Takeoff and Landing in a Downburst

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Investigations into landing and takeoff in a downburst are made with a simple wind model based on the flow toward a flat plate. Approaches along a given nominal glide path are analyzed. The influence of the changing wind on the aircraft's demand for energy is calculated. The results are given in energy height errors. Computer simulations of an aircraft with fixed controls show the well-known flight-path pattern of accidents in manual flight. As far as the demand for energy is concerned, approaching through a downburst is not a problem. This can be pointed out by computer simulations with a modern autopilot and autothrottle control system. The energy situation of an aircraft in a downburst is more dangerous for takeoff than for landing. Heavy thunderstorms can produce wind conditions under which a takeoff is not possible. Gentle downbursts can be crossed by a simple escape maneuver. The acquired knowledge of landing and takeoff in a downburst contains some important aspects for the go-around.

Nomenclature

DF	= relative thrust
E	= energy
g	= geographical acceleration
G	= aircraft weight
H	= height
H_E	= energy height
m	= aircraft mass
s	= flight-path coordinate
t	= time coordinate
u_{Wg}	= horizontal wind component
u_{Wx}	= horizontal wind gradient, $= \partial u_{Wg}/\partial x_g$
V	= airspeed
V_K	= flight-path speed
V_s	= stall speed
V_W	= windspeed
V_2	= minimum nominal takeoff airspeed
w_{Wg}	= vertical wind component
w_{WH}	= vertical wind gradient, $= \partial w_{Wg}/\partial H$
x_g	= geographical coordinate
γ	= flight-path inclination angle
Δ	= difference
$(\dot{\ })$	= time derivative

Subscripts

nom	= nominal value
ref	= reference value
min	= minimum value

Introduction

WIND shear on landing and takeoff may crucially restrict flight safety. The most dangerous gradients of wind shear can be found in downbursts. From 1964 to 1975, the FAA identified 25 accidents caused by low-level wind shear; 13 of them occurred in thunderstorms.[1] Although since 1975 a number of investigations have dealt with the downburst phenomenon, those accidents continue at present. For example, on August 2, 1985, in Dallas, 134 people lost their lives when a Lockheed Tri Star had a ground impact during approach. This accident again pointed out that the downburst phenomenon is well known, but we still have no control of the inherent problems.

In this paper, a simple method to calculate the energy height error caused by the change in wind along a constant flight path is applied. The main parameters of influence are discussed. Flight-path patterns computed by aircraft simulation by means of nonlinear differential equations of motion will be compared with accident flight paths. From the results, conclusions can be drawn to improve flight safety.

Many different wind models describing the flow conditions in a downburst are available.[1-3] In the present study, no exact meteorological models, but simple engineering models, which describe the main important characteristics of a downburst, are used. The investigations into flights in thunderstorms are made for a modern twin-engine-powered aircraft of about 137 tons maximum takeoff weight.

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Wind Models

Downburst Core

Stipulating steady conditions and only regarding the aircraft's symmetrical plane, Krauspe[4] evaluated a model of a downburst, which is based on the flow toward a flat plate. The model uses only two constant wind gradients, u_{Wx} and w_{WH}. The wind components then can be calculated by

$$u_{Wg} = u_{Wx}\partial x_g + u_{Wg\ \mathrm{ref}} \tag{1}$$

$$w_{Wg} = w_{WH}\partial H + w_{Wg\ \mathrm{ref}} \tag{2}$$

Compared with the wind conditions in real downbursts, the model is a good approximation, but only for the limited range of the downburst's core (Fig. 1, area A). For great distances to the stagnation point, the computed wind from Eqs. (1) and (2) becomes unrealistically great. For investigations into entering or going out of a downburst, the model must be completed.

Completed Downburst Model

On both sides, the downburst core (A) is completed by a "transition flow" (B) and a "surrounding flow" (C), as shown in Fig. 1.[5] The boundaries of these areas are given by streamlines of the flow toward a flat plate. All three areas can be chosen unsymmetrically to the center of the downburst. Figure 1 shows a model combination with a constant headwind in the surrounding area joined to the core by a function to the power of 2 in the "transition area."

Energy Height Error and Hazard Limit

Changing winds influence the energy situation of an aircraft. Therefore, the variation of energy is a criterion for the severity of the wind shear. The total energy can be determined by

$$E = mgH + 1/2(mV_K^2) \tag{3}$$

Related to the aircraft's weight $G = mg$, we get the energy height[6]:

$$H_E = H + V_K^2/(2g) \tag{4}$$

For a constant airspeed, the nominal flight-path speed depends only on the actual wind of a given wind field (see Fig. 2)

$$V_{K\,\mathrm{nom}} = V_{\mathrm{nom}} + V_W \tag{5}$$

If a specific flight path is required, the nominal height at each distance along the flight path is known. The nominal energy height then can be computed by

