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TAKE-OFF AND LANDING IN A DOWNBURST*

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Abstract

Wind shear on landing and take-off may crucially restrict flight safety. The most dangerous gradients of wind shear can be found in downbursts. To represent the configuration of flow in a downburst, a simple potential flow model is used. It is based on the flow towards a flat plat. The investigations into flights in thunderstorms are made for a modern twin engine aircraft of about 137 tons maximum take-off weight.

Approaches along a given nominal glide path through a downburst are analysed. The influence of the changing wind on the aircraft's demand for energy is calculated. The results are given in energy height errors. The main parameters of influence are the airspeed, nominal glide path slope and the distance of the nominal point of touch-down to the centre of the downburst. The demand for energy increases with gentle glide path slopes and high airspeeds. It increases also when the nominal touch-down is far behind the centre of the downburst.

Computer simulations of an aircraft with fixed controls show the well known flight path pattern of accidents in manual flight. So it can be assumed, that the todays cockpit instrumentation is not sufficient to give the pilot enough information for detecting wind shear and reacting properly. During landing in a downburst the maximum thrust setting won't be necessary if the pilot knows the demand for thrust timely. Concerning the demand for energy approaching through a downburst is not a problem. This can be pointed out by computer simulations with a modern autopilot and autothrottle control system. This equipment allows a proper touch-down on the runway even under wind conditions like those in a downburst.

It can be shown, that flight conditions in a downburst during take-off are quite different from those during approach. Regarding the demand for energy take-off is more dangerous than landing. Heavy thunderstorms can produce wind conditions under which a take-off is not possible.Gentle downbursts can be crossed by a simple escape manoeuvre.

The acquired knowledge of landing and take-off in a downburst encloses some important aspects for the go-around.

List of symbols and abbreviations

DF	relative thrust
E	energy
g	geographical acceleration
G	aircraft weight
H	height
$\dot{H}_E$	rate of enrergy height (=SEP)
m	aircraft mass
s	flight path co-ordinate
t	time co-ordinate
u_{Wg}	horizontal wind component
$\dot{u}_{Wg}$	horizontal wind acceleration
u_{Wx}	horizontal wind gradient
$\underline{V}$	airspeed vector
$\underline{V}_K$	flight path speed vector
V_s	stall speed
$\underline{V}_W$	wind speed vector
V_2	minimum nominal take-off airspeed
w_{Wg}	vertical wind component
w_{WH}	vertical wind gradient
x_g	geographical co-ordinate
γ	flight path inclination angle
Δ	difference
nom	nominal value
ref	reference value
SEP	specific excess power (=$\dot{H}_E$)

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I. Introduction

For the period between 1964 and 1975 the FAA identified 25 accidents caused by low-level wind shear, thirteen of them occured in thunderstorms.(1) Although since 1975 a number of investigations have dealt with the downburst phenomenon those accidents have happened until today. For example on August 2nd, 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 the following paper the main parameters of influence while flying through a downburst will be discussed. A simple method to calculate the energy height error along a constant flight path is used. Flight path patterns computed by aircraft simulation by means of non-linear differential equations of motion will be compared with accident flight paths. From the results conclusions can be drawn to improve flight safety. Simple windmodels which can help to point out the basic problems are shortly described at the beginning of the paper.

II. Windmodels

The field of flow in a downburst is rather complex. Many different windmodels describing the flow conditions in a downburst are available.(1,2,3) For systematical investigations in the phenomenons which are important for an aircraft flying through a downburst it is necessary to use simple windmodels to set general conclusions. We don't need any exact meteorological models but engineering models which describe the main important characteristics of a downburst. Therefore some simplifications must be brought in.

Core of a downburst

Stipulating steady conditions and only regarding the aircraft's symmetrical plane KRAUSPE (4) evaluated a model for the core of a downburst, which is based on the flow towards a flat plat (see FIG. 1, area A). The model uses only two constant wind gradients:

$$\text{horizontal wind gradient} \quad u_{Wx} = \frac{\partial u_{Wg}}{\partial x_g} \qquad (1)$$

$$\text{vertical wind gradient} \quad w_{WH} = \frac{\partial w_{Wg}}{\partial H} \qquad (2)$$

The wind components can be calculated by:

$$\text{horizontal wind} \quad u_{Wg} = u_{Wx} \cdot \partial x_g + u_{Wg\ ref} \qquad (3)$$

$$\text{vertical wind} \quad w_{Wg} = w_{WH} \cdot \partial H + w_{Wg\ ref} \qquad (4)$$

The horizontal wind only depends on the distance to the stagnation point and the vertical wind on the height. Compared with the wind conditions in real downbursts the model is a good approach but only for the limited range of the downburst's core. For great distances to the stagnation point the computed wind from the equations (3) and (4) becomes unrealistic great. For investigations in entering or going out a downburst the model must be completed.

