Analysis of Aircraft Performance During Lateral Maneuvering for Microburst Avoidance

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Much of the prior research on aircraft escape procedures during microburst encounters has assumed that the aircraft penetrates the center of the microburst in straight flight. The microburst core is the region where the strongest head-to-tail wind and downburst are present. Aircraft response to a severe and a moderate three-dimensional microburst model using nonlinear numerical simulations of a Boeing 737-100 was studied and the relative performance loss was compared for microburst escape procedures with and without lateral maneuvering. The results showed that the hazards caused by the penetration of a microburst in the landing phase were attenuated if lateral escape maneuvers were applied in order to turn the aircraft away from the microburst core rather than flying straight through. If, however, the lateral escape maneuver was initiated close to the microburst core, high bank angles tended to deteriorate aircraft performance. Therefore, lateral maneuvering should be employed if the position of the microburst is known; however, only low bank angles should be applied once the core has been penetrated. Lateral maneuvering was also found to reduce the advanced warning required to escape from microburst hazards, but required that information of the existence and location of the microburst be available (i.e., remote detection) in order to avoid an incorrect turn toward the microburst core.

Introduction

LOW-ALTITUDE wind shear presents a significant hazard to aircraft during landing and takeoff operations. Severe microbursts, storm downdrafts, which are small in horizontal cross sections and highly transient, present the greatest danger to aircraft, ranging from small general aviation aircraft to jet transports. The risks posed by all forms of wind shear can be reduced if information is available to warn the pilot about the presence of low-level wind shear and if the pilot has the best available information on escape techniques. Most of the prior research on aircraft flight dynamics and microburst escape procedures has focused on longitudinal dynamics. This is equivalent to the aircraft penetrating the center of the microburst where only the effect of the horizontal head-to-tail wind components and the vertical downburst are considered. Currently, the FAA Windshear Training Aid[1] recommends microburst escape procedures that are limited to maneuvers in the longitudinal plane. With the advent of systems that can remotely detect microburst, such as Doppler weather radar, the possibility of lateral maneuvering for microburst avoidance should be considered.

Based on the assumption that information about the existence and location of a microburst is available, studies were conducted to evaluate the relative performance loss and recovery capability for microburst escape procedures with and without lateral maneuvering. Severe and moderate microburst cases were considered. From the simulation results, recommendations were made for improving microburst recovery capability.

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Method of Approach

Equations of Motion

The set of nonlinear equations of motion describing the aircraft dynamics in the three-dimensional space is derived from Ávila de Melo[2] in the inertial velocity axes following Psiaki and Stengel's[3] procedure and using the notation of Etkin.[4]

Aircraft Data

The simulations used a simplified nonlinear aerodynamic model of the Boeing 737-100 (NASA Langley ATOPS research aircraft).[5] The power plant dynamics were approximated as a first-order model with a time response of 2 s up to the maximum thrust of 13,000 lb.

$$\dot{T} = (\delta T - T)/T_R, \qquad T_R = 2\ \text{s}$$

In the initial condition, the aircraft was assumed to be at a constant airspeed of 130 knots, on a 3-deg glide slope, with angle of attack of 1.3 deg and weight of 80,000 lb. Landing gear and flaps are in the landing configuration. The trim positions of the control devices were the following:

δ_e = 2.9 deg—elevator deflection
δ_s = −5 deg—spoiler deflection
δ_a = 0 deg—aileron deflection
δ_r = 0 deg—rudder deflection
T = 8081 lb—total thrust

Microburst Model

The microburst model used for this study is similar to the three-dimensional microburst model by Oseguera and Bowles.[6] However, for simplicity, the model was made invariant with altitude. The maximum intensity horizontal and vertical velocity profiles were used to represent a worst case. It should be noted that this somewhat exaggerates the hazard, since the maximum horizontal and vertical intensity do not normally occur at the same altitude. Details on the analytic microburst equations are given in Ávila de Melo.[2]

Two different microburst magnitudes were modeled by specifying the radius of peak outflow and the maximum wind velocity. The radius of the downdraft is assumed in the Oseguera and Bowles model[6] to be approximately 89% of the radius of peak outflow. In this work, the microburst core is considered to be the region from the peak head wind to the peak tail wind, i.e., within the peak outflow velocity contour.

1) Severe microburst: The severe case was based on the Andrews Air Force Base event (Camp Spring, Maryland on August 1, 1983),[7] with a wind shear intensity of approximately 120 knots in 4000 ft. The maximum horizontal velocity was assumed to be 60 knots and the maximum vertical velocity was 45 knots (see Figs. 1).