$$H_{E\,\mathrm{nom}} = H_{\mathrm{nom}} + V_{K\,\mathrm{nom}}^2/(2g) \tag{6}$$

The energy height error now is defined as

$$\Delta H_E = H_E - H_{E\,\mathrm{nom}} \tag{7}$$

The nominal approach situation is given by $\gamma_{\mathrm{nom}} = -3$ deg, and $V_{\mathrm{nom}} = 1.3V_S$. The hazard limit is based on the facts that the aircraft is not allowed to sink below a specific obstacle surface and that the airspeed must be higher than $V_{\mathrm{min}} = 1.1V_S$.[8] The minimum height for a Cat I approach is defined by the Obstacle Assessment Surface of the PANS-OPS.[7] For the departure, there is no specific nominal takeoff flight path comparable to the approach path. So the energy height deviation referred to steady level flight will be defined as energy height error. That means, for negative energy height errors, the aircraft is not able to maintain height at constant airspeed. The nominal height $H_{\mathrm{nom}} = 11$ m is chosen where the computation started. The takeoff airspeed V_{nom} for the simulated aircraft is V_2 plus an addition for gusts. The hazard limit for the departure procedure is defined by $H_{\mathrm{min}} = 11$ m and $V_{\mathrm{min}} = 1.1V_S$.

Landing

During the final approach the aircraft flies with a fixed configuration. The pilot has to maintain a constant airspeed and the required glide slope. Applying these conditions, a relation can be expanded for the calculation of the required change in thrust to compensate for variable winds. The linearized nondimensional equation to maintain constant airspeed and glide slope is[8]

$$\Delta F/G = \dot{u}_{Wg}/g + (\Delta u_{Wg}/V_{\mathrm{nom}})\gamma_{\mathrm{nom}} + \Delta w_{Wg}/V_{\mathrm{nom}} \tag{8}$$

The wind difference is calculated by the actual wind minus the wind where the computation is started and the aircraft is trimmed. If there is no variation in wind, the aircraft will continue its steady flight with constant thrust. With the balance of power for steady flight

$$V_K \Delta F + G\Delta \dot{H}_E = 0 \tag{9}$$

and

$$V_K = \frac{\partial s}{\partial t} \tag{10}$$

the energy height error becomes

$$\Delta H_E = -\int (\Delta F/G)\partial s \tag{11}$$

With Eq. (8) it can be assumed that the following applies:

$$\Delta H_E = -\int [\dot{u}_{Wg}/g + (\Delta u_{Wg}/V_{\mathrm{nom}})\gamma_{\mathrm{nom}} + \Delta w_{Wg}/V_{\mathrm{nom}}]\partial s \tag{12}$$

In the preceding equation, only the nominal approach speed and the nominal flight-path slope are needed to determine the energy height error in a given wind field. The energy height error caused by wind variation can be split up into three terms:

$$\Delta H_{E\dot{u}} = -\int (\dot{u}_{Wg}/g)\partial s \tag{13}$$

$$\Delta H_{Eu} = -\int (\Delta u_{Wg}/V_{\mathrm{nom}})\gamma_{\mathrm{nom}}\partial s \tag{14}$$

$$\Delta H_{Ew} = -\int (\Delta w_{Wg}/V_{\mathrm{nom}})\partial s \tag{15}$$

Landing in a Downburst Core

On June 24, 1975, in New York, a downburst accident happened during the approach of a B-727 jet liner. The average of the wind gradients in the core was found to be $u_{Wx} = 0.005$/s and $w_{WH} = 0.02$/s.[4] Figure 3 shows the nominal approach path in that core. The resulting energy height error components of Eqs. (13–15) are very typical of a landing in a downburst. At the beginning of the calculation, the errors are zero because the aircraft is trimmed as required. During the approach only the horizontal wind acceleration causes a loss of energy height. The two terms ΔH_{Eu} and ΔH_{Ew} effect an addition of energy height. During an approach through a downburst's core, the loss of energy height increases and a maximum is reached. Then the energy height error decreases until the aircraft touches down.

One parameter affecting the demand for energy is the flight-path inclination angle. With steeper slopes the maximum energy height loss decreases to zero (Fig. 4). The energy height error at touchdown can even become positive. Another important parameter is the position of the nominal point of touchdown in relation to the center of the down-

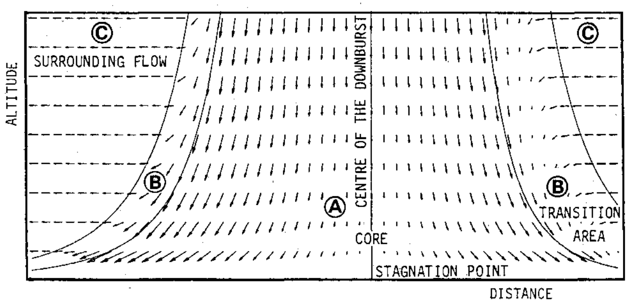

Fig. 1 Completed model of a downburst.

