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Windshear Recovery Using Fuzzy Logic Guidance and Control

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I. Introduction

THE generic term *windshear* refers to a rapid change in the wind speed and/or direction.[1] The microburst, a dangerous form of windshear, is produced by a strong sudden downdraft of cool air, which strikes the ground and outflows in all directions. The hazard of the low-altitude microburst arises from the rapid change from a performance increasing headwind to a strong performance decreasing tailwind and downdraft. To cope with the headwind, the pilot intuitively, or the autopilot automatically, takes actions to prevent the aircraft from climbing. Next, these actions are compounded by the energy loss caused by the ensuing downdraft and tailwind. The sudden energy loss poses a serious risk to arriving and departing aircraft.

As windshear may exceed the performance capability of aircraft, avoidance has been emphasized. Because of the recent advances in windshear forward-looking detection systems, timely recognition and avoidance has helped to reduce the hazard significantly.[2] However, because of the short-lived, transient nature of this phenomenon, timely detection might not be always possible. Hence, certain procedures and techniques should be applied to cope properly with the energy loss in case of an encounter. For the guidance and control problem during the windshear phenomenon, it is proposed to apply a fuzzy logic controller based on energy principles that is extended to convey tight energy control and flight envelope protection.

II. Microburst Windshear Hazard

Windshear can be considered as an energy management problem in which the energy decrement of the aircraft results in a loss of either potential energy (altitude) or kinetic energy (airspeed). Because the windshear affects, in particular, the longitudinal motion of an aircraft, the total energy balance in the vertical plane is considered.[3] The airplane total specific energy or potential altitude h_p is defined as

$$h_p = E/mg = \left(V_A^2/2g\right) + h \tag{1}$$

where V_A is the airspeed, mg is aircraft weight, and h is the altitude. Differentiating this expression and using the general equations of motion yields

$$\dot{h}_p = (V_A/g)\dot{V}_A + \dot{h} = V_A\left(\frac{T\cos\alpha - D}{mg} - \frac{\dot{w}_x}{g}\cos\gamma_A - \frac{\dot{w}_h}{g}\sin\gamma_A + \frac{w_h}{V_A}\right) \tag{2}$$

where T is the thrust in the direction of the x axis of the body frame, D is the aircraft drag, w_h and w_x are the time derivatives of the vertical and horizontal wind velocity components, α is the angle of attack (the angle between the x axis of the body frame and the air-mass direction of V_A), and γ_A is the air-relative flight-path angle. The first term is the airplane's excess thrust-to-weight ratio. The subsequent three wind terms describe the windshear impact on the aircraft energy state. The three terms can be combined into the so-called $\mathcal{F}$-factor[2]

$$\mathcal{F} = (\dot{w}_x/g) - (w_h/V_A) \tag{3}$$

A positive $\mathcal{F}$-factor can be physically interpreted as the loss in available excess thrust-to-weight ratio. From Eqs. (2) and (3), it can be seen that the aircraft loses energy if the windshear (associated) energy loss cannot be compensated by an energy-increasing positive thrust change $\Delta T/mg$ because of a limited maximum excess thrust-to-weight ratio. In such a condition, the aircraft descends and/or loses airspeed. In a landing situation, the windshear problem also involves the decision whether to initiate an escape maneuver[4] or to continue the landing. Several optimal guidance schemes and control laws have been developed for safe flight through windshear during abort landing[5] and penetration landing.[6,7,8] In most penetration landing studies, the descending flight path is controlled by pitch/elevator and the airspeed (or inertial speed) by thrust, both with high gains. Miele et al.[6] have performed an extensive optimization study and have provided practical guidance and control laws. The guidance laws include the control of flight path, which is done by angle of attack determined as function of windshear intensity, and the control of airspeed, which is done by thrust, also as a function of windshear intensity. In the guidance laws, tracking the flight path is preferred above airspeed. Psiaki and Park[7] use a pitch steering strategy, which controls the flight path in conjunction with a thrust guidance, which controls the minimum of airspeed and inertial velocity (often referred to as groundspeed). This is done to prevent the energy loss due to the headwind. The idea of explicitly controlling air-relative energy during the penetration of a windshear is also considered by KrishnaKumar and Bailey.[8] The importance of proper energy distribution is emphasized as well. However, the energy partition in this energy-based controller is fixed, i.e., an a priori choice is made on how to distribute the available energy. The recovery concept in this Note proposes a variable energy distribution according to the margins with respect to a stall situation and a minimum altitude. A smooth and variable energy distribution, for each flight mission, is conveyed through the application of fuzzy logic.

