Control of an Aircraft in Downbursts

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Guidance schemes are designed to approximate the optimal survival and optimal performance paths through downbursts, which were determined in the previous paper. Specifically, climb-rate command following is used to achieve performance, and altitude command following is used to enhance survivability. Nonlinear simulations are conducted to investigate the effects of the climb-rate command and altitude command. Takeoff flight is considered and full thrust is assumed. In a mild to moderate downburst, an aircraft can follow a constant, smaller-than-nominal climb rate without stall. Better survival capability is achieved by climbing at a lower rate accompanied by lower altitude, and vice versa. In a severe downburst, the aircraft must descend to avoid stall. The farther it descends, the higher the survival capability, but the poorer the performance. If the downburst is very severe, the best strategy is to descend immediately to the lowest safe altitude. Since the intensity of a downburst is hard to evaluate prior to penetration, it is advisable to keep a high airspeed. Therefore, use of the survival strategy is recommended that employs maximum thrust and allows the aircraft to descend to a safe minimum altitude immediately upon entering a downburst on takeoff.

Introduction

DOWNBURST phenomena, though rare, produce the most threatening types of windshears and downdrafts when they do occur, thus presenting serious hazards to the safe operation of commercial aircraft. Studies have been made in the past in the areas of meteorological studies, modeling of downbursts, detection techniques, and the determination of flying strategies.[1,2] See the sources cited in Ref. 3.

Miele et al.[4,5] designed various guidance laws for aircraft through windshears on takeoff. Feedback guidance laws were designed using local wind information and aircraft states. Aircraft following these laws will climb or descend according to different wind intensities of the proposed downburst structure. Psiaki and Stengel[6] analyzed control strategies for downburst encounter. Tight control of air-relative energy, pitch-up response to decreasing airspeed, and proper modifications of phugoid mode were found to improve downburst penetration characteristics. Bailey and Krishnakumar[7] applied the total energy concept to flight in windshear and emphasized the importance of proper inertial energy distribution. An even simpler strategy, advised by Boeing,[8] is to keep a constant pitch angle during takeoff in a downburst. On the other hand, Bray argued that "the best performance was seen as the result of an immediate pushover that establishes the aircraft in level flight at the minimum altitude."[9]

To obtain a clear decision picture, the previous paper considered and compared the two most important criteria in such a case: survival and performance.[3] Optimal takeoff paths were determined via dynamic optimization to maximize the survival capability of an aircraft and to minimize the deviation of climb rate from its nominal value. These two considerations were in conflict and thus produced different results.

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The current paper designs guidance laws to approximate the previously determined optimal paths. Climb-rate command following achieves the optimal performance path, whereas altitude command following produces the optimal survival path. The effects of the climb-rate command and altitude command are studied through nonlinear simulations using different values of the commands.

The two-dimensional point-mass equations of motion of an aircraft are repeated here for convenience. Again, the B-727 aircraft is used as the example airplane. The nomenclature remains the same.

$$\dot{x} = V \cos\gamma + W_x(x,h) \tag{1}$$

$$\dot{h} = V \sin\gamma + W_h(x,h) \tag{2}$$

$$m\dot{V} = T\cos(\alpha+\delta) - D - mg\sin\gamma - m\dot{W}_x\cos\gamma - m\dot{W}_h\sin\gamma \tag{3}$$

$$mV\dot{\gamma} = T\sin(\alpha+\delta) + L - mg\cos\gamma + m\dot{W}_x\sin\gamma - m\dot{W}_h\cos\gamma \tag{4}$$

The simplified ring-vortex downburst model is again used with the two sets of parameters.[3]

Nonlinear Feedback Logic

A downburst may cause large deviations of aircraft states from their nominal values. As a result, nonlinear relations between the states and the control will have to be considered. Since the linearized point-mass equations are essentially the "phugoid" model and the phugoid is usually lightly damped, stability augmentation using linear feedback is required.