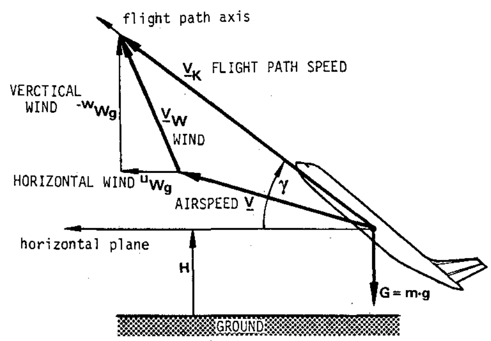

Fig. 2 Vector diagram of speeds in the aircraft symmetrical plane.

burst. As shown in Fig. 5, a negative distance means that the nominal point of touchdown is before the core's center. The maximum energy height loss increases with the distance of the touchdown behind the center of the downburst and so does the energy height error at touchdown. The higher the nominal approach speed, the higher the maximum energy height loss and the energy height error at touchdown (see Fig. 6).

Another situation is present if the pilot approaches with a higher airspeed than the nominal approach speed $V = V_{nom} + \Delta V$. Here the pilot tries to build up an energy storage caused by a higher kinetic energy. The assumed excess energy (in regard to the additional airspeed) is shown in Fig. 7. It increases with positive airspeed differences. But the higher airspeed produces a more intensive energy release while crossing the downburst's core. So the effective excess energy at touchdown is less than assumed. The same effect can be obtained for the maximum energy height loss. It can be stated that the recommendation to fly with a higher airspeed than the nominal approach speed can improve flight safety but it is less effective than assumed. In summary, one

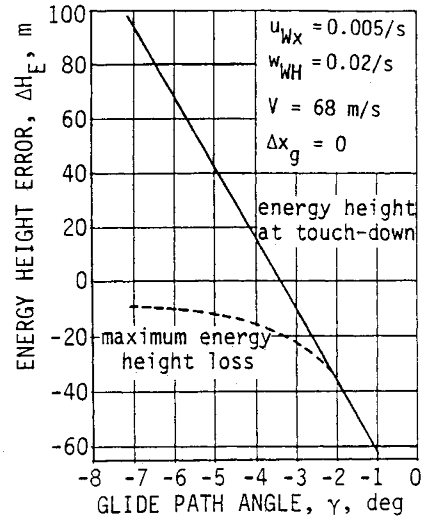

Fig. 4 Effect of the nominal glide-path angle upon ΔH_E.

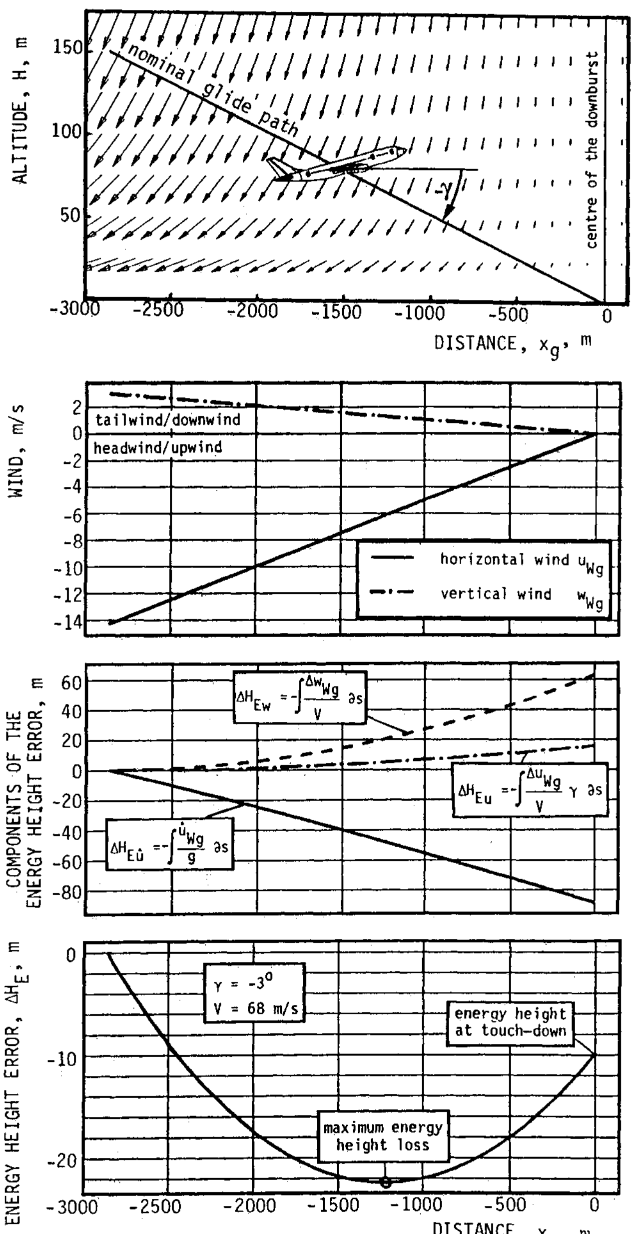

Fig. 3 Landing in the core of a downburst.

