UNRESOLVED ISSUES IN WIND SHEAR ENCOUNTERS

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ABSTRACT

Much remains to be learned about the hazards of low-altitude wind shear to aviation. New research should be conducted on the nature of the atmospheric environment, on aircraft performance, and on guidance-and-control aids. In conducting this research, it is important to distinguish between near-term and far-term objectives, between basic and applied research, and between uses of results for aircraft design or for real-time implementation. Advances in on-board electronics can be applied to assuring that aircraft of all classes have near-optimal protection against wind shear hazards.

INTRODUCTION

While the earth's atmosphere provides a medium within which fast point-to-point travel is possible, it also challenges that travel through various meteorological phenomena. The principles of aircraft motion in a quiescent air mass are well understood; given accurate mathematical models of inertial, aerodynamic, and thrust characteristics, these motions can be predicted precisely, and both manual and automatic procedures for guidance and control are straightforward. Unfortunately, the atmosphere is rarely quiescent; winds and rain provide major (potentially life-threatening) disturbances to aircraft motion [1]. While meteorological trends are predictable to some extent, the four-dimensional nature of the air mass, existing as it does in space and time, makes deterministic prediction of these disturbances difficult, if not impossible. Consequently, aeronautical operations are conducted with a high degree of uncertainty about the disturbance environment.

Reducing the uncertainty associated with air travel can be considered an unifying factor of research programs dealing with the wind shear hazards. Still, it must be recognized that there is a diversity of objectives and approaches. Some research focuses on the atmosphere, while other work concentrates on the aircraft. These programs can be further divided into those that seek to increase the knowledge base for design and planning and those that address real-time operations and control. An additional dimension is added to the classification by the intended time frame for application of results; it is desirable to increase the near-term protection of existing aircraft against the wind shear hazard, but it is also important to investigate concepts for long-term improvements in aircraft, systems, and operational procedure.

The remainder of this paper addresses unresolved issues in three areas of technical knowledge regarding wind shear hazards to aircraft. The first deals with the atmospheric environment, which works both for and against the aircraft, and which is unaffected by human intervention. Microbursts, which are unusually severe downdrafts accompanied by intense outflows, can be especially hazardous. The second relates to aircraft dynamic response, which can be modified by design,

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to some extent, for maximum realizable protection against the hazard. The third area is guidance-and-control aids, which offer the opportunity to use available performance in an optimal way for wind shear penetration or avoidance.

While the most prudent approach is to avoid hazardous meteorological conditions whenever possible, there always will be those borderline cases in which pilots are called upon to weigh hazards against mission objectives. Because the future is uncertain, there will be instances when the pilot presses on even though hindsight will prove that to have been the wrong choice. The issues raised here relate principally to the identification of these borderline situations and to safe flight in hazardous conditions.

ATMOSPHERIC ENVIRONMENT

The atmosphere exists in three spatial dimensions, and its characteristics vary in time. These characteristics include scalar quantities (pressure, density, humidity, and temperature), the wind vector, and contaminants, e.g., rain, insects, and dust. The scalar quantities normally vary over large space and time scales, and the contaminants often are "patchy", i.e., there are discrete changes in otherwise uniform distributions of these elements. The wind vector contains both steady and unsteady components; it is customary to distinguish between a mean component, which varies slowly in time and gradually in space, and a perturbation component (turbulence and gusts) that changes quickly and over short distances.

Relative to the standard atmosphere, variations in all of these quantities can be considered potential disturbances to aircraft flight. The slow, long-wavelength disturbances can be accommodated by changes in trim settings and operational procedures. These are amenable to synoptic prediction, so pilots have advance warning and can plan accordingly. The fast, short-wavelength disturbances are much less predictable. They constitute hazards to flight when their magnitudes are sufficient to cause extreme deviations from the flight path or to overstress the aircraft. The extent of the hazard depends upon the flight condition, the aircraft's structural and aerodynamic integrity, and the control policies that are employed during the encounter.