Differentiating Eq. (2) and using Eqs. (3) and (4) to eliminate $\dot{V}$ and $\dot{\gamma}$ essentially lead to an expression for the summation of forces in the vertical plane with respect to the air mass (see Fig. 2 in Ref. 3)

$$T\sin(\alpha+\delta+\gamma) + L\cos\gamma - D\sin\gamma = m(g+\ddot{h}) \tag{5}$$

Given a climb-rate command $\dot{h}_c$, one can solve the flight-path angle γ using Eq. (2) as

$$\gamma = \sin^{-1}\left(\frac{\dot{h}_c - W_h}{V}\right) \tag{6}$$

The angle of attack to achieve the desired climb rate $\dot{h}_c$ can then be found from Eqs. (5) and (6), and the nonlinear inverse problem solution is obtained.

Since

$$D \ll L, \qquad |\ddot{h}| \ll g, \qquad |\gamma| \ll 1$$

Eq. (5) can be approximated as

$$\frac{T}{m}\sin(\alpha+\delta+\gamma) + \frac{L}{m} - g = 0 \tag{7}$$

A reasonably accurate solution for α in terms of V and $\dot{h}_c$ can be obtained by expanding Eq. (7) to second order in α and solving the resulting quadratic equation

$$A(\alpha-\alpha_1)^2 + B(\alpha-\alpha_1) + C = 0$$

where (see Appendix A in Ref. 3)

$$A = C_2\mathbf{1}(\alpha-\alpha_1)$$

$$B = C_1 + \frac{T}{C_q V^2}$$

$$C = B\alpha_1 + C_0 + \frac{T(\delta+\gamma) - mg}{C_q V^2}$$

and where $\mathbf{1}(x)$ is the unit step function.

The solution is

$$\alpha_c(V,\dot{h}_c) = \begin{cases} \alpha_1 - \dfrac{C}{B} & \alpha \le \alpha_1 \\ \alpha_1 + \dfrac{-B+\sqrt{B^2-4AC}}{2A} & \alpha_1 < \alpha \le \alpha_{\max} \end{cases}$$

If the downburst is severe and/or the airspeed is very low, the value inside the square root may be negative. This means that the aircraft needs a larger lift than is possible to balance the vertical force. The following condition is added:

If

$$B^2 - 4AC < 0$$

let

$$B^2 - 4AC = 0$$

After a linear feedback is included, the guidance laws will look like

$$\alpha = \alpha_c(V,\dot{h}_c) - K\Delta X$$

where ΔX is the state variation and K the feedback gain.

The contribution of the nonlinear part to stability should be included in the linear analysis. This can be obtained by taking the partial differentiation of Eq. (7)

$$\delta\alpha_c \approx -0.0014\delta V$$

If we use airspeed V and climb rate $\dot{h}$ as the state variables and linearize around the nominal takeoff flight condition without winds, Eqs. (2), (3), and (5) lead to

$$\begin{bmatrix}\delta\dot{V}\\ \delta\ddot{h}\end{bmatrix} = \begin{bmatrix}-0.0096 & -0.1163\\ 0.2150 & 0\end{bmatrix}\begin{bmatrix}\delta V\\ \delta\dot{h}\end{bmatrix} + \begin{bmatrix}-16.47\\ 150.4\end{bmatrix}\delta\alpha_T + \begin{bmatrix}-32.2\\ 0\end{bmatrix} f_w$$

where f_w is the wind factor defined as

$$f_w \approx \frac{\dot{W}_x}{g} - \frac{W_h}{V}$$

and $\delta\alpha_T$ is the total variation of α

$$\delta\alpha_T = \delta\alpha_c + \delta\alpha$$

Horizontal wind rate and downdraft are seen to be the major energy-consuming wind components. In the following analysis of linear control system design, the f_w term is omitted. The equations are then

$$\begin{bmatrix}\delta\dot{V}\\ \delta\ddot{h}\end{bmatrix} = \begin{bmatrix}0.0136 & -0.1163\\ 0.0029 & 0\end{bmatrix}\begin{bmatrix}\delta V\\ \delta\dot{h}\end{bmatrix} + \begin{bmatrix}-16.47\\ 150.4\end{bmatrix}\delta\alpha \tag{8}$$