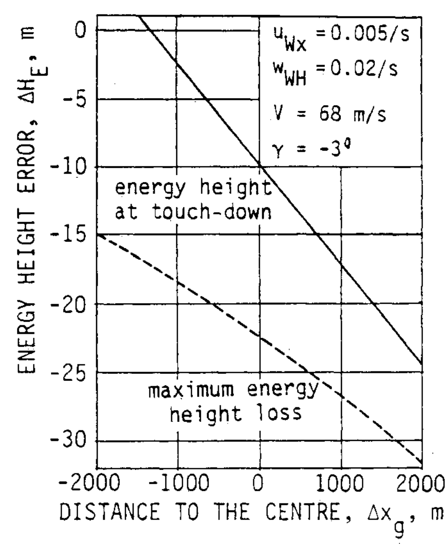

Fig. 5 Effect of the nominal point of touchdown upon ΔH_E.

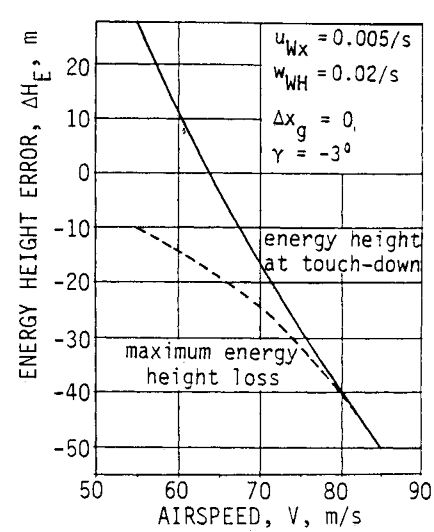

Fig. 6 Effect of the nominal approach speed upon ΔH_E.

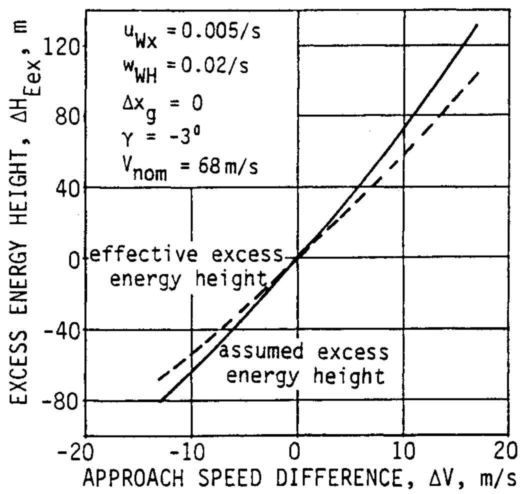

Fig. 7 Excess energy height vs approach speed variation.