2) Moderate microburst: The moderate case was based on the microburst encountered by Delta Airlines Flight 191 (Dallas/Fort Worth Airport on August 2, 1985)[7] with a wind shear intensity of approximately 60 knots in 4200 ft. The maximum horizontal velocity was 30 knots and the maximum vertical velocity was 22 knots.

Simulation Description

Control Laws and Guidance Schemes

Linear automatic control laws as described by McRuer et al.[8] were used to simulate pilot control actions or to stabilize the nonlinear aircraft model. For the pitch attitude control, integral pitch angle feedback was used to control elevator deflection with an integrator. The roll attitude control was accomplished by feeding back roll attitude and roll rate to control aileron deflection.

The reference longitudinal-only escape maneuver was based on the FAA Windshear Training Aid.[1] It consisted of the following:

1) Rotating the aircraft to 15 deg of pitch angle.
2) Applying maximum thrust.

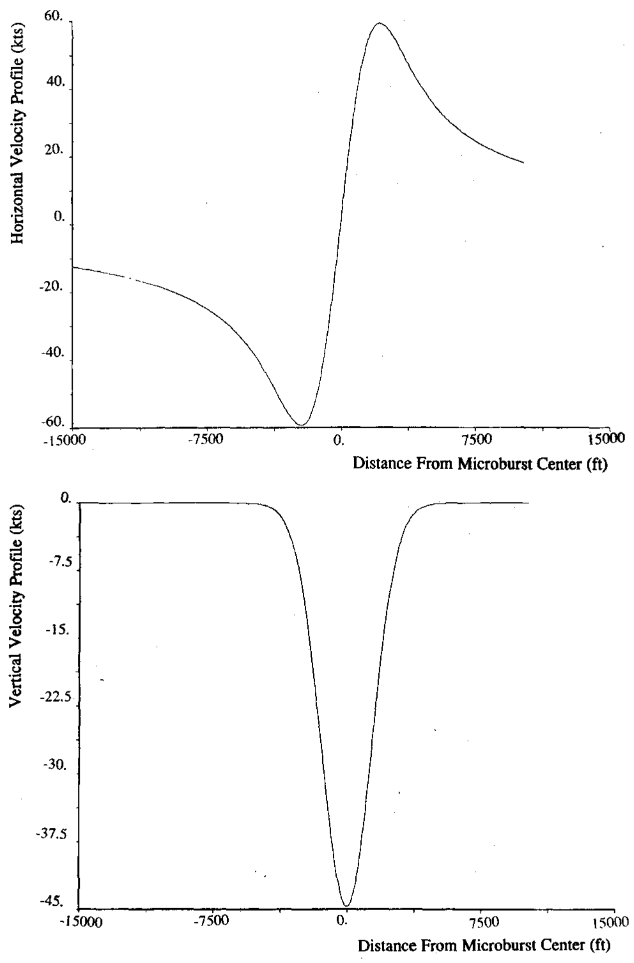

Fig. 1 Horizontal and vertical velocity profiles for the severe microburst case.

3) Maintaining landing gear and flap configuration.
4) Respecting stick shaker (i.e., not allowing angles of attack greater than the stall angle).

In the longitudinal-only escape maneuver, a maximum thrust equal to 13,000 lb per engine was applied, the stabilizer was deflected to −3.6 deg, and the elevator was controlled to maintain either a pitch angle of 15 deg or the incipient stick shaker. In the cases where the aircraft flew off the microburst axis of symmetry, automatic lateral control was required in order to keep the aircraft flying straight and to avoid the aircraft rolling toward the microburst due to the strong crosswind component.

In the lateral escape maneuver, in addition to the longitudinal procedure described above, a step command in aileron was initially applied within an approximate roll rate of 5 deg/s. When the desired bank angle was reached, the automatic lateral control was used in order to maintain the desired bank angle. When the aircraft had turned 90 deg in heading, opposite aileron was applied so that the bank angle reduced to zero. Sufficient rudder was applied to keep sideslip angle close to zero in the case where there was no microburst (i.e., normal coordinated turn).

Nonlinear Model Description

Nonlinearities such as aerodynamic stall characteristics play important roles in limiting microburst penetration capabilities. Therefore, the simulation of the aircraft nonlinear equations of motion and aerodynamic data was essential. Also, deviations from steady motion were not small and the longitudinal and lateral motions were coupled. It was therefore necessary to use the complete set of nonlinear equations of motion in the simulation.