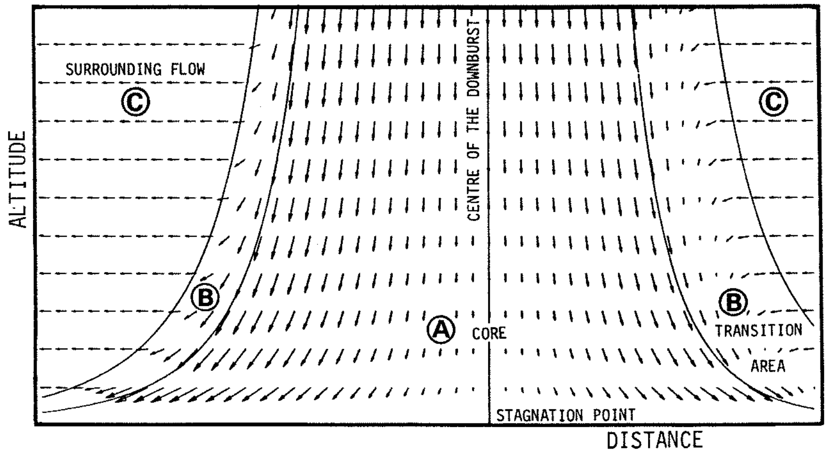

FIG. 1: COMPLETED MODEL OF A DOWNBURST

A: core of the downburst (flow towards a flat plat)

B: transition flow (a function by the order of second power)

C: surrounding flow (parallel flow)

Completed model of a downburst

On both sides the downburst's core (A) described by equations (3) and (4) 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 towards a flat plat. All three areas can be chosen unsymmetrically to the centre of the downburst. The 'surrounding flow' can be e.g. a field of vorticity or a parallel flow. In the transition area the 'surrounding flow' is joined to the core by a transition function (e.g. linear, to the power of two or exponential function). FIG. 1 shows a model-combination with a constant headwind in the surrounding area joined to the core by a function to the power of two in the 'transition area'.

III. Energy height error and hazard limit

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

$$E = \frac{1}{2} \cdot m \cdot V_K^2 + m \cdot g \cdot H \qquad (5)$$

where V_K is the flight path speed, H is the altitude, g the geographical acceleration and m the aircraft mass as shown in FIG. 2. Related to the aircraft's weight $G = m \cdot g$ we get from the equation above the actual energy height (6)

$$H_E = \frac{V_K^2}{2 \cdot g} + H \; . \qquad (6)$$

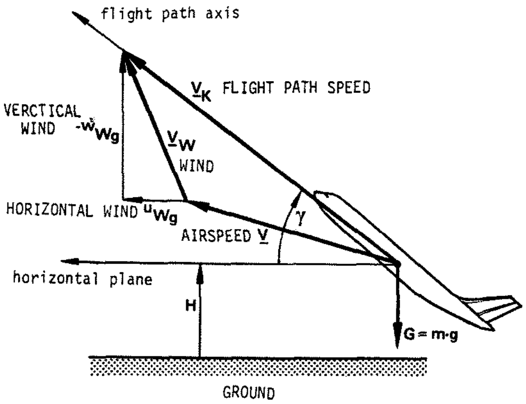

FIG. 2: VECTOR DIAGRAM OF SPEEDS IN THE AIRCRAFT SYMMETRICAL PLANE

If a specific flight path is required the nominal height H_{nom} at each distance along the flight path is known. For a constant airspeed $\underline{V}_{nom}$ the nominal flight path speed $\underline{V}_{K\,nom}$ only depends on the actual wind $\underline{V}_W$ of a given wind field (see FIG. 2)

$$\underline{V}_{K\,nom} = \underline{V}_{nom} + \underline{V}_W \; . \qquad (7)$$

The nominal energy height can be computed by

$$H_{E\,nom} = \frac{V_{k\,nom}^2}{2 \cdot g} + H_{nom} \qquad (8)$$

The energy height error now is defined as

$$\Delta H_E = H_E - H_{E\,nom} \; . \qquad (9)$$

The nominal approach situation is defined with a glide path angle of $\gamma_{nom} = -3°$ and an approach speed of: $V_{nom} = 1.3 \cdot V_S$. The hazard limit is based on the facts that the aircraft is not allowed to sink below a specific obstacle surface and the airspeed must be higher than: $V_{min} = 1.1 \cdot V_S$. 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 take-off flight path comparable to the approach path defined. So the energy height deviation referred to steady level flight will be defined as energy height error. That means for positive energy errors the aircraft is able to climb and for negative energy height errors the aircraft is not able to maintain height at a constant airspeed. As nominal height $H_{nom} = 11m$ is chosen where the computation started. The take-off 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 $H_{min} = 11m$ and $V_{min} = 1.1 \cdot V_S$.

IV. Landing

During the final approach the aircraft flies with a fixed configuration. The pilot has to maintain a constant airspeed V_{nom} and the required glide slope γ_{nom}. Applying these conditions a relation can be expanded for the calculation of the required change in thrust ΔF to compensate variable winds. The linearized non-dimensional equation to maintain constant airspeed and glide slope is (8)

$$\frac{\Delta F}{G} = \frac{\dot{u}_{Wg}}{g} + \frac{\Delta u_{Wg}}{V_{nom}} \cdot \gamma_{nom} + \frac{\Delta w_{Wg}}{V_{nom}} . \qquad (10)$$

In the above equation $\dot{u}_{Wg}$ is the horizonal wind acceleration, Δu_{Wg} is the horizontal and Δw_{Wg} is the vertical wind difference 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.