III. Generic Flight Recovery Concept

The basic philosophy of this recovery concept is that a compromise between airspeed and altitude is pursued continuously during the encounter with respect to the associated safe operating altitude and stall speed margins, regardless of the specific flight mission, the guidance strategy, and the microburst intensity.[9,10] This protection mechanism can be easily integrated in the longitudinal fuzzy controller of Refs. 11 and 12, which is based on total energy principles.[13] This controller has been designed and extensively tested with respect to other control law designs in a recently formulated civil aircraft benchmark problem.[14]

In Fig. 1, the extended controller is shown. According to the total energy concept, where both airspeed and altitude are controlled simultaneously, thrust T increases the total energy E, whereas an exchange between kinetic (airspeed) and potential energy (altitude) is achieved by pitch angle changes (via elevator). Two inputs to the controller are velocity error V_e, the difference between a reference airspeed $V_{A,\mathrm{ref}}$ and the actual airspeed V_A, and altitude error h_e, the difference between a reference altitude h_{ref} and the actual altitude h.

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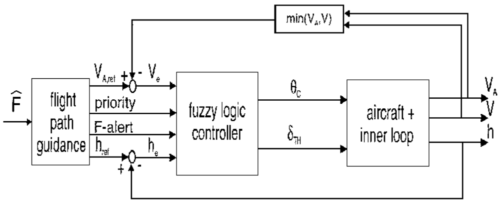

Fig. 1 Block-schematic representation of the extended longitudinal outer loop controller.

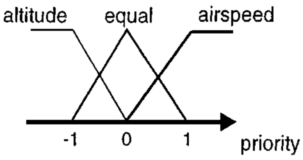

Fig. 2 Membership functions for priority controller input.

The airspeed is given by V_A, whereas inertial speed or groundspeed is given by V. The control actions are the throttle settings δ_{TH} ($= \delta_{TH1} = \delta_{TH2}$), which result in changes in thrust T and the pitch angle commands θ_c. The aircraft block represents the aircraft dynamics including an inner-loop pitch angle controller.

Besides considering the energy distribution, a protection mechanism aims at preventing excursions from the flight envelope. A new priority input is introduced, which indicates whether more priority should be given to altitude (altitude priority) or airspeed (airspeed priority) based on the margins with respect to a predefined minimum airspeed $V_{A,\min}$ and minimum altitude $h_{\min}$. The priority input is determined in the flight-path guidance block (see Fig. 1). With the priority as a new input, a gain-scheduled controller is implicitly obtained in which either the control loop between airspeed and pitch changes or altitude and pitch changes is reinforced.

To define the priority input, consider the specific energy of the aircraft, see Eq. (1). With respect to altitude and airspeed changes Δh and ΔV_A, the specific energy changes by

$$(\Delta h_p)_h = \Delta h \tag{4}$$

$$(\Delta h_p)_{V_A} = (1/g)\left[V_A \cdot \Delta V_A + \tfrac{1}{2}(\Delta V_A)^2\right] \tag{5}$$

Considering a minimum airspeed $V_{A,\min}$ and a minimum altitude $h_{\min}$, the energy margins with respect to these minimum values can be calculated as

$$(\Delta h_p)_h = h - h_{\min} \tag{6}$$

$$(\Delta h_p)_{V_A} = (1/g)\left[V_{A,\min}(V_A - V_{A,\min}) + \tfrac{1}{2}(V_A - V_{A,\min})^2\right] \tag{7}$$

The new priority function $f(h, V_a)$ is then defined as

$$f(h, V_A) = \begin{cases} \dfrac{4}{\pi}\arctan\left[\dfrac{(\Delta h_p)_h}{(\Delta h_p)_{V_A}}\right] - 1 & \text{if} \quad (\Delta h_p)_{V_A} \neq 0 \\ 1 & \text{if} \quad (\Delta h_p)_{V_A} = 0 \end{cases} \tag{8}$$

Negative values of $f(h, V_a)$ indicate a need for altitude priority, whereas positive values indicate a need for airspeed priority. A value of $f(h, V_a) = 0$ indicates an equal partition between potential and kinetic energy. To integrate the priority variable in the controller, three membership functions are defined, as shown in Fig. 2. Each membership function belongs to a rule base for pitch angle commands. As explained in Ref. 12, the membership functions are defined such that a linear interpolation is achieved between one of the special rule bases and the normal rule base. The rule bases are selected by fuzzy logic resulting in a smooth interpolation between the control modes.