A program containing the aircraft nonlinear equations of motion, the microburst analytic equations, and the aircraft aerodynamic data was used to simulate the aircraft flight through the three-dimensional microburst. In the program, the nonlinear differential equations were solved by a hamming-predictor corrector integration routine.[9] The control laws and guidance schemes were incorporated in the program in order to simulate the escape maneuver actions a pilot would take and to stabilize the aircraft or keep it flying at the desired attitude. The output of the program was in the form of plots of the state variables.

Flight Through the Microburst Axis of Symmetry

In each set of simulations, the performance of the aircraft employing lateral maneuvering to avoid the microburst was compared with the performance of the aircraft flying straight through the microburst and applying only the FAA Windshear Training Aid[1] recommended escape maneuver. Four bank angles were used in the lateral maneuvering cases: 5 deg, 10 deg, 15 deg, and 20 deg. The aircraft was initially flying in a trajectory along the microburst axis of symmetry that penetrated the microburst core (see Fig. 2). The escape procedure was initiated at various distances away from the microburst core.

Severe Microburst Case

In the severe microburst case, five sets of simulations were run. In the first set, the escape maneuver was initiated at the distance of 10,000 ft from the microburst center. This was the point where, due to the outflow, an increase in airspeed of approximately 15 knots was detected. This is one of the recommended microburst recognition criteria suggested by the FAA Windshear Training Aid.[1] In the last set, the escape procedure initiated at the microburst center where the aircraft experienced the greatest loss of altitude and change in vertical speed. In between these two extreme cases, three other intermediate points of escape maneuver initiation were considered. The point at 2000 ft from microburst center was approximately the point of peak outflow velocity and peak airspeed increase. The points at 6000 ft and at 4000 ft from

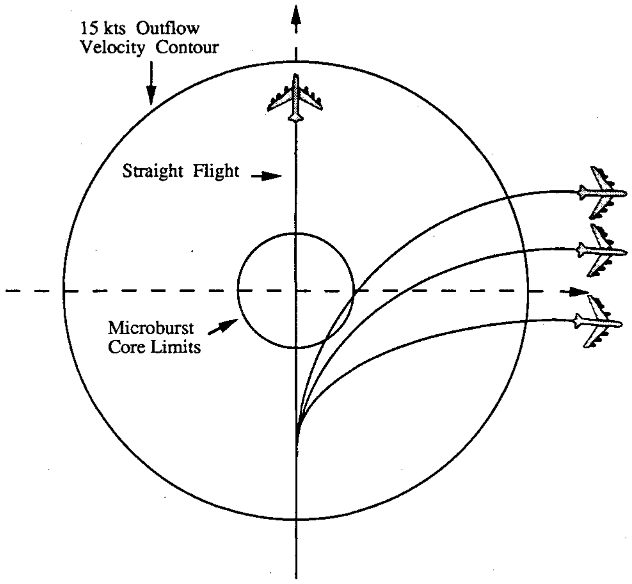

Fig. 2 Flight through the microburst axis of symmetry.

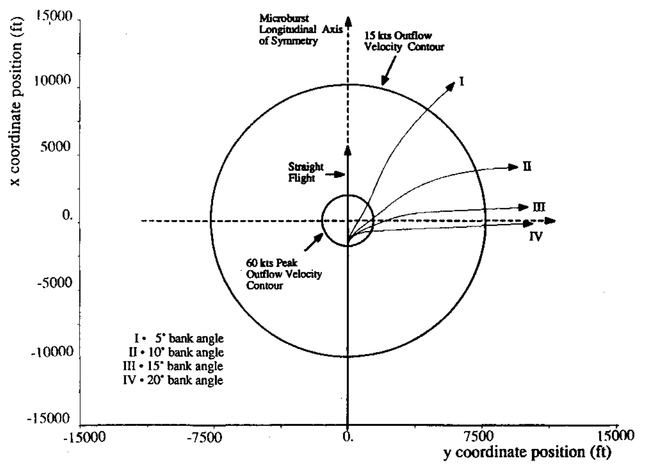

Fig. 3 Aircraft trajectory for escape maneuver initiated at peak outflow velocity of severe microburst.

microburst center were studied in order to check the effects of initiating the escape maneuver while the aircraft was transiting the region of increasing head wind and before it got into the microburst core.