The balance of power for steady flight is

$$V_K \cdot \Delta F + G \cdot \Delta \dot{H}_E \overset{!}{=} 0. \qquad (11)$$

ΔF is a difference of thrust to compensate a difference in the specific excess power (SEP) $\Delta \dot{H}_E = \partial \Delta H_E / \partial t$ caused by the change in wind. An increase in specific excess power requires a reduction of thrust to maintain steady flight. The flight path speed along the path s is

$$V_K = \frac{\partial s}{\partial t} . \qquad (12)$$

With the equations (11) and (12) the energy height error becomes

$$\Delta H_E = -\int \frac{\Delta F}{G} \partial s. \qquad (13)$$

With equation (10) it can be assumed that the following applies:

$$\Delta H_E = -\int \left(\frac{\dot{u}_{Wg}}{g} + \frac{\Delta u_{Wg}}{V_{nom}} \cdot \gamma_{nom} + \frac{\Delta w_{Wg}}{V_{nom}} \right) \partial s . \qquad (14)$$

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

$$\Delta H_{E\dot{u}} = -\int \frac{\dot{u}_{Wg}}{g} \partial s , \qquad (15)$$

$$\Delta H_{Eu} = -\int \frac{\Delta u_{Wg}}{V_{nom}} \cdot \gamma \, \partial s , \qquad (16)$$

$$\Delta H_{Ew} = -\int \frac{\Delta w_{Wg}}{V_{nom}} \partial s . \qquad (17)$$

Landing in the core of a downburst

On June 24th, 1975 in New York a downburst accident happened during the approach of a B727 jet liner. The aircraft reached the core at an altitude of approximately H = 150m. The wind gradients in the core were found out as $u_{Wx} = 0.005 \ s^{-1}$ and $w_{WH} = 0.02 \ s^{-1}$.(4)

FIG. 3 shows an approach path in the core of a downburst with the above wind gradients. The resulting energy height errors of the three terms of equations (15), (16) and (17) are very typical for a landing in a downburst. In the beginning of the calculation the energy height errors are zero because the aircraft is trimmed as required. During the approach only the horizontal wind acceleration causes a loss of energy height $\Delta H_{E\dot{u}}$. The two terms ΔH_{Eu} and ΔH_{Ew} effect an addition of energy height. At first the influence of $\dot{u}_{Wg}$ predominates and then the other two terms depending on the wind dif-