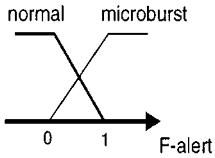

Fig. 3 Membership functions for $\mathcal{F}$-alert controller input.

Apart from distributing the energy according to a safe flight envelope, tight thrust control is required to cope with fast energy changes. However, because the control activity must be small under high-frequency turbulence conditions as well,[14] a sort of gain scheduling is necessary to fulfill both windshear and turbulence conditions. To this purpose, a new variable, $\mathcal{F}$-alert, is defined. This variable indicates the encounter of a microburst windshear based on an estimate of the $\mathcal{F}$-factor, e.g., from a reactive detection system. This variable is used to select either the normal or a more aggressive rule base for the thrust defined in case of an encounter. The alert is activated ($\mathcal{F}$-alert $= 1$) if the estimated $\mathcal{F}$-factor exceeds a threshold of 0, 10 (Ref. 4) and is slowly deactivated ($\mathcal{F}$-alert $= 0$), as it decreases below the threshold. For the $\mathcal{F}$-alert, two membership functions are defined (see Fig. 3) such that a smooth interpolation between the normal and tight control modes is achieved for values between 0 and 1.

Finally, the headwind to tailwind microburst characteristics are taken into account. When the microburst is not anticipated in a landing situation, the increasing headwind will lead to a thrust reduction. To avoid this thrust reduction, control of airspeed and groundspeed, whichever is smaller to its nominal value, can be pursued.[7] As a result, extra energy is preserved and can be used at the downdraft/tailwind stage of the microburst.

It should be noted that this recovery concept can be used for different flight missions, i.e., landing or takeoff.[15] To this purpose, the margins for the priority variable are defined according to the specific situation. Another favorable characteristic of this recovery concept in a takeoff or landing is that it yields correct results despite false alarms. In all of these cases, the controller just provides tight path and airspeed tracking.

IV. Recovery During Landing

For the microburst simulation, the model of Oseguera and Bowles[16] is used. In the simulations, the microburst parameters are chosen such that a maximum $\mathcal{F}$-factor of 0.27 is encountered. To determine the priority value, the minimum airspeed and altitude bounds have to be defined. The minimum airspeed is defined as the stall speed. For the determination of the minimum altitude, the constraints of a category II landing are selected: At the decision altitude, the aircraft should have a vertical deviation less than 12 ft and a lateral deviation less than 20 ft. In the simulation example, the intended (inertial) flight-path angle or glide slope is chosen as $\gamma = -3$ deg. The maximum allowed deviation from the flight path is defined as $\Delta\gamma \pm 0.3$ deg, corresponding to one dot (on the flight instrument used for landing), which falls within the decision window at the decision altitude. The windshear $\mathcal{F}$-factor is computed directly from the simulated wind velocities and delayed by 6 s to simulate a realistic airborne detection.[17]

The Research Civil Aircraft Model (RCAM) is nonlinear, has six degrees of freedom, and represents a two-engined aircraft with a mass of 150,000 kg.[14] Engine and elevator dynamics are included as well. Only the vertical plane is considered, and the aircraft is trimmed on the glide slope of -3 deg. The initial altitude is 400 m. The reference value for the minimum airspeed/groundspeed strategy is 65 m/s. Because of the headwind, at the beginning of the simulations the aircraft has an airspeed of about 70 m/s, whereas the groundspeed is 65 m/s. Normally, the reference airspeed is chosen during the landing phase as 1.3 times stall speed plus a margin of 2.5 m/s (5 kn). For the aircraft mass of 150,000 kg, this results in $1.3 \times 57.9 + 2.5 \approx 78$ m/s. In the following example, a lower reference value is defined to better show the unfavorable effect of a microburst encounter. This in a sense compensates the high excess thrust-to-weight ratio of the RCAM, which is 0.20. When the $\mathcal{F}$-factor exceeds the threshold of 0.10, the tight energy control