An example is shown in Figs. 3 and 4 that plots the aircraft horizontal trajectory and altitude vs time, respectively, with and without lateral maneuvering for the case where the escape procedure was initiated at the point of peak outflow velocity. This point was approximately 2000 ft from the microburst center. In all escape maneuvers, the aircraft fell below the 3-deg glide slope line and was in stick shaker condition from the point of escape initiation. In the 20-deg bank angle maneuver, the aircraft loss of altitude was greater than the straight flight. The major reason for that was the very intense tail wind (Fig. 5) combined with the loss of lift due to steep bank angle. There was not a significant improvement in performance for the 5 deg of bank case, since the aircraft trajectory continues to cross most of the region of high head-to-tail wind shear and intense downburst. Some improvement in performance occurred with 10 deg of bank angle, and the best recovery capability was achieved by banking the aircraft to 15 deg. The tendency of the aircraft to weather cock toward the microburst center for low bank angles can be seen in the trajectory plot of Fig. 3. Recovery is defined as the point where the aircraft assumes a steady-state positive climb rate.

Figures 6 show a comparison of the aircraft altitude vs time plots when the escape maneuvers were initiated at 6000 ft, 4000 ft, 2000 ft (peak outflow velocity) from the microburst center and at the microburst center. For escape procedure initiated before the peak outflow velocity point, lateral maneuvering presents better recovery capability than the straight flight. Lateral maneuvers take the aircraft away from the microburst core where the strongest head-to-tail wind and downburst are present.

Figures 6 and 7 show that the aircraft performance varies with the bank angle, but, for the cases where escape maneuver was initiated before and at the peak outflow velocity point, banking the aircraft to 10 deg showed enough capability to fly away from the microburst core and significant performance improvement when compared with the straight flight. Banking the aircraft to smaller angles did not show a significant improvement in recovery capability, larger bank angles tend to deteriorate aircraft performance. The deeper the aircraft is in the microburst core, the greater is the performance degradation due to performance loss at steep bank angles.

Moderate Microburst Case

In the moderate microburst, five sets of simulations were run. In the first set, the escape maneuver was initiated at the distance of 6000 ft from the microburst center, where an increase in airspeed of approximately 15 knots was detected.

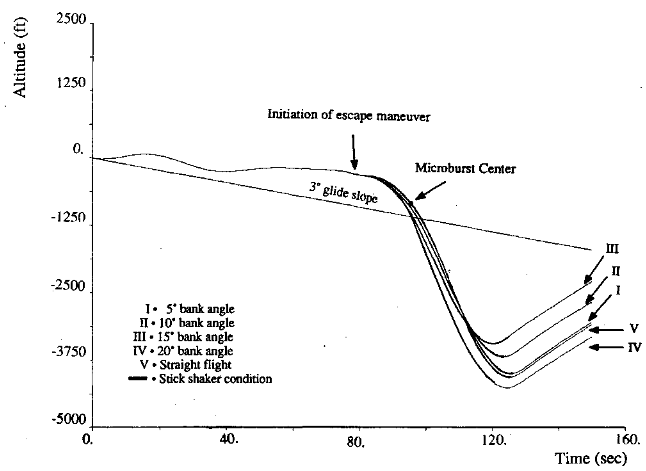

Fig. 4 Aircraft altitude for escape maneuver initiated at peak outflow velocity of severe microburst.

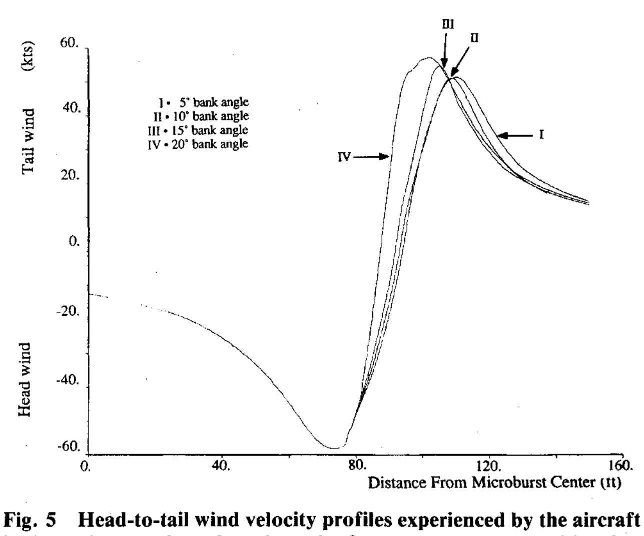

Fig. 5 Head-to-tail wind velocity profiles experienced by the aircraft in the various bank angle trajectories for escape maneuver initiated at peak outflow velocity of severe microburst.

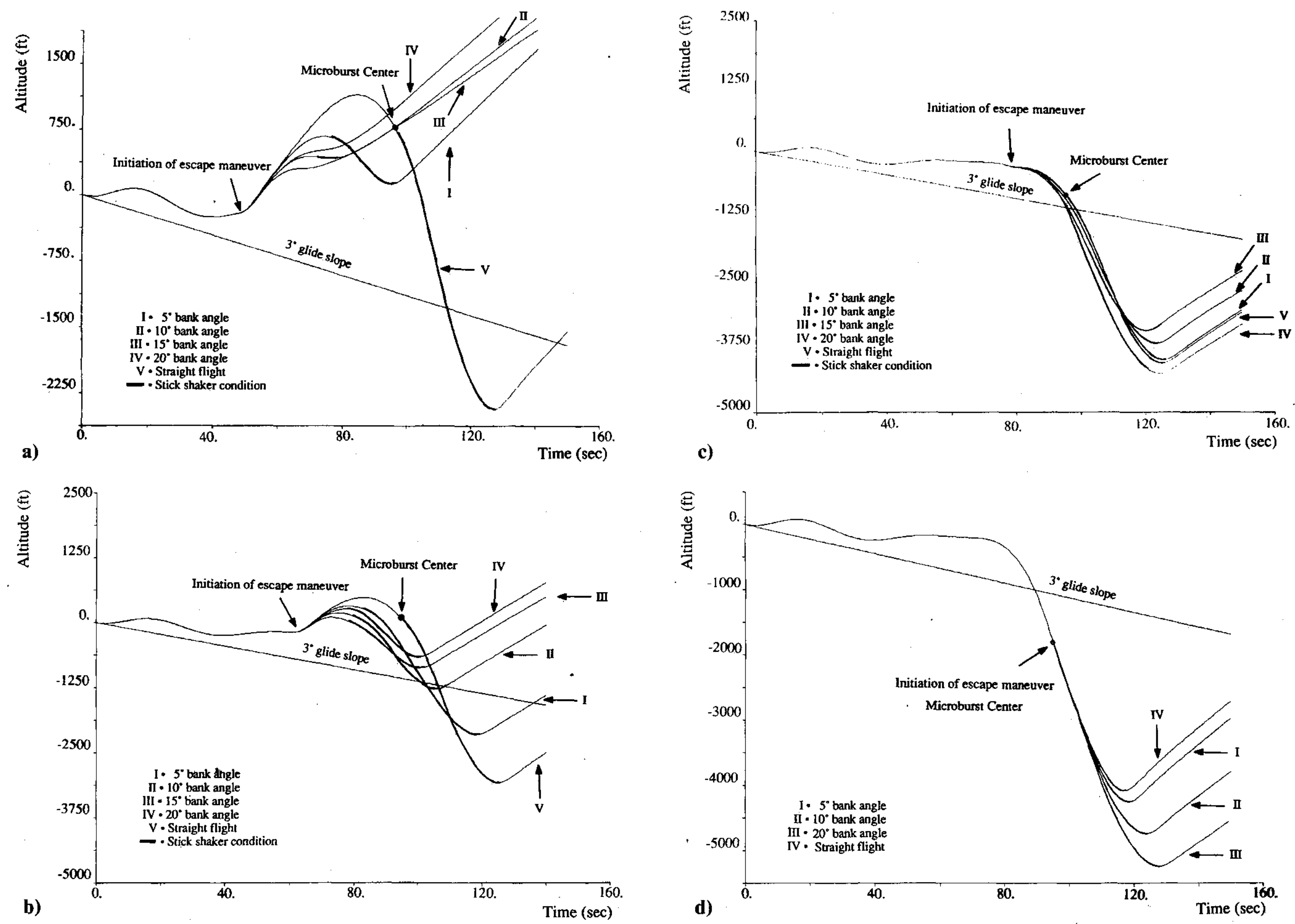

Fig. 6 Comparison of the aircraft altitude vs time plots when escape maneuver is initiated at a) 6000 ft, b) 4000 ft, c) 2000 ft (peak outflow velocity) from microburst center, and d) at microburst center.

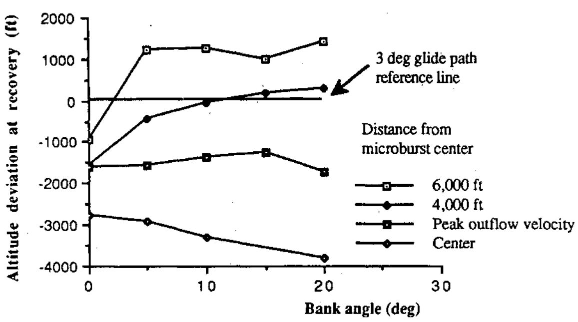

Fig. 7 Aircraft altitude deviation from the 3-deg glide slope path at the point of recovery (severe microburst case). Positive values mean aircraft is above 3-deg glide slope line, negative value means below.

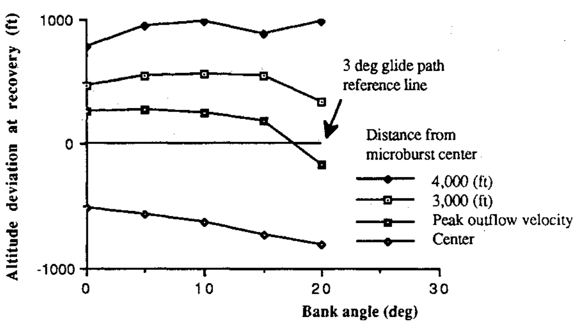

Fig. 8 Aircraft altitude deviation from the 3-deg glide slope path at the point of recovery (moderate microburst case). Positive values mean aircraft is above 3-deg glide slope line, negative value means below.

This is one of the recommended recognition criteria suggested by the FAA Windshear Training Aid.[1] In the last set, the escape procedure was initiated at the microburst center, the point where the aircraft experienced the greatest altitude loss and change in vertical speed. In between these two extreme conditions, three other intermediate points of escape maneuver initiation were considered. The point at 2360 ft from the microburst center was approximately the point of peak outflow velocity and peak airspeed increase. The points at 4000 ft and 3000 ft from microburst center were studied in order to check the effects of initiating the escape maneuver while the aircraft was transiting the region of increasing head wind and before it got into the microburst core. Since it is a moderate microburst, the effects of the wind components in the aircraft performance were not as strong as in the severe case discussed previously.

Figure 8 shows the behavior in the moderate case similar to that observed for the severe case with significantly less performance loss.

Analysis and General Results

For the cases studied, a bank angle of 10 deg appeared to provide the best average performance. Banking too steeply causes performance loss, particularly if the aircraft is deep in microburst core. The deeper the aircraft is in the microburst, the less it should be banked, and, if it has penetrated the core, no lateral maneuver should be applied.

Lateral maneuvering reduced the advanced warning required to escape from the microburst. An example is shown in Fig. 9 for the severe microburst. The straight flight escape maneuver must be initiated at 10,000 ft from the severe microburst center to provide approximately the same recovery capability as 10-deg bank lateral maneuver initiated at 4000 ft from the severe microburst center. This 6000 ft difference represents 38 s less required warning time in the simulation.

Flight Off the Microburst Axis of Symmetry

Simulations were run in order to evaluate the hazards associated with an incorrect lateral maneuver that would take the aircraft toward the microburst core, as shown in Fig. 10. In each set of simulations, the aircraft was assumed to initially penetrate the microburst on a trajectory offset from the microburst core. Three situations were considered: 1) the aircraft turned toward the microburst core; 2) the aircraft turned away from the microburst core; and 3) the aircraft flew straight ahead in an offset trajectory parallel to the microburst axis of symmetry.

The simulations were run considering only the points of escape maneuver initiation and the bank angle values that in the case of a turn towards the microburst core would take the aircraft in a trajectory crossing the microburst core. This was an approximation of the worst case.

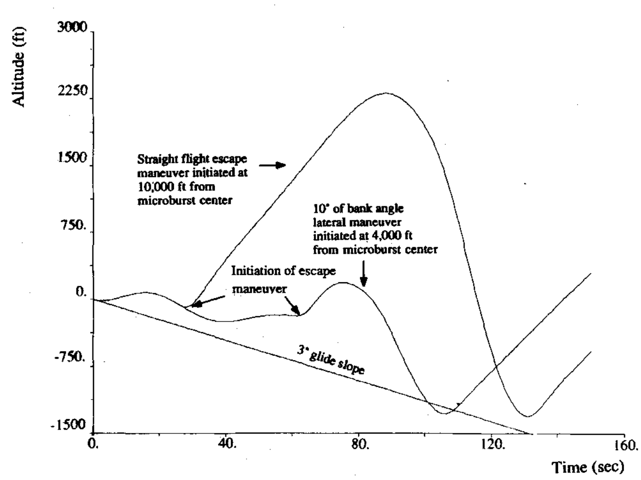

Fig. 9 Comparison of aircraft altitude for straight flight escape maneuver initiated at 10,000 ft from severe microburst center and for 10 deg of bank angle when the lateral maneuver was initiated at 4000 ft from the severe microburst core.

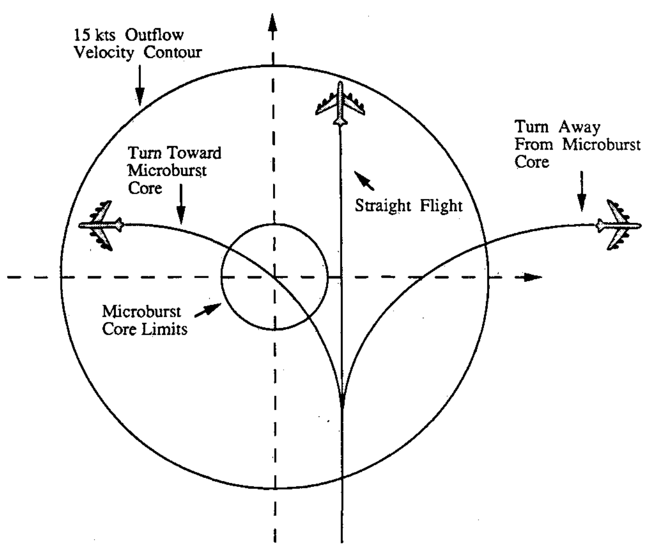

Fig. 10 Flight off microburst axis of symmetry.

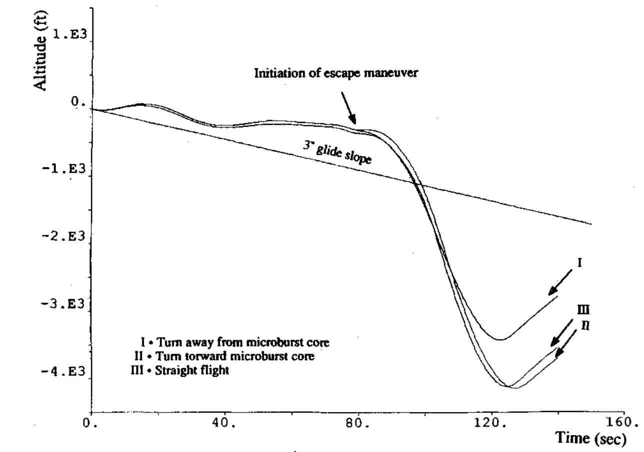

Fig. 11 Comparison of the aircraft altitude when the aircraft turns away or towards the severe microburst center and when it flies straight through the microburst lateral displacement of 430 ft.

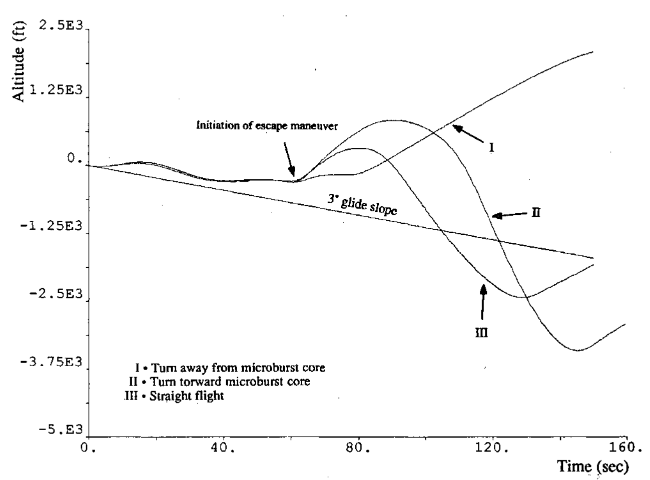

Fig. 12 Comparison of the aircraft altitude when the aircraft turns away or towards the severe microburst center, and when it flies straight through the microburst lateral displacement of 3000 ft.

During the simulations, it was observed that direct axisymmetric penetrations of the microburst core have been found to be less hazardous than those slightly offset from the core. The difference in performance was not significant and was thought to be a result of crosswind component effects. Also, it was necessary to use automatic control to maintain the roll angle close to zero and to compensate for the rolling effects of the wind, which were quite strong in the severe microburst case. No calculations were done in order to evaluate stick forces, which, with lateral maneuvering, may be very high in order to counteract natural airplane pitching tendencies resulting from the crosswind as well as airspeed and lift losses.

Severe Microburst Case

Two sets of simulation were run. In the first set, the escape maneuver was initiated at a lateral position of 430 ft from the microburst axis of symmetry and at 2000 ft from microburst center. In the second set, the escape maneuver was initiated at a lateral position of 3000 ft from the microburst axis of symmetry and at 4000 ft from microburst center.