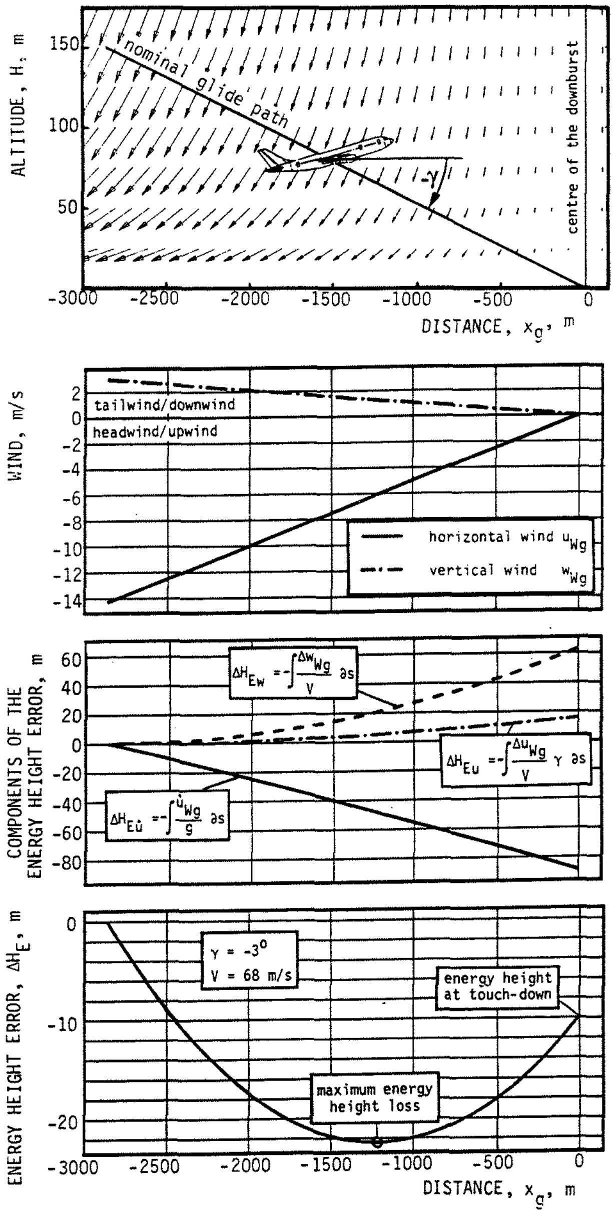

FIG. 3: LANDING IN THE CORE OF A DOWNBURST

ferences gain importance. The total amount of the energy height error is shown in the lower diagram of FIG. 3. While approaching 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 γ. With steeper slopes the maximum energy height loss decreases to zero (see FIG. 4). The energy height error at touch-down becomes less critical. Another important parameter is the position of the nominal point of touch-down in relationship to the centre of the downburst. In FIG. 5 a negative distance Δx_g means that the nominal point of touch-down is before the core's centre. The maximum energy height loss increases with the distance of the touch-down behind the centre of the downburst and so does the energy height error at touch down. The influence of the nominal approach speed shows FIG. 6. The higher the nominal approach speed the higher is the maximum energy height loss and the energy height error at touch-down.

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 ΔV. But the higher airspeed is implying a more intensive energy release while crossing the downburst's core. So the effective excess energy at touch down is less than the assumed. The same effect can be obtained for the maximum energy hight 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.

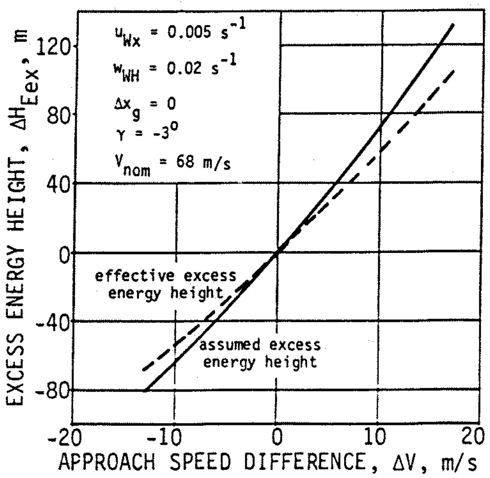

FIG. 7: EXCESS ENERGY HEIGHT AT TOUCH DOWN AS A FUNCTION OF THE APPROACH SPEED VARIATION

In summary, one can say that a landing in the core of that New York downburst from the standpoint of energy need not be fatal. Only in cores with very strong horizontal wind gradients combined with

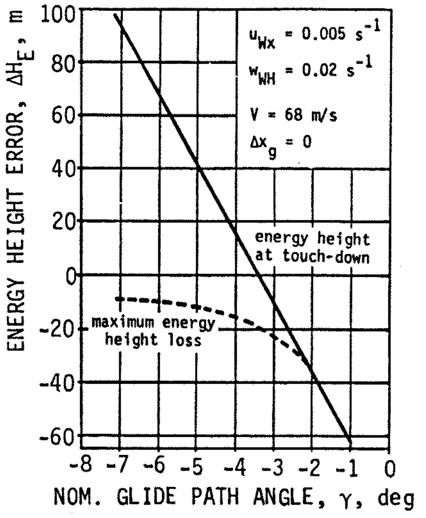

FIG. 4: ENERGY HEIGHT ERROR AS A FUNCTION OF THE GLIDE PATH INCLINATION ANGLE

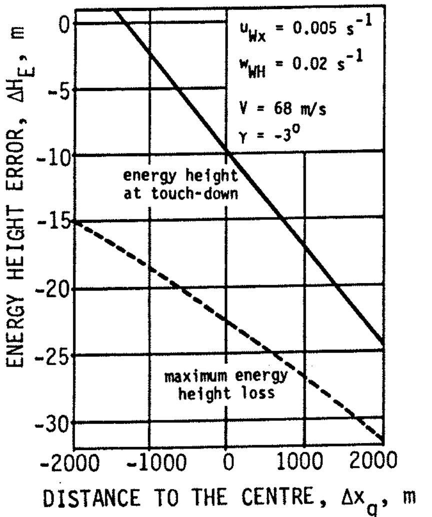

FIG. 5: ENERGY HEIGHT ERROR AS A FUNCTION OF THE DISTANCE BETWEEN THE TOUCH DOWN AND THE CENTRE OF THE DOWNBURST

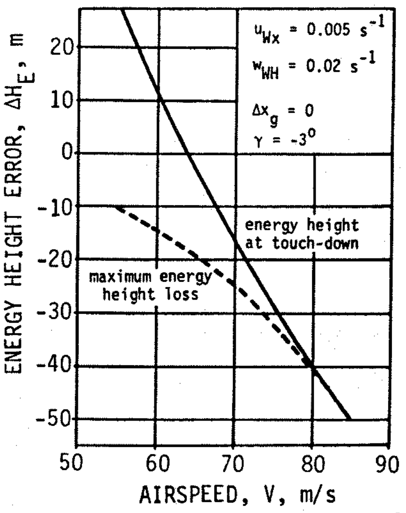

FIG. 6: ENERGY HEIGHT ERROR AS A FUNCTION OF THE NOMINAL APPROACH SPEED

small vertical wind gradients the hazard limit can be reached. But normally strong horizontal wind gradients only occur with strong vertical wind gradients.(4) So the reasons for the downburst accidents cannot exclusively be found in the wind situation in the core.