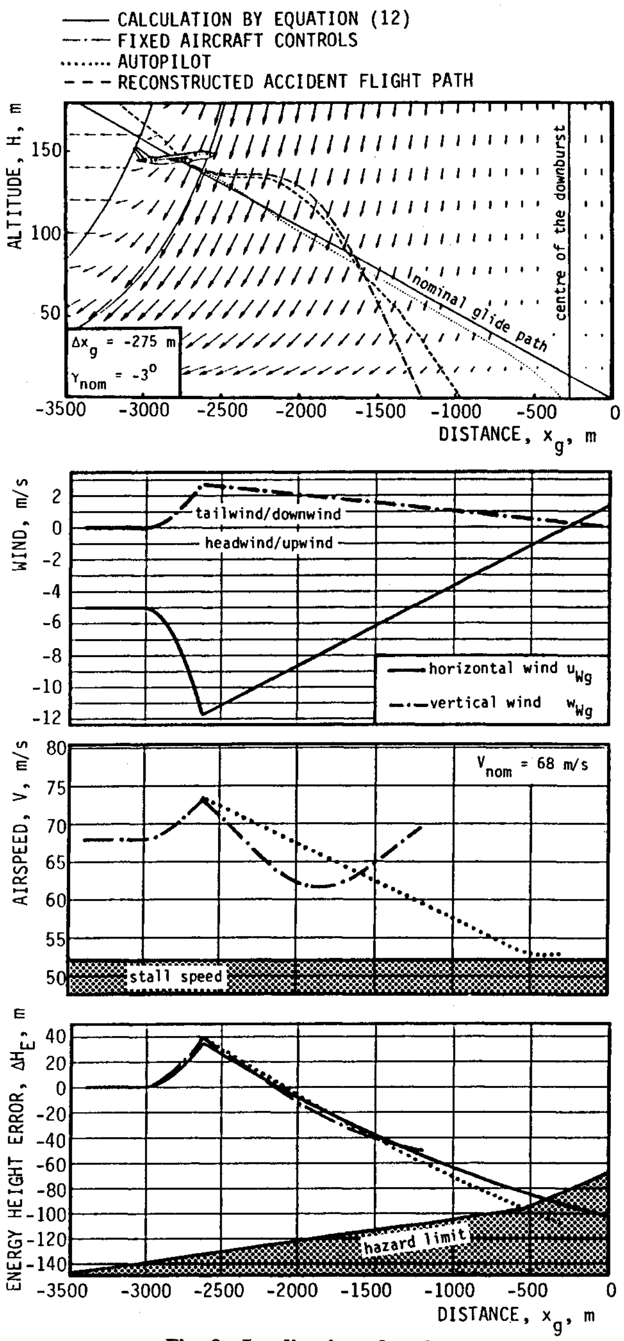

Fig. 8 Landing in a downburst.

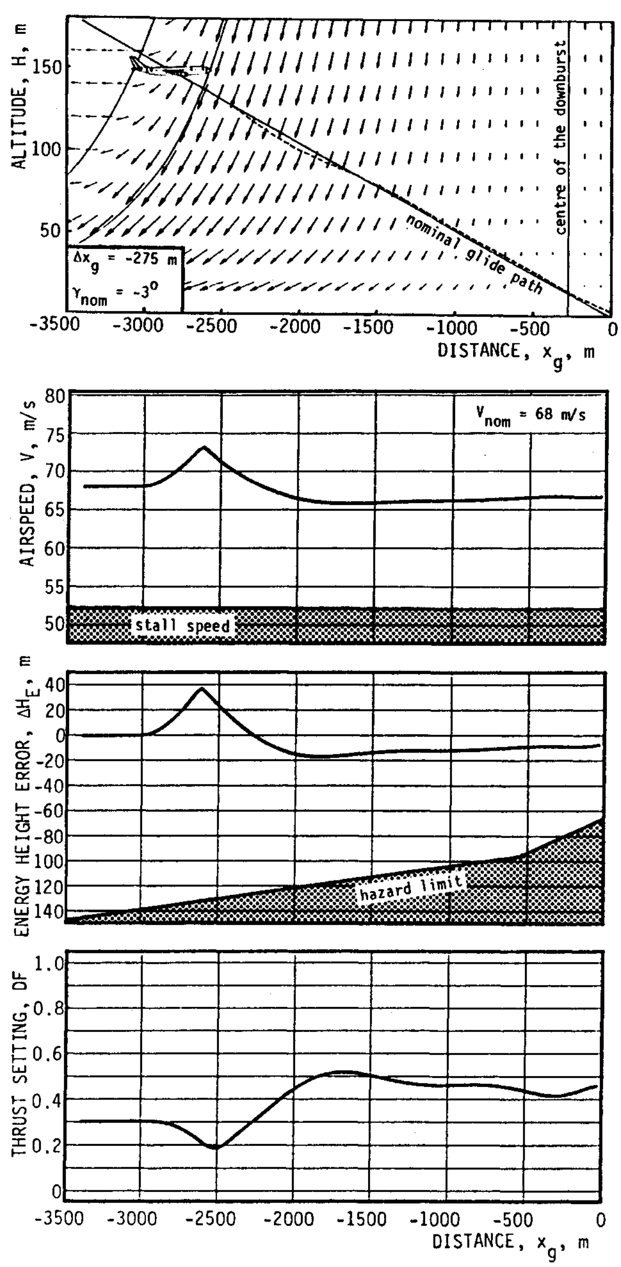

Fig. 9 Landing with an automatic flight control system.

can say that during the approach in the core of that New York downburst, the defined energy hazard limit is never reached.

Investigations with the Completed Downburst Model

In the preceding investigations, the aircraft is already trimmed for the wind conditions in the downburst's core which are at the point where the calculation started. In a real approach the aircraft will be trimmed for the wind situation before it reaches the downburst. Figure 8 shows the wind field of the expanded downburst model based on the conditions of the B-727 approach accident in New York on June 24, 1975. Some flights are simulated passing this downburst.

The flight path with fixed aircraft controls is very close to that of the accident flight. Thus we can assume that the pilot reacts much too late and not efficiently. When the aircraft encounters the downburst, the headwind increases, and so does the airspeed and the energy height. When entering the core, the energy height loss starts. The aircraft has a ground impact with a proper airspeed. The energy height error along the nominal glide path computed by Eq. (12) demonstrates that the hazard limit would be reached some hundred meters later.