Performance Takeoff Guidance

The flight path is maintained as close as possible to the nominal path in a performance takeoff. This can be realized approximately through climb-rate command logic, since the optimal performance path has a roughly constant climb rate. The stability of the phugoid mode can be augmented by feeding back the climb-rate deviation to the angle-of-attack variation.

The transfer function from $\delta\alpha$ to $\delta\dot{h}$ can be obtained from Eq. (8) as follows:

$$\frac{\delta\dot{h}(s)}{\delta\alpha(s)} = \frac{150.4(s-0.0139)}{(s-0.0068)^2 + (0.0169)^2}$$

If a proportional feedback is used,

$$\delta\alpha = -k_\alpha\delta\dot{h}$$

the closed-loop characteristic equation can be expressed in Evan's form:

$$-150.4k_\alpha = \frac{(s-0.0068)^2 + (0.0169)^2}{s-0.0139}$$

A root locus vs k_α is plotted in Fig. 1.

Because of the nonminimum phase zero, a large proportional feedback gain will produce an unstable pole! However, this pole will be very close to the zero and will not play an important role in a 1-min period. For example, the set of closed-loop poles are the following for $k_\alpha = 0.003$:

$$s = 0.0132 \qquad \text{and} \qquad s = -0.4509$$

The analyses using available data on Navion and Boeing-747 all indicate a similar zero close to the origin in the open loop.[10] However, the zeros are in the left half-plane in these cases, and a simple proportional feedback will be adequate. Since the climb-rate command logic is used here for only 20–40 s, this

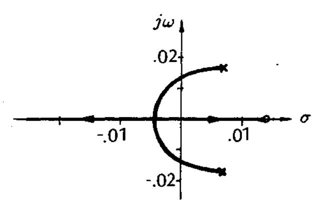

Fig. 1 Root locus vs k_α.

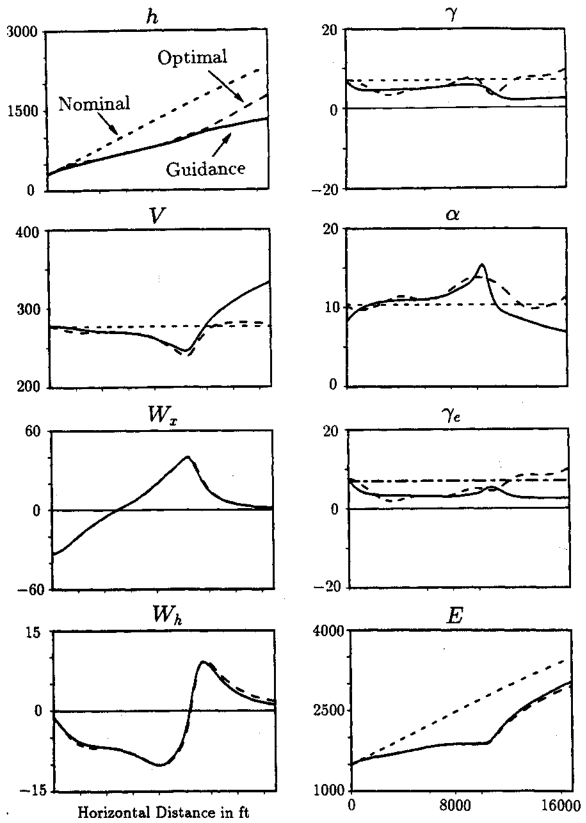

Fig. 2 Performance guidance law.

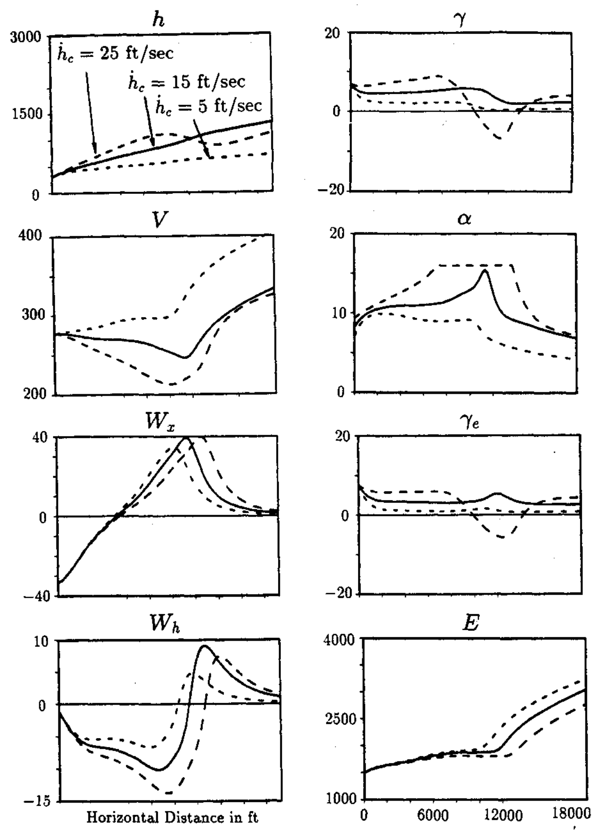

Fig. 3 Climb-rate command.

simple feedback law is adopted in the simulation. The performance guidance law is

$$\alpha = \alpha_c(V, \dot{h}_c) - 0.003(\dot{h} - \dot{h}_c) \tag{9}$$

For the moderate downburst scenario, this guidance law is simulated and compared with the optimal solution in Fig. 2, where $\dot{h}_c = 15$ ft/s. The encounter is assumed to happen at the point where the increasing headwind turns into an increasing tailwind. This corresponds to $X_1 = X_2 = 5000$ ft. The angle of attack is limited to 16 deg in the simulation.

The guidance law approximates the optimal solution very well. When the windshear attenuates, the optimal path climbs to resume the nominal climb rate, while the guidance law follows the same climb-rate command. A switch logic could be added to the guidance law.

During a downburst encounter, intuition might suggest climbing as fast as possible, since the downburst is pushing the aircraft down. However, a fast climb will decrease the airspeed and present the aircraft with a hidden danger: stall. Actually, a maximum possible climb rate exists in a downburst, at which the lowest airspeed is right above stall.

In Fig. 3, three different climb-rate commands using the same guidance law are compared for flight through the moderate downburst. They are $\dot{h}_c = 25$ ft/s, $\dot{h}_c = 15$ ft/s, and $\dot{h}_c = 5$ ft/s. The nominal climb-rate command is $\dot{h}_c = 33.7$ ft/s when there is no wind.

When $\dot{h}_c = 25$ ft/s, the aircraft stalls. It then loses some altitude in exchange for airspeed. The corresponding angle of attack stays at saturation for quite a long time. It experiences the worst downdraft and loses the most energy of the three cases. Actual stall is much more dangerous and should be avoided by all means.

When $\dot{h}_c = 5$ ft/s, the aircraft maintains a high airspeed. The altitude history is the lowest of the three, but acceptable. This aircraft experiences the least downdraft and loses the least energy. The angle of attack is far from stall at all times.

When $\dot{h}_c = 15$ ft/s, the case is somewhere in between. The aircraft does not stall as with the higher climb-rate command, but the airspeed is not as high as with the lower climb-rate command either.