Investigations with the completed downburst model

In the above 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.

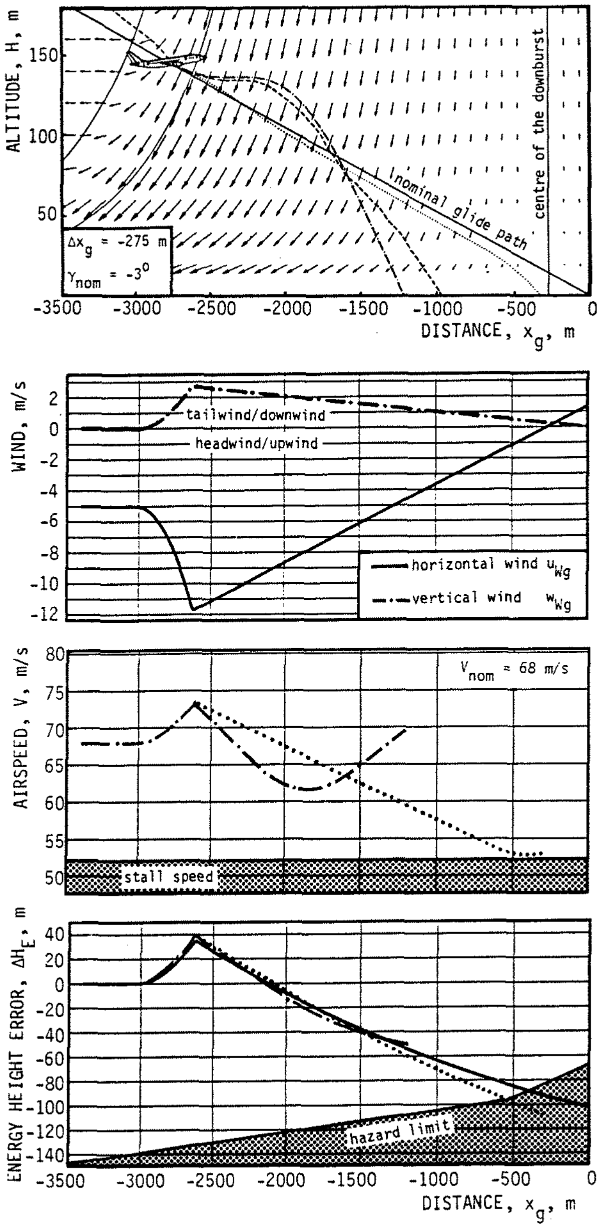

FIG. 8: LANDING IN A DOWNBURST
——— calculation by eqation (17)
—·— fixed aircraft controls
········· autopilot
----- reconstructed accident flight path

FIG. 8 shows the wind field of the expanded downburst model based on the conditions of the B727 approach accident in New York on 24th, 1975. Some flights are simulated by means of non-linear differential equations of motion of an aicraft passing this downburst. For comparison the reconstructed flight path of the New York accident (FIG. 8, broken line) is plotted.(4)

The flight path with fixed aircraft controls (indicated by a dot-dash line) is very close to that of the accident flight. So we can assume that the pilot reacts much too late and less efficient. When the aircraft encounters the downburst the head-wind 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 equation (14) demonstrates that the hazard limit would be reached some hundred meters later.

An activated autopilot (FIG. 8, dotted lines) 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. So even if the pilot is able to maintain the nominal glide path the hazard limit is reached. A comparsion of the energy height error calculated by the simple equation (14) with those of non-linear simulation along the individual flight paths with fixed aircraft controls or autopilot demonstrates only small differences. With the simple but powerful method of equation (14) it is possible to estimate the dangerousness of the landing in a downburst. A safe landing will only be possible with an additional supply of energy by thrust control.

FIG. 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 seeting DF (actual thrust related to the maximum thrust) adjusted by the autothrottle never reaches its maximum. A safe touch-down on the runway will be possible. Generally 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 required thrust setting caused by the actual wind situation.

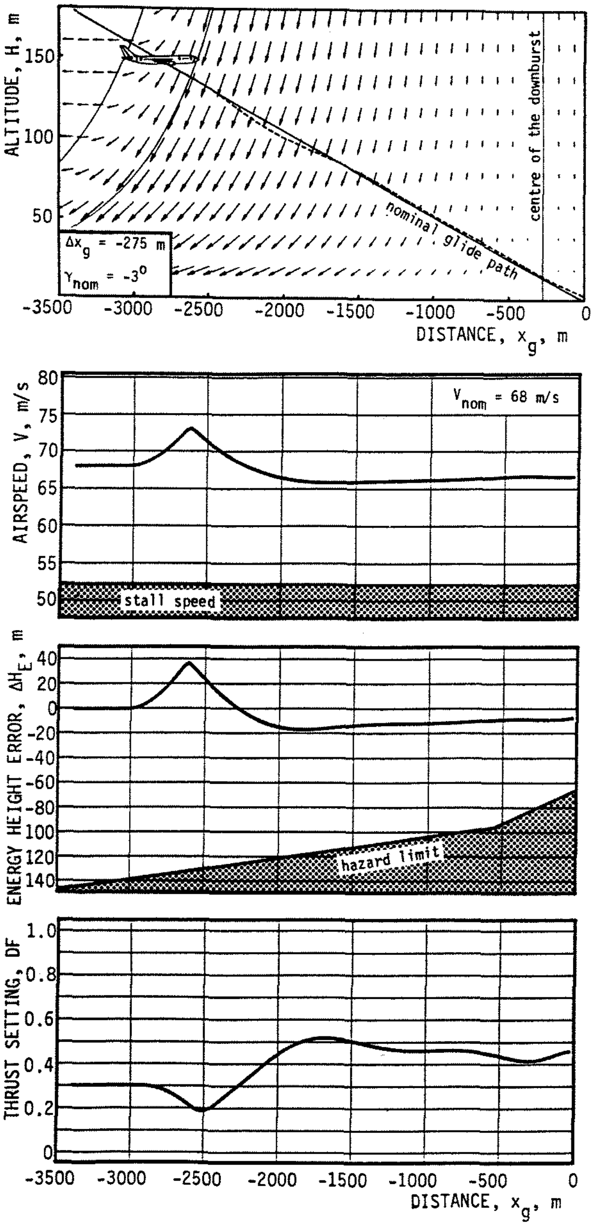

FIG. 9: LANDING IN A DOWNBURST WITH AUTOMATIC FLIGHT CONTROLS

V. Take-off

While approaching the energy height error can be compensated by thrust control. Contrary to landing during take-off the aircraft is flying at its maximum performance capability. Anyway the wind conditions in a downburst affect the take-off in a quite different way than a landing.

Compared to landing the more dangerous situation during take-off becomes clearly recognizable when the energy height error along a hypothetical constant take-off path is computed by equation (14). The gradients reconstructed for the

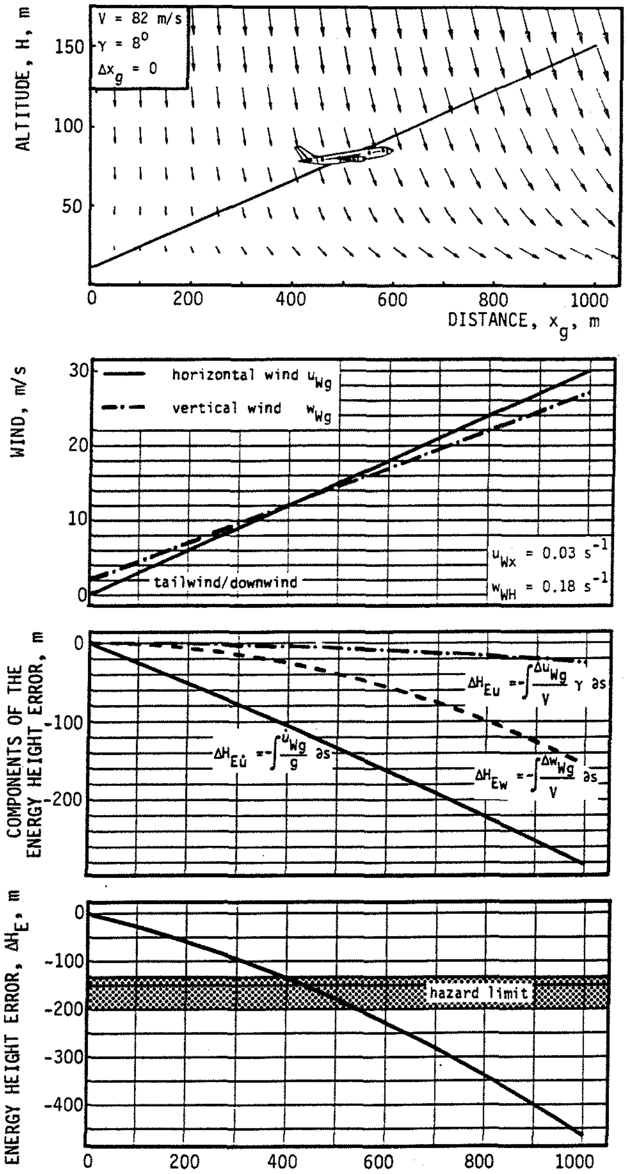

FIG. 10: TAKE-OFF IN THE CORE OF A DOWNBURST ALONG A GIVEN FLIGHT PATH

take-off accident of a B727 in Denver on August 7th, 1975 are $u_{Wx} = 0.03\ s^{-1}$ and $w_{WH} = 0.18\ s^{-1}$.(4) These gradients are chosen for the investigations. FIG. 10 illustrates the hypothetical flight path and the increasing tail- and down-wind after lift off. From the beginning on the aircraft progressively releases energy. All three parts of energy height errors as defined in the equations (15), (16) and (17) have negative values. For the landing there was only one part negative (see FIG. 3). In reality an aircraft affected by variable winds is not able to maintain a constant take-off path as plotted in FIG. 10. The flight path angle extremely depends on the actual wind situation.

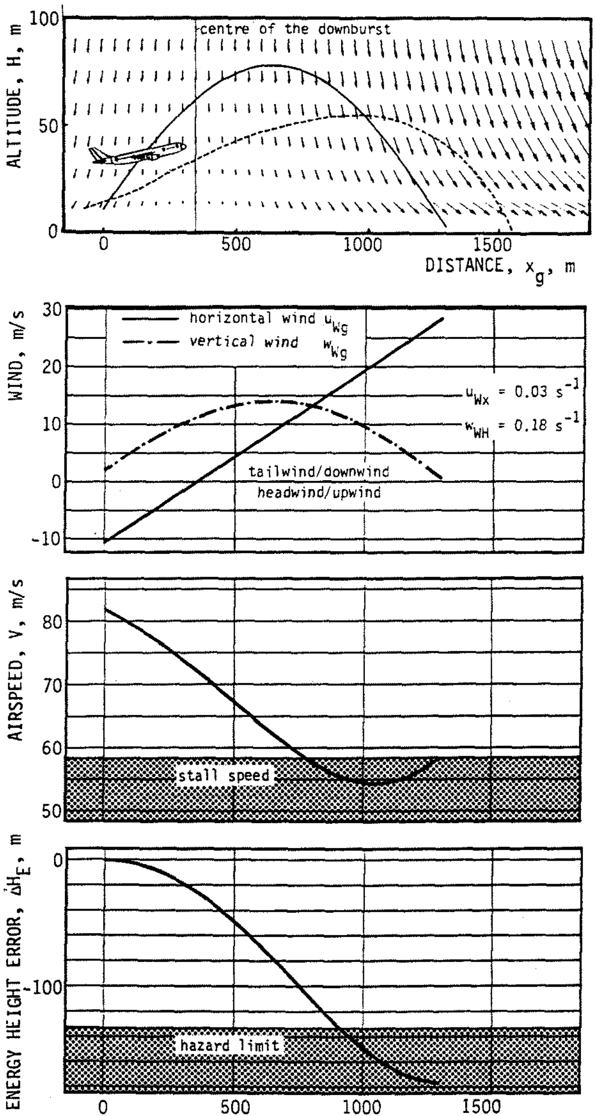

FIG. 11: TAKE-OFF IN THE CORE OF A DOWNBURST
—— fixed aircraft controls
– – – reconstructed accident flight path

FIG. 11 shows a numerical aircraft simulation with controls fixed. The simulation starts at a distance of $\Delta x_g = -350$m before the centre of the downburst comparable to the Denver accident. Although all engines are running, the aircraft is not able to climb out. The energy height loss increases from the beginning and the aircraft is

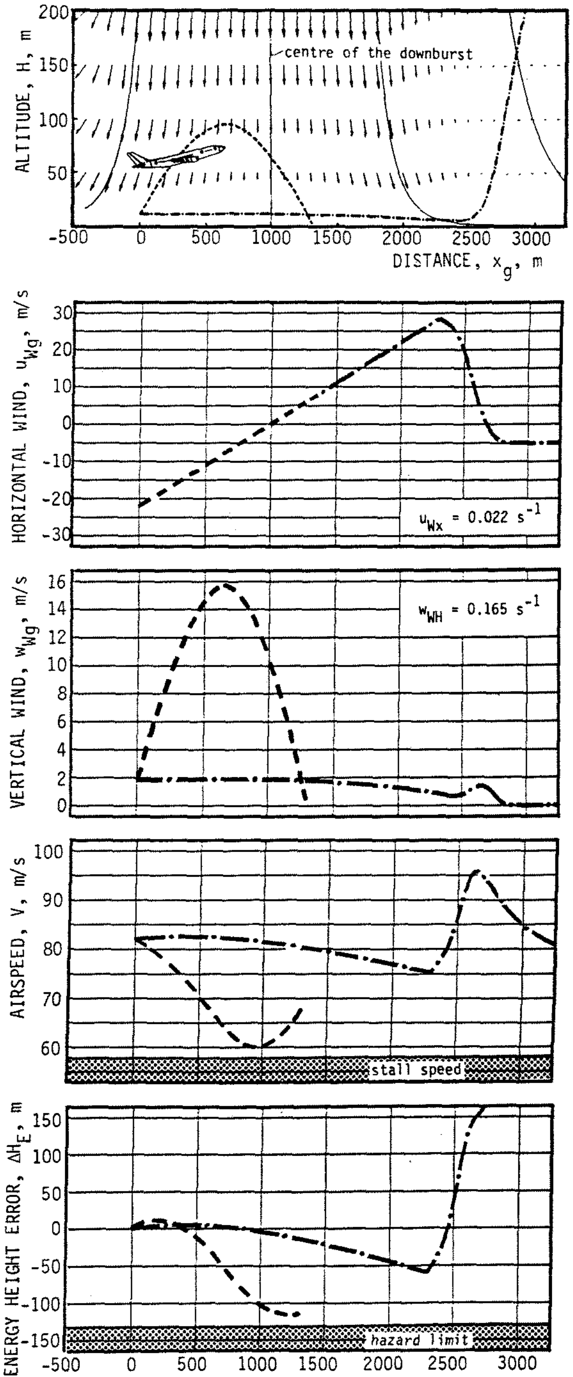

FIG. 12: ESCAPE MANOEUVRE IN A DOWNBURST
– – – fixed aircraft controls
–·–– level flight through the core