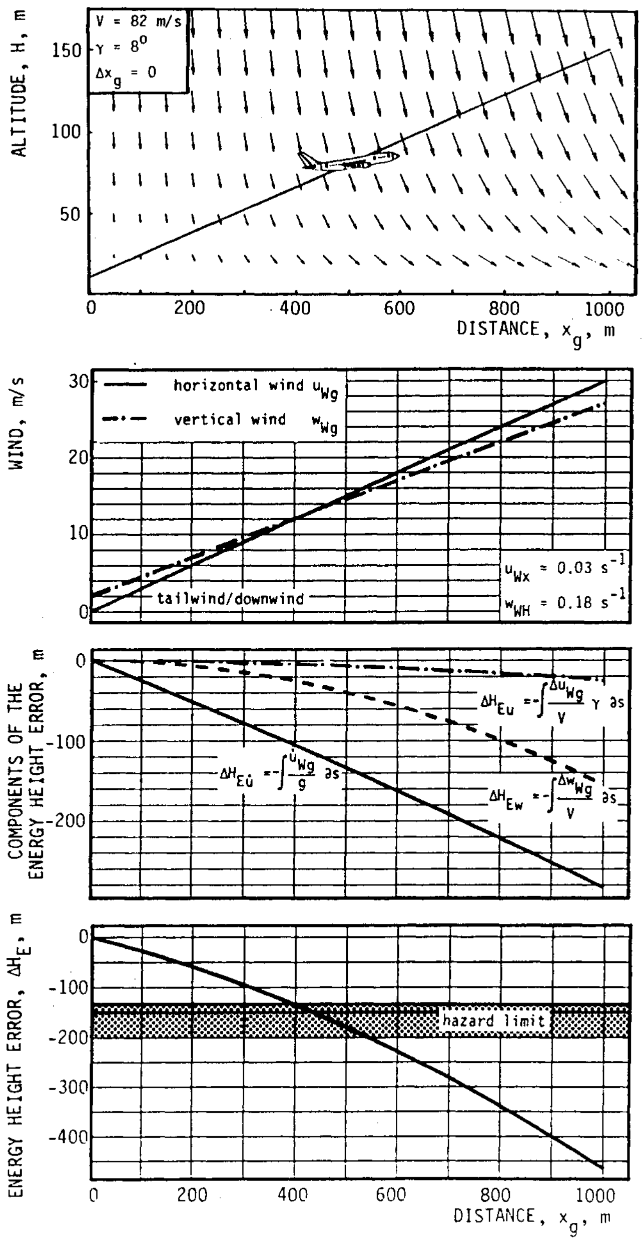

Fig. 10 Takeoff along a given flight path.

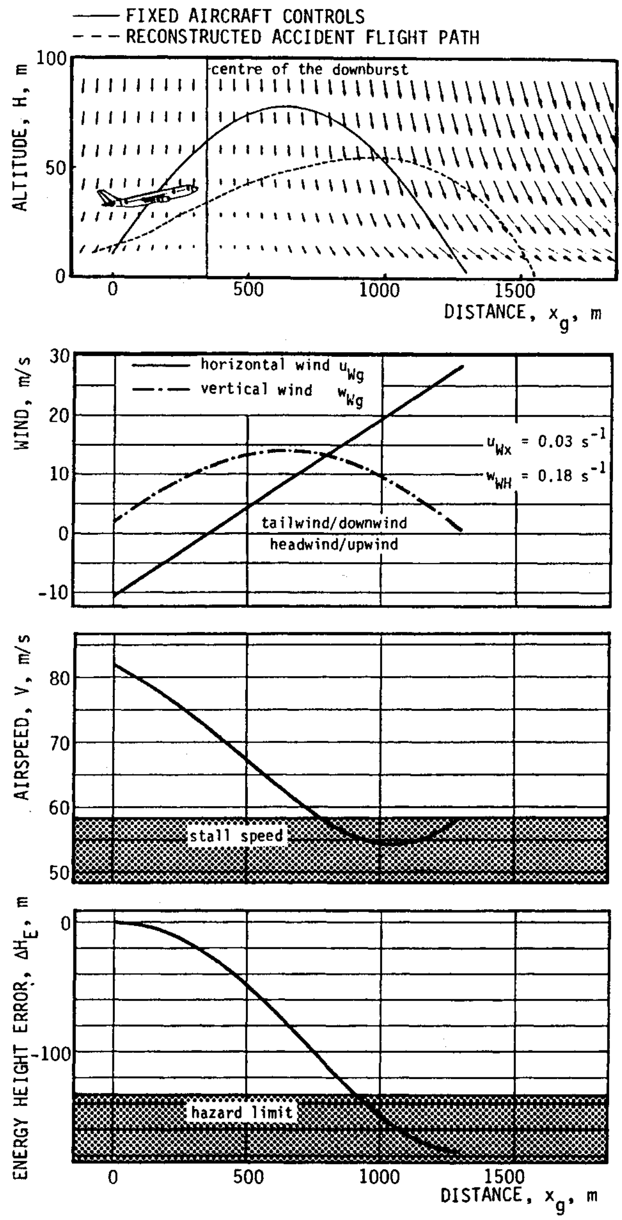

Fig. 11 Takeoff in the core of a downburst.