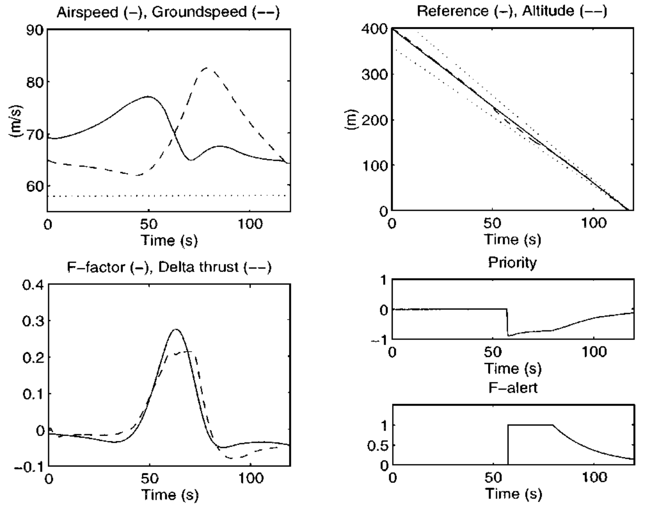

Fig. 4 Aircraft response in landing example: dotted lines are the stall speed and the altitude margins in the respective figures.

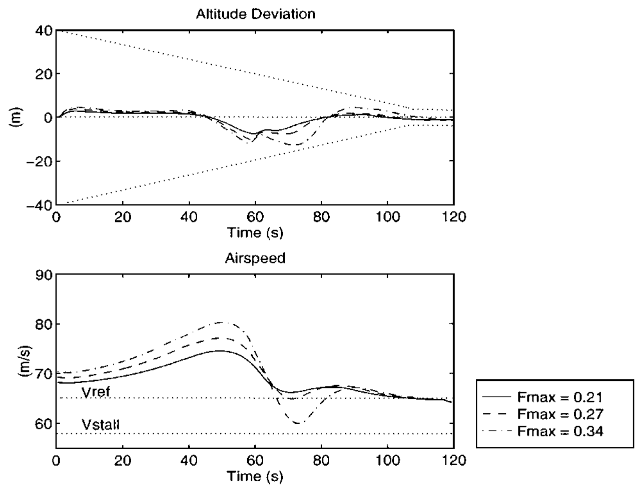

Fig. 5 Aircraft responses for varying microburst in landing scenario.

and the flight envelope protection mechanism are activated. If the $\mathcal{F}$-factor decreases below the threshold value, a smooth transition to the nominal controllers is performed by smoothly scaling the priority with $\mathcal{F}$-alert.

In Fig. 4, the simulation results are shown. The airspeed further increases as the result of the minimum airspeed/groundspeed strategy and the increasing headwind. The increase in air-relative energy is also observed in the thrust change $\Delta T/mg$. Then, at 58 s, the microburst is detected, and both the aggressive throttle rule base and the flight envelope protection mechanism are activated. Although the excess thrust-to-weight ratio is smaller than the maximum $\mathcal{F}$-factor, both airspeed and altitude deviation remain within their safety margins. This is achieved by trading airspeed for altitude (the priority has a negative value). At $t = 110$ s, the aircraft is at the decision altitude while satisfying the category II conditions, and a flare could be initiated shortly after this point.

In the following simulations, the microburst strength is varied and the peaks of the $\mathcal{F}$-factors vary between 0.20 and 0.35, which are realistic values.[1] In Fig. 5, the airspeed and altitude responses are shown. In all cases, both the airspeed and altitude margins are respected because of the flight envelope protection mechanism. For the increasing microburst strength, more energy is automatically built up by tracking the groundspeed and the aggressive throttle. This energy is used to compensate for the altitude loss. For increasing microburst strength, the airspeed and altitude drops are larger. However, as long as recovery is possible, i.e., enough energy margin, a safe compromise between airspeed and altitude is automatically achieved, as shown in the examples of moderate to strong microburst.

V. Concluding Remarks

A windshear recovery concept has been introduced that conveys aggressive thrust management and flight envelope protection. The aggressive throttle management is achieved by incorporating aggressive throttle control laws. Moreover, the minimum of airspeed and inertial speed (groundspeed) is controlled such that an energy reserve is built up at the beginning of the encounter. For the distribution of the available energy, a flight envelope protection mechanism is introduced. The energy is distributed between altitude and airspeed by pitch angle according to a variable priority assignment, activated at the encounter of the windshear. Both the tight energy controller and protection mechanism are integrated as one fuzzy logic control system making a smooth interpolation and a smooth transition possible between the rule bases for normal operation and the microburst recovery handling.

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