 42nd meeting of the Flight Mechanics Panel of AGARD held at Woburn Abbey, Bedfordshire, England, on 14-17, May 1973.

6. "Wind Shear Fluctuations at a Typical Urban V/STOL Port Site," J.V. Ramsdell, Pacific Northwest Laboratories, Richland, Wash., Sixth Conference on Aerospace and Aeronautical Meteorology of the American Meteorological Society, November 12-15, 1974, El Paso, Texas.

7. Clarke, R.H., and G.D. Hess, "Geostrophic Departure and the Function A and B of the Rossby-Number Similarity Theory," Boundary Layer Meteorology 1, 1974.

8. Goff, R. Craig, "Thunderstorm Outflow Kinematics and Dynamics," NOAA Technical Memorandum ERL NSSL-75, National Severe Storms Laboratory, Norman, Oklahoma, December, 1975.

9. Eastern Air Lines, Inc., Boeing 727-225, N8845E, John F. Kennedy International Airport, Jamica, hew York, June 24, 1975. Aircraft Accident. Report Number: NTSB-AAR-76-8., National Transportation Safety Board.

10. Continental Air Lines, Inc., Boeing 727-224, N88777, Stapleton International Airport, Denver, Colorado, August 7, 1975. Aircraft Accident. Report Number: NTSB-AAR-76-14, National Transportation Safety Board.

11. Iberia Lineas Aereas de Espana (Iberian Airlines), McDonnell Douglas DC-10-30, EC CBN, Logan International Airport, Boston, Massachusetts, December 17, 1973. Aircraft Accident. Report Number: NTSB-AAR-74-14, National Transportation Safety Board.

12. McCarthy, John and Edward F. Blick, "Aircraft Response to Boundary Layer Turbulence and Wind Shear Associated with Cold-Air-Outflow from a Severe Thunderstorm." Seventh Conference on Aerospace and Aeronautical Meteorology and Symposium on Remote Sensing from Satellites, American Meteorological Society, November 16-19, 1976, Melbourne, Fla.

13. Fujita, T. Theodore and Fernando Caracena, "An Analysis of Three Weather Related Aircraft Accidents," Research conducted at the Department of the Geophysical Sciences, The University of Chicago, Chicago, Illinois.

NOMENCLATURE

$\dot{q}$	time derivative of the pitching rate (q)
L_T	effective moment arm of the thrust vector
M	pitching moment
I_{YY}	moment of inertia about the symmetry plane of the aircraft
$\dot{( )}$	refers to the derivative with respect to time
g	magnitude of the acceleration of gravity
V	dimensionless magnitude of the velocity relative to the earth
γ	angle between $\vec{V}$ and x-axis (the flight path angle)
m	aircraft mass
δ_T	angle between the thrust vector and the fuselage reference line (FRL)
a	angle of attack
6	angle between $\vec{V}_a$ and $\vec{V}$
$\vec{F}_T$	thrust of the engines
$\vec{L}$	lift
$\vec{D}$	drag
$m\vec{g}$	gravitational forces
$\vec{V}$	dimensionless velocity vector relative to the earth
$\vec{V}_a$	dimensionless velocity vector relative to the air mass
FRL	fuselage reference line
x	dimensionless distance parallel to the surface of the earth
z	dimensionless distance perpendicular to the surface of the earth (positive downward)
D_i	(i = 1, 2, 3, 4, 5, 6, 7) dimensionless constants
Z_o	surface roughness
u_b	friction velocity
W_x	wind speed horizontal to ground
W_z	wind speed vertical to ground

a

TABLE 1.

WIND ENVIRONMENT DEFINITION

'SURVEY OF FLOW FIELDS AROUND IRREGULAR TERRAIN FEATURES

•QUALITATIVE INTERPRETATION RELATIVE TO AIRCRAFT SAFETY

REPORTED IN

"Review of Data and Prediction Techniques for Wind Profiles Around Manmade Surface Obstructions," presented at the 42nd Flight Mechanics Panel Meeting Symposium, on "Flight in Turbulence." Woburn Abbey, UK, May, 1973, published in Proceedings AGARD-CP-140 (1973), by Walter Frost.

"Sources of Low Level Wind Shear Around Airports," Proceedings of the Society of Air Safety Investigators, Fifth International Seminar, September 1974, Washington, D.C., G. H. Fichtl and Walter Frost.

"Sources of Low Level Wind Shear Around Airports," Journal of Aircraft, Vol. 14, No. 1, January 1977, G. H. Fichtl, D. W. Camp and Walter Frost.

TABLE 2.

WIND ENVIRONMENT DEFINITION

ANALYTICAL MODELLING

- BOUNDARY-LAYER ANALYSIS
  - SEMI-ELLIPTICAL GEOMETRY
  - FENCE GEOMETRY
- TRANSIENT BLOCK GEOMETRY
  - TWO-DIMENSIONAL CONSTANT VISCOSITY
  - SMAC
- TWO-DIMENSIONAL NAVIER-STOKES EQUATIONS
  - FORWARD FACING STEP
  - REARWARD FACING STEP
  - BLOCK GEOMETRY

TABLE 3.