An activated autopilot tries to position the aircraft on the nominal glide path. The flight-path deviation is small, but the energy height error leads to significant airspeed errors. When the energy height error crosses the energy hazard limit, the airspeed is very close to the stall speed. The aircraft does not reach the runway. Thus, even if the pilot is able to maintain the nominal glide path, the hazard limit is reached. A comparison of the energy height error calculated by the simple Eq. (12) with those of the nonlinear simulation along the individual flight paths with fixed aircraft controls or autopilot demonstrates only small differences. With the simple but powerful method of Eq. (12), it is possible to estimate the danger of the landing in a downburst. A safe landing will be possible only with an additional supply of energy by thrust control.

Figure 9 illustrates an approach in the same downburst with a conventional modern automatic flight control system (autopilot and autothrottle). The aircraft follows the nominal glide slope and maintains the approach speed with small deviations. The thrust setting (actual thrust related to the maximum thrust) adjusted by the autothrottle never reaches its maximum. A safe touchdown on the runway will be possible. In general, it can be said that during landing in a downburst the flight performance is normally not the limiting factor.[9] The problem is that the pilot needs sufficient information about the necessary control activities, especially about the required thrust setting caused by the actual wind situation.

Takeoff

On approach, the energy height error can be compensated by thrust control. During takeoff the aircraft is flying at its maximum performance capability. In any case, the wind conditions in a downburst affect the takeoff in a quite different way than a landing. Compared to landing, the more dangerous situation during takeoff becomes clearly recognizable when the energy height error along a hypothetical constant takeoff path is computed by Eq. (12). The chosen gradients reconstructed from the takeoff accident of a B-727 in Denver on August 7, 1975, are $u_{Wx} = 0.03/s$ and $w_{WH} = 0.18/s$.[4] Figure 10 illustrates the hypothetical flight path and the increasing tail- and downwind after liftoff. From the beginning, the aircraft progressively releases energy. All three parts of the energy height error, as defined in Eqs. (13–15), have negative values.

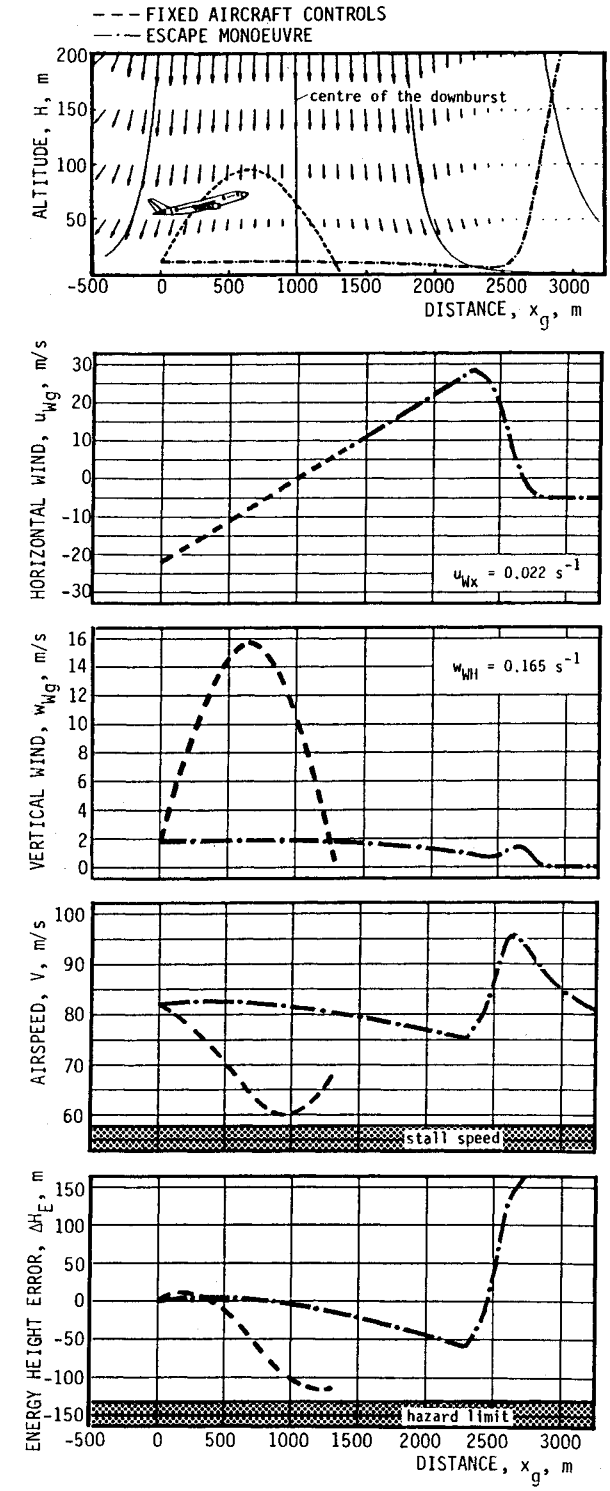

Fig. 12 Escape maneuver in a downburst.

In reality, an aircraft affected by variable winds is not able to maintain a constant takeoff path as assumed in Fig. 10. A numerical aircraft simulation with controls fixed is shown in Fig. 11. The simulation starts 350 m before the center of the downburst comparable to the Denver accident. The energy height loss increases from the beginning and the aircraft is permanently losing airspeed. The stall speed is reached shortly before crossing the hazard limit. The reconstructed flight path of the Denver accident is similar to the flight path with fixed aircraft controls. Thus, once again it can be assumed that the pilot's inputs are not very efficient. However, in view of the energy height error, this accident must be classified as inevitable.

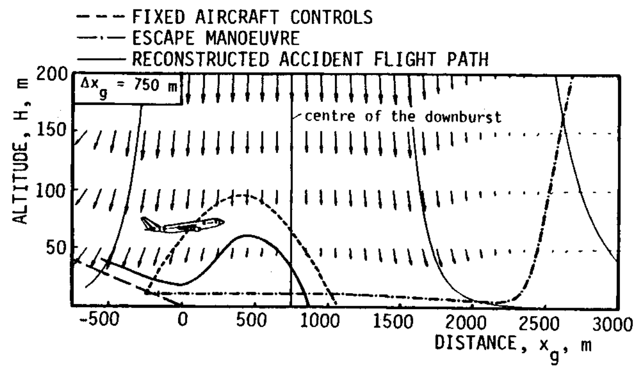

Fig. 13 Go-around in a downburst.

Downbursts with moderate wind gradients can be crossed by a simple escape maneuver: A considerable energy release is the result of the vertical wind increasing with height (Fig. 10). If we imagine a level flight very close to the ground (as close as permitted by obstacles), the effect of the vertical wind diminishes and so does the effect of the horizontal wind difference.

The wind gradients found in the downburst accident in Philadelphia on June 23, 1976, are $u_{Wx} = 0.022/\text{s}$ and $w_{WH} = 0.165/\text{s}$. The flight path of the above-described escape maneuver in that downburst is shown in Fig. 12. During the flight through the core, the airspeed is far away from the stall speed and the energy height error is not critical. After leaving the core, a safe takeoff climb is possible. With regard to that maneuver, it can be said that even in such bad conditions a takeoff is possible if the aircraft leaves the core of the downburst before it reaches its stall speed.

As gathered from Fig. 11, a realistic pilot behavior in downbursts comes close to simulations with fixed aircraft controls. Such a simulation carried out in the Philadelphia downburst is also plotted in Fig. 12. Airspeed and energy height error are rapidly decreasing and the hazard limit is nearly reached when the aircraft has ground impact.

Aspects for the Go-Around

In principle, the go-around can be assumed as a combination of approach and takeoff climb. By taking the results discussed previously into consideration, the following conclusions can be drawn: Regarding the energy height error, in most of the downbursts a landing is possible provided that the pilot or the automatic flight control system reacts in the required manner. If the approach glide slope and the approach airspeed cannot be maintained even with nearly full thrust, then a go-around is certainly impossible.

The decision to land in a downburst or to go around is hard to make based on the information the pilot gets from his instruments. However, if the wind conditions admit a go-around, the above-described level flight procedure is to be preferred for crossing the core. Figure 13 shows the reconstructed flight path of the go-around accident in Philadelphia on June 23, 1976. The takeoff paths in the same downburst of Fig. 12 are also plotted. The accident aircraft approached above the nominal glide path. When the pilot started the go-around and the aircraft began to climb, the flight path looks very similar to the simulated flight with fixed aircraft controls. The aircraft has a ground impact at a distance of about 1000 m behind the nominal point of touchdown. Carrying out the discussed escape maneuver, the downburst can be crossed.

Summary and Conclusions

The reasons for the approach accidents cannot be found exclusively in the wind situation in the core of a downburst. The critical situation results from the fact that the aircraft's thrust setting for the approach will have been done before it reaches the downburst. Computer simulations with fixed aircraft controls show flight-path patterns similar to those of real aircraft accidents. Thus, it can be assumed that the pilot's inputs are not efficient. However, even if the pilot is able to maintain the nominal glide path, a landing is possible only with the supply of energy by thrust control. A safe approach is possible with the help of conventional modern automatic flight control systems (autopilot and autothrottle). Thus, it can be concluded that the cockpit instrumentation of today is not sufficient to give the pilot enough information for detecting wind shear and reacting properly.

The wind conditions in a given downburst are more dangerous for takeoff than for landing. In some cases, a takeoff can be impossible. In moderate downbursts, a practicable escape maneuver is the level flight at a low height to pass the core of the downburst before starting the climb. The discussed results for the takeoff can also be applied on the go-around.

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