permanent losing airspeed. The stall speed is reached short before crossing the hazard limit defined in chapter III. The reconstructed flight path of the Denver accident is similar to the flight path with fixed aircraft controls. So it can be assumed again that the pilot's inputs are not very efficient. But looking at the energy height error this accident must be classified as inevitable.

Downbursts with wind gradients less than those of the above Denver accident can be crossed by a simple escape manoeuvre: A considerable energy release is the result of the vertical wind increasing with height (see 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 which were found in the downburst accident in Philadelphia on June 23rd, 1976 are $u_{Wx} = 0.022\ s^{-1}$ and $w_{WH} = 0.165\ s^{-1}$. FIG. 12 shows a flight path of the above described escape manoeuvre of level flight (dot-dash line) starting at a distance of $\Delta x_g = -1000m$ before the centre of the downburst. During the flight through the core the airspeed is far away from the stall speed and the energy height error is uncritical. After leaving the core a save take-off climb is possible. With regard to that manoeuvre it can be said that even in such bad conditions a take-off 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 behaviour in downbursts comes close to simulations with fixed aircraft controls. Such a simulation carried out in the Philadelphia downburst is illustrated by the broken lines in FIG. 12. Airspeed and energy height error are rapidly decreasing and the hazard limit is nearly reached when the aircraft has a ground impact.

A practicable escape manoeuvre is the level flight at a low height to pass the core of the downburst before starting the climb. But it must be realized that wind conditions can occur in a downburst, so that a take-off is impossible.

VI. Aspects for the go-around

In principle the go-around can be assumed as a combination of approach and take-off climb. By taking the above discussed results into consideration the following conclusions can be drawn: Regarding the energy height 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 whether landing in a downburst or better going around is hardly to take by the information the pilot gets from his instruments. But if

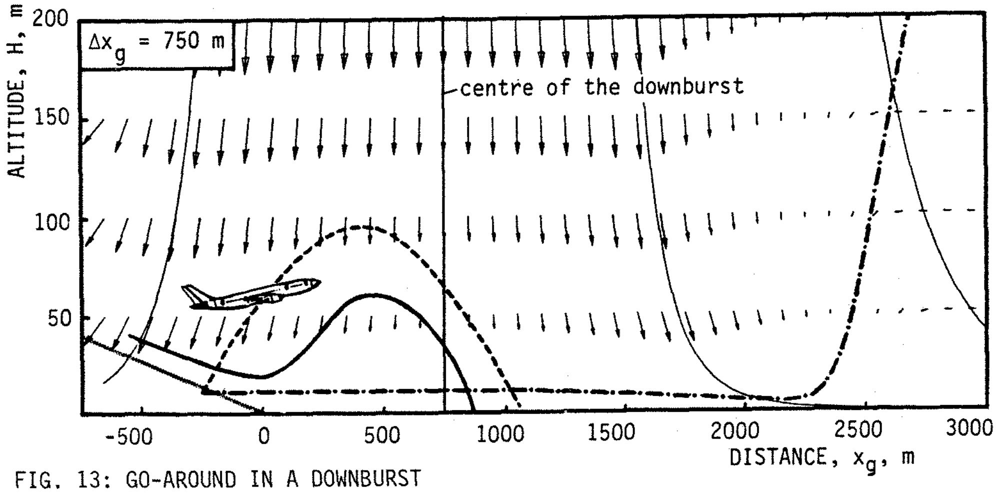

FIG. 13: GO-AROUND IN A DOWNBURST

— — — fixed aircraft controls
—·— level flight through the core
——— reconstructed accident flight path

the wind conditions admit a go-around, the above described level flight procedure is to prefer for crossing the core. FIG. 13 shows the reconstructed flight path of the go-around accident in Philadelphia on June 23rd, 1976. The centre of the downburst was localized 750m behind the nominal point of touch-down. The take-off 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 aicraft has a ground impact at a distance of about 1000m behind the nominal point of touch-down. Carrying out the discussed escape manoeuvre the downburst can be crossed.

VII. Summary and conclusions

The reasons for the approach accidents cannot exclusively be found 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 be done before it reaches the downburst. Computer simulations with fixed aircraft controls show similar flight path patterns like those of real aircraft accidents. So it can be assumed that the pilot's inputs are not efficient. But even if the pilot is able to maintain the nominal glide path a safe landing is only possible with the supply of enery by thrust control. A safe touch-down is possible by the help of conventional modern automatic flight control systems (autopilot and autothrottle). So it can be concluded that the pilot needs better information about the aircraft's situation during passing a downburst.

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

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