Flight at a Lateral Displacement of 430 Feet

Figure 11 shows a comparison of the aircraft altitude when, in a 10-deg bank angle, the aircraft turned away or toward the microburst center. In the case of the incorrect lateral maneuver, the aircraft trajectory took it into the microburst core. Consequently, the aircraft was taken to an altitude 40 ft lower than the straight flight trajectory and 750 ft lower than the turn away from the microburst core trajectory. There is a significant advantage in turning away from microburst core, and relatively minor loss in performance due to the turn toward the core.

In this severe microburst case, the weather cocking effect was very strong, due to the high intensity of the crosswind velocity at this lateral position. For this reason, it was impossible to simulate the aircraft flying in a straight line through the microburst. Very high automatic control gains were necessary in order to avoid the aircraft's tendency to turn into the microburst center. The very high gains increased the computational time significantly. Therefore, the highest gain value that did not sacrifice too much computational time was used to keep the aircraft flying as close as possible to straight flight. In a real situation, the high required gains would represent a significant increase in the pilot's workload in order to make the course corrections required to keep the aircraft aligned with the runway centerline.

Flight at a Lateral Displacement of 3000 Feet

Figure 12 shows a comparison of the aircraft altitude when, in a 15 deg of bank turn, the aircraft turned away or toward the microburst center. For this large initial displacement, the recovery capability in straight flight was about 900 ft larger than in the case of an incorrect lateral maneuver towards the microburst core. However, it should be noted that this represented the worst case of incorrect lateral maneuver.

In this severe microburst, the weather cocking effect of the crosswind was still strong even at this larger lateral distance. However, the very high control gains were not necessary to avoid the aircraft's tendency to turn into the microburst center.

Analysis and General Results

The moderate microburst case showed similar results, except that the difference in performance loss between the turn toward the microburst center and the straight flight was more attenuated.

The recovery capability when the aircraft turned away from the microburst core was, in all cases, greater than when the aircraft flew straight or turned toward the microburst core. As expected, turning toward the microburst core represented a decrease in performance, since, besides experiencing the strongest wind shear and downdraft, the aircraft suffered performance deterioration due to the bank angle. It shows that these incorrect trajectories were selected to penetrate the core and, therefore, reported the worst case of incorrect lateral maneuvering. Also, if the escape maneuver was initiated at larger lateral distances from the microburst center than the ones evaluated in these simulations, the risk associated with an incorrect turn toward the microburst core appeared to be relatively minor, since the aircraft would have already gained sufficient altitude before penetrating the microburst core.

Conclusions

In summary, the simulations found:

1) Significant improvement in the escape capability was obtained with moderate lateral maneuvering. For the aircraft studied in this work, the optimal bank angle for the cases studied appeared to be 10 deg. Banking the aircraft to smaller angles did not show a significant improvement in recovery capability; larger bank angles tend to deteriorate aircraft performance.

2) The deeper the aircraft penetrated the microburst core, the less bank should be applied. Significant performance improvement was obtained in comparison with the straight flight if lateral escape maneuver was initiated before or at the point of peak outflow velocity, but there was no advantage in lateral maneuvering if the aircraft had already penetrated the microburst core.

3) Lateral maneuvering reduced the advanced warning required to escape from microburst hazards. For example, in the simulation of a severe microburst encounter, a 10-deg lateral escape maneuver could be executed up to 38 s later than the longitudinal-only maneuver with similar recovery performance.

4) Although the difference was not significant, direct axisymmetric penetrations of the microburst core have been found to be less hazardous than those which were slightly offset from the core.

5) For trajectories offset from the microburst axis of symmetry, simulation of incorrect lateral maneuver (i.e., turning towards the microburst core) resulted in increased performance loss, and turning away from the microburst core always resulted in the greatest performance increase.

In conclusion, the hazards caused by the penetration of a microburst during the landing phase can be attenuated if lateral escape maneuvers are applied in order to turn the aircraft away from the microburst core rather than flying straight through. However, airplane performance degradation during turning flight can reduce the success of surviving the microburst encounter if the turn is too steeply banked or delayed till the aircraft has actually penetrated the microburst core. The availability of precise information about the existence and location of the microburst core through remote detection or other means is a prerequisite to the use of lateral maneuvering for microburst avoidance. However, lateral maneuvering reduces the advance warning required. It should be noted that this study did not address the operational factors which would be required to implement lateral avoidance strategies. Factors such as air traffic control coordination, terrain avoidance, and traffic conflicts during multiple runway operations must be considered before recommendations for lateral maneuvering strategies are given to flight crews.

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