Frozen Wind Profiles and Statistics of Uncertainty

Because the wind vector is three-dimensional, there are nine terms in the wind shear gradient with respect to spatial coordinates, as well as three terms in the wind's time-derivative. Although it is often satisfactory to idealize an aircraft as a point mass for dynamic calculations, an aircraft's size plays a role in determining its response to wind shear gradients--for example, a spanwise gradient in the vertical wind produces a rolling moment that would not appear in the equations of motion written for a constant wind field.

Response to the wind shear gradient and time-derivative should be distinguished from response to the wind velocity itself. The former contributes principally to aeroelastic response, while the latter has more direct effect on an aircraft's flight path response. A spanwise gradient such as that mentioned above could be an exception, in that rolling response integrates into net heading changes that must be corrected to maintain the intended flight path. Even though the wind field has a spatial distribution, this is transformed into a temporal distribution by an aircraft's transit through the wind field. Consequently, temporal and spatial variations become indistinguishable along a given flight path--at least from the standpoint of an aircraft's dynamic response.

It should be possible, therefore, to specify frozen spatial distributions (with sufficient resolution to derive gradients) that could be used in flight simulation to represent the disturbance environment. The mass of data collected in the Joint Airport Weather Studies (JAWS) and related programs could be used to specify time-invariant wind fields in a variety of useful formats. One such format would be a series of wind fields possessing distinctive features that are potentially hazardous and that are differentiated by varying intensities and length scales. Another would be a range of statistics, e.g., probability density functions and spectra at various confidence levels, indicating the uncertainties associated with the disturbance inputs that an aircraft would experience on paths through these wind fields.

It would be particularly useful to assess spatial correlations in the more hazardous wind fields. Given a certain wind intensity, how likely is it that conditions will be worse 500 or 1000 or 1500 feet ahead of the aircraft? Are there patterns that signal especially hazardous conditions?

Pressure and Temperature Variations in Microbursts

Although attention has been focused on the adverse effects of tail winds and downdrafts, unusual local variations in ambient pressure and temperature could have detrimental effects as well. Most aircraft rely on air data--at least in part--to determine altitude, airspeed, and rate of climb or descrnt. Warnings and guidance strategies for abort or penetration would make use of such data, so it is important to know whether or not there are meteorological factors that would degrade these data on the time scale of aircraft motions.

Correlation of Wind Shear with Heavy Rain

Although microbursts can occur in dry weather, hazardous wind shears often are accompanied by heavy rain. Heavy rain can have two dangerous effects. First, it can affect combustion in turbine engines; engines have been quenched by heavy rain, an unacceptable alternative for either takeoff or landing. Second, it can degrade the aircraft's lift, moment, and drag characteristics. Although much wind-tunnel testing remains to be carried out, even modest changes in lift-drag ratio or pitching moment characteristics could have major impacts on aircraft performance and controllability. The combination of adverse wind-shear and heavy rain effects could be much worse than the effects of either phenomenon alone; therefore, it is important to understand the interrelationships between the two.

AIRCRAFT DYNAMIC RESPONSE

Aircraft are configured to achieve mission objectives subject to design constraints. Underlying the design process are considerations of effectiveness, pilot workload, life-cycle cost, maintainability, comfort, and safety. Although most aircraft are optimized for one or more mission profiles, the wide diversity of configurations that are ostensibly designed to satisfy similar criteria attests to the allowable freedoms in aircraft design. These differences can be attributed to differences in the value placed on opposing design objectives, as well as to differences in the styles of competing airframe manufacturers. Thus, competing aircraft can be considered "optimal" in some sense, even though one has better specific fuel consumption, another has lower direct operating costs, another has better flying qualities, and so on.

It is unlikely that wind-shear penetration characteristics ever will become major drivers in configuration design, but better understanding of these characteristics could identify factors which would reduce the wind shear hazard while satisfying principal objectives. Greater attention to aerodynamics of the stall region is an obvious example of this point. Both longitudinal and lateral-directional aerodynamics are of concern--an otherwise benign stall break could become disastrous if accompanied by divergent roll-spiral oscillations or loss of lateral control. In addition to the usual effect on pitch damping, tail-lag aerodynamics could produce unexpected response to vertical wind inputs. The heavy-rain effects mentioned above could impact the selection of airfoil sections and the design of engine inlets.