If an aircraft follows a higher climb rate, its airspeed will be lower. The corresponding angle of attack will be closer to stall and it will lose more energy. If it uses too high a climb rate at the beginning, stall will occur. The opposite is true if a lower climb-rate command is used. In short, performance is maintained by flying the aircraft at a climb rate close to the maximum possible value, at the expense of decreased survivability. On the other hand, survival capability is enhanced by following a lower climb rate. Since the actual downburst is not known before penetration, it is important to maintain a high airspeed. There, it is advisable to follow a *lower* climb rate or even to descend.

Survival Takeoff Guidance

Optimal survival takeoff solutions consist of three arcs: initial descending flight, horizontal flight in the downburst region, and the climb-resuming flight toward the end.[3] The major feature of a survival strategy is that energy is stored in airspeed by descending. Therefore, the first two arcs can be approximated by an altitude command scheme.

To develop an altitude command guidance law, a third equation is needed to include the altitude variation as a state. The equations are now the following:

$$\begin{bmatrix} \delta\dot{V} \\ \delta\ddot{h} \\ \delta\dot{h} \end{bmatrix} = \begin{bmatrix} 0.0136 & -0.1163 & 0 \\ 0.0029 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \delta V \\ \delta\dot{h} \\ \delta h \end{bmatrix} + \begin{bmatrix} -16.47 \\ 150.4 \\ 0 \end{bmatrix} \delta\alpha \tag{10}$$

The transfer function from $\delta\alpha$ to δh is

$$\frac{\delta h(s)}{\delta\alpha(s)} = \frac{150.4(s-0.0139)}{s\left[(s-0.0068)^2+(0.0169)^2\right]}$$

A proportional feedback is clearly not enough. A derivative term has to be included

$$\delta\alpha(s) = -k_h(s+a)\delta h(s)$$

The closed-loop characteristic equation in Evan's form is

$$-150.4k_h = \frac{s\left[(s-0.0068)^2+(0.0169)^2\right]}{(s-0.0139)(s+a)}$$

The zero is chosen at $a=0.1$. A root locus vs k_h is plotted in Fig. 4.

The closed-loop poles for $k_h=0.004$ are

$$s=0.0138, \quad s=-0.1274, \quad \text{and} \quad s=-0.4745$$

Again, there is an unstable pole in the closed loop, but it plays essentially no role in a 1-min period due to the cancellation effect. The response is dominated by the modified phugoid poles. The survival takeoff guidance law is

$$\alpha = \alpha_c(V,0) - 0.004\dot{h} - 0.0004(h-h_c) \tag{11}$$

where h_c is the altitude command.

Simulation using this guidance law shows satisfactory results (see Fig. 5), where $h_c=400$ ft, the same as the minimum altitude constraint in the optimal solution. The severe downburst scenario is used and $X_1=X_2=5000$ ft. The angle of attack is limited to 16 deg in the simulation.

In Fig. 6, three different altitude commands are compared. The downburst is the severe one used previously, but the encounter position is assumed to occur even later ($X_1=X_2=4500$ ft). The initial altitude is assumed to be 500 ft. The altitude commands are taken to be $h_c=600$, 400, and 200 ft, respectively. The first command, $h_c=600$, is higher than the initial altitude.

With $h_c=600$ ft, the aircraft increases its altitude at the beginning, but suffers from stall later due to the heavy loss of airspeed. The lowest point is almost on the ground. The angle of attack stays at saturation for quite a long time. The aircraft experiences the worst downdraft and its energy is the lowest of the three cases.

With $h_c=400$ ft, the angle of attack saturates for a short while, but there is less threat to the aircraft than in the preceding case.

The solid-line trajectories follow the altitude command of $h_c=200$ ft. The airspeed history is much higher than in the preceding two cases and stall does not occur. The angle of attack is far from saturation all the time. This aircraft experiences the least downdraft and enjoys the largest final energy.

If the downburst had been more severe, the first aircraft would have crashed, the second flight would have been more

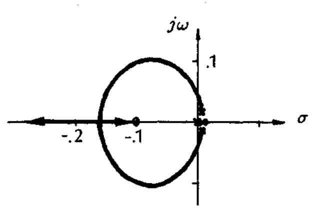

Fig. 4 Root locus vs k_h.

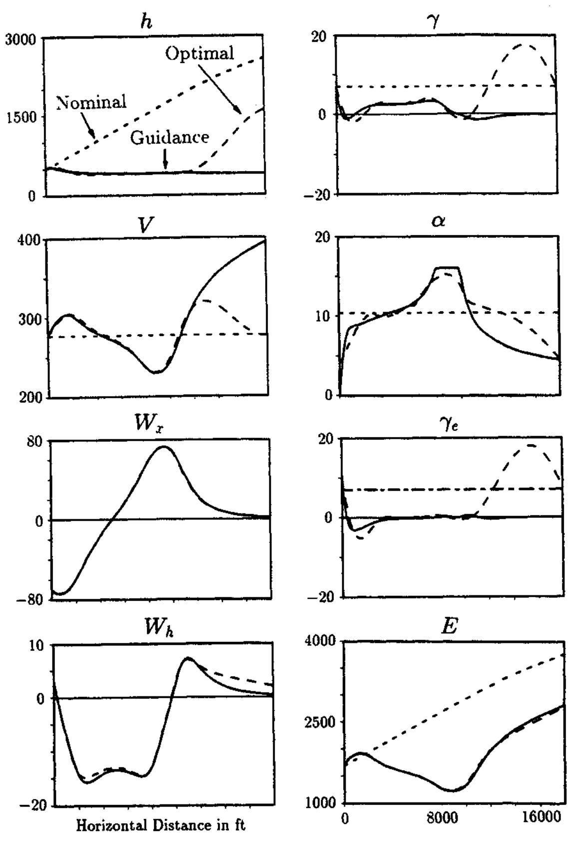

Fig. 5 Survival guidance law.

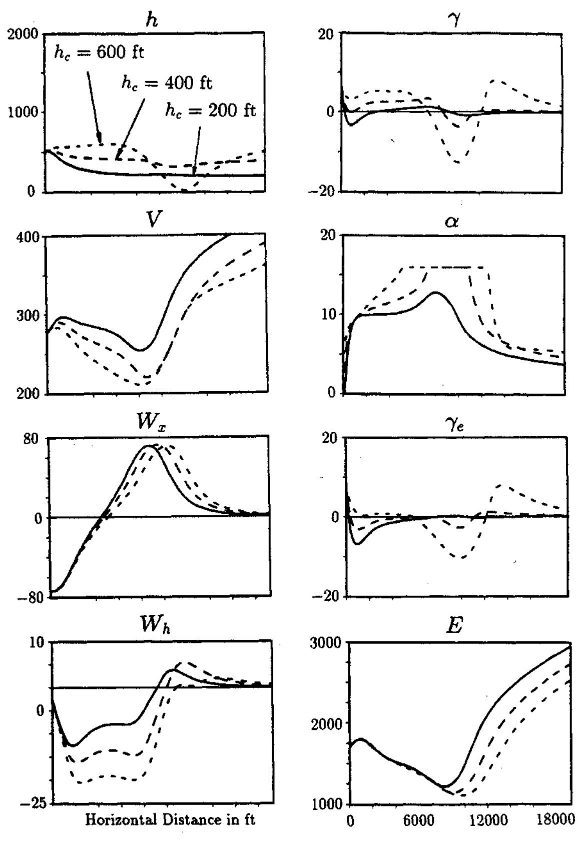

Fig. 6 Altitude command.

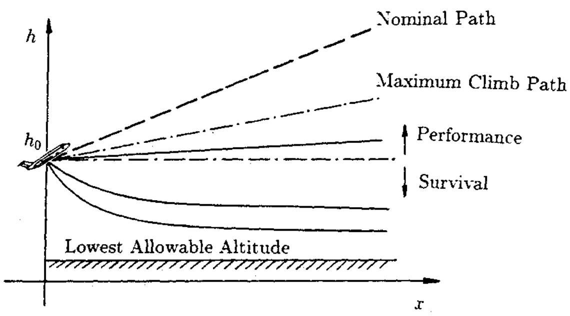

Fig. 7 Decision chart.

thrilling, and the third path would still have been safe. If the downburst becomes much more severe, the aircraft would have to descend farther to survive. Actually, the best course of action upon detecting a severe downburst is to immediately descend to and maintain the lowest safe altitude.

Discussion

The main effect of a downburst on an aircraft is to cause it to lose energy. Therefore, full thrust must be used immediately when the pilot believes that he has entered a downburst on takeoff. A survival strategy causes an aircraft to descend to a lower altitude. Thus, the airspeed will be higher, the energy loss will be slightly less, and the aircraft will experience downdrafts of smaller intensity. A performance strategy tends to climb as much as possible with the constraint of no stall; thus, the altitude will be higher, the energy loss will be slightly greater, and the aircraft will experience downdrafts of higher intensity. Since the angle of attack mainly affects energy distribution between altitude and airspeed, performance takeoff strategy stores energy in altitude, whereas survival takeoff guidance reserves energy in airspeed. If the downburst is mild or moderate, a constant climb rate lower than the nominal value can be followed. This means reducing the climb rate at the beginning. If the downburst is severe, however, the aircraft should descend to and maintain a lower safe altitude until it is essentially through.

For a given downburst model, an aircraft can follow a higher climb rate without stall, but the low airspeed makes the aircraft vulnerable to uncertainties in downburst intensities and/or length. The survival strategy suggests maintaining a high airspeed at all times with a minimum altitude constraint, so the aircraft can tolerate some uncertainties.

Actual windshears and downdrafts may have characteristics not shared by the simplified ring-vortex model. For example, they may not have the headwind build-up part, or the updraft. They do, however, exhibit some common features. As the altitude decreases, the downdraft will reduce and the horizontal wind component will not change much if it does not decrease. Thus, it is generally beneficial to fly at a low altitude. Uncertainties in downburst intensities and/or structure *require* a high airspeed reserve, which in turn helps slightly to reduce energy loss caused by downbursts. Therefore, survival strategy is advisable. In practice, modifications may be made to smooth transient response.

Figure 7 summarizes possible decisions that the pilot can make. The nominal path represents the altitude history without wind. The maximum climb rate is the largest possible constant climb rate an aircraft can maintain without stall in a specified interval. It decreases as the intensity of the downburst increases. Higher climb rate will result in stall. The lowest allowable altitude represents the physical limitations of hills and buildings. The choices are in between. Within this range, the higher the climb rate the aircraft follows, the closer the actual path is to the nominal path, but the poorer the survivability. If the aircraft descends, a similar argument holds. Lower coasting altitude corresponds to higher survival potential and vice versa. Following a horizontal flight at the initial altitude represents a compromise between performance and survival. If the pilot is unsure about the intensity of the downburst ahead, he should follow a *lower* climb rate, or descend to a *lower* safe altitude.

If the initial encounter altitude is roughtly the same or even lower than the lowest allowable altitude, the aircraft cannot descend. It should level off or climb at a *lower* rate.

An important question is determining when an aircraft has entered a downburst. Remote-sensing technology is still something to desire, and pilots should use all of the available information and their own judgment to make a sound decision.

Conclusion

Nonlinear guidance laws were developed to fly an aircraft through a downburst on takeoff. Performance takeoff strategy keeps a constant but reduced climb rate, whereas survival takeoff strategy causes the aircraft to descend to and maintain a lower safe altitude. The higher an aircraft goes, the closer it is to the intended flight path, but the lower its survival potential, and vice versa. Since the intensity of a downburst is difficult to assess prior to penetration, the use of a survival strategy that involves the immediate application of maximum thrust and causes the aircraft to descend to and maintain a low safe altitude is highly recommended.

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