WIND ENVIRONMENT DEFINITION

BOUNDARY LAYER ANALYSIS

REPORTED IN

"A Boundary Layer Approach to the Analysis of Atmospheric Motion over a Surface Obstruction," NASA CR 2182 (1973) by Walter Frost, J. R. Maus, W. R. Simpson.

"A Boundary Layer Analysis of Atmospheric Motion over Semi-Elliptical Surface Obstruction," Boundary-Layer Meteorology, 7 (1974), pp. 165-184, by Walter Frost with R. M. Maus and G. H. Fichtl.

"Analysis of Atmospheric Flow over a Surface Protrusion Using the Turbulence Kinetic Energy Equation," Boundary Layer Meteorology, 8 (1975), pp. 401-418, by Walter Frost with W. L. Harper and G. H. Fichtl.

"Analysis of Atmospheric Flow over a Surface Protrusion Using the Turbulence Kinetic Energy Equation with Reference to Aeronautical Operating Systems," NASA CR-2630 (1975), by Walter Frost and W. L. Harper.

"Development of SMAC Computer Code for Atmospheric Science Application," M.S. thesis, The University of Tennessee Space Institute, Tullahoma, Tennessee 37388.

"A Simple Analysis of Vortex Formation on Buildings," accepted for publication in the Journal of Industrial Aerodynamics, by Walter Frost with E. E. Hutto and G. H. Fichtl.

a

TABLE *4.*

WIND ENVIRONMENT DEFINITION

FIELD STUDY OF BLUFF BODY IN THE NATURAL WIND

- 'EIGHT-TOWER ARRAY
- •INSTRUMENTATION
  - *HORIZONTAL WIND SPEED CUP-ANEMOMETERS
  - 'DIRECTION VANE ANEMOMETERS
  - 'VERTICAL WIND SPEED PROPELLOR ANEMOMETERS
- •RESULTS
  - 'MEAN VELOCITY PROFILES
  - 'TURBULENCE INTENSITIES
  - 'REYNOLDS STRESSES
  - *CORRELATIONS
    - 'AUTO-CORRELATIONS
    - 'CROSS-CORRELATIONS
    - 'COHERENCE FUNCTIONS

REPORTED IN:

"A Field Study of the Wind over a Simulated Block Building," report contract number NSF GK-42942 (1976), by Walter Frost and A. M. Shahabi.

"Mean Horizontal Wind Profiles Measured in the Atmospheric Boundary Layer About a Simulated Block Building," Proceedings Second U.S. National Conference on Wind Engineering Research, June 1975, Colorado State University, Fort Collins, Colorado, by Walter Frost, G. H. Fichtl, J. R. Connell, and M. L. Hutto.

"Mean Horizontal Wind Profiles Measured in the Atmospheric Boundary Layer About a Simulated Block Building," Boundary Layer Meteorology, 1 (1977), by Walter Frost, G. H. Fichtl, J. R. Connell, and M. L. Hutto.

a

TABLE 5.

WIND ENVIRONMENT DEFINITIONS

'TURBULENCE SIMULATION WITH COHERENCE MATCHING

REPORTED IN

"Three Velocity Component, Nonhomogeneous Atmospheric Boundary Layer Turbulence Modelling, AIAA Paper No. 76-413, AIAA 9th Fluid and Plasma Dynamics Conference, San Diego, California (1976), by Morris Perlmutter, Walter Frost and G. H. Fichtl.

"Three Velocity Component Atmospheric Boundary Layer Turbulence, Contract No. NAS8-29548 Report, University of Tennessee Space Institute, Tullahoma, Tennessee 37388 (1976), by Walter Frost and Morris Perlmutter.

TABLE 6.

AIRCRAFT DYNAMICS

- TWO-DIMENSIONAL EQUATIONS OF MOTION WITH VARIABLE WIND
  - MEAN WIND
  - WIND SHEAR
  - TURBULENCE
- CONTROL SIMULATION
  - FIXED CONTROLS
  - DIGITAL AUTOMATIC CONTROLS
- SOLUTION FOR FLIGHT PATHS THROUGH COMPUTED WIND FIELDS
- AERODYNAMIC COEFFICIENTS IN VARIABLE WINDS

REPORTED IN:

"The Influence of Wind Shear on Aerodynamic Coefficients," Proceedings of the 6th Conference on Aerospace and Aeronautical Meteorology, El Paso, Texas, November 1974, by Walter Frost and Enice Hutto.

"Helicopter Response in Gusty Winds About a Building," Proceedings of the 7th Conference on Aerospace and Aeronautical Meteorology, Melburne, Florida, November 1976, by Walter Frost, K. R. Reddy and D. W. Camp.