Edges of the Envelope

For given aircraft configurations, the limiting magnitudes and profiles of horizontal and vertical wind inputs should be determined. While static or quasi-static response to shears of fixed value are of interest, wind-shear encounter is a dynamic event. Correspondences of elevator and throttle trim settings to fixed changes in the wind must be understood, but the dividing line between safe and unsafe encounter is affected by the phasing of control inputs, as well as by the "stored" energy and momentum (both translational and angular) at the time of encounter. Static analyses are not necessarily conservative, nor do they reveal the full potential for successful wind-shear penetration.

The "edges of the envelope" can be defined using trajectory optimization or reachable-set evaluation. These involve accurate mathematical models of the aircraft combined with flight-path simulation and search algorithms. A distinction is made between these analyses and simulation to identify piloting procedures or control system designs. The purpose is to understand what the aircraft's true limits are, establishing standards against which further developments can be evaluated.

Control Power and Flying Qualities Requirements

An aircraft's control "power" usually is described by the maximum available angular accelerations that result from full deflection of its control surfaces; however, a broader definition is implied here. In the context of wind-shear encounter, thrust, lift, and drag controls also should be considered, and it is necessary to address the time lags associated with control actuation. It is easy to postulate fast-acting, high-force effectors that would counter wind effects, but it is not known if such effectors are practical, necessary, or even effective.

Control and power requirements for elevator, ailerons, and rudder already address important elements of control against the wind, and it seems appropriate to develop similar insights about the possible utility of flaps, spoilers, drag brakes, and thrust augmentation. Making an approach with partially deflected spoilers, for example, would afford a measure of "instant L/D" on wind-shear encounters; aside from current operational objections to such a procedure, it is not obvious that the incremental lift increase and drag reduction would materially aid flight path management during encounter. If, however, the spoilers could be effective in this role, consideration should be given to the design and operational changes necessary to effect such control. Similarly, the value of optimal direct-lift control via flaps should be determined.

Current flying qualities requirements address both fast and slow response characteristics of aircraft, although the former have received greater attention in recent research. Nevertheless, it is the latter that have the more significant relationship to wind-shear response. It would be appropriate for flying qualities specifications to reflect the impact of phugoid- and spiral-mode stability on an aircraft's response to wind-shear inputs, as these modes can be very lightly damped, even slightly unstable in some circumstances. Because the time scale of a microburst encounter may be of the same order as the phugoid-mode period, a resonant response is possible; this amplifies the resulting interchange between kinetic and potential energy, which is to say there is a greater deviation from the nominal flight path than would occur with a well-damped mode.

There must be greater concern for high-angle-of-attack flying qualities, not only for maneuvering high-performance aircraft, but for aircraft of all classes. Exposure to high angle of attack and unusual attitudes is likely during wind-shear encounter. A departure-from-controlled-flight during takeoff or in the landing pattern would be catastrophic. The classic symptoms of inertial coupling during rolling pullups, loss of roll damping near the stall, and degraded control effectiveness all can be experienced by jet transports, general-aviation (GA) aircraft, and helicopters during wind-shear encounter.

General Aviation Aircraft and Helicopters

Tragic accidents involving commercial jet transports encountering wind shear have focused attention on the subject, but small aircraft are at least as (if not more) susceptible to windshear-induced accidents. Because their inertial and aerodynamic characteristics are so different, wind fields that are hazardous for one aircraft type may be less hazardous for another type. The principal distinctions are due to airspeed and wing loading, i.e., the aircraft weight divided by the wing area. Aircraft with high airspeed and wing loading appear to be more sensitive to gradients in head/tail wind, while aircraft with low airspeed and wing loading are more adversely affected by downdrafts [2]. Trajectory deviations are extreme when the disturbance input's wavelength is close to the aircraft's phugoid-mode wavelength. Since the phugoid-mode wavelength is proportional to the square of the forward speed, a wind profile that resonates one aircraft type may not resonate another. Consequently, it is difficult to generalize about the atmospheric conditions that constitute a hazard to aviation in general.

The possibilities of dangerous wind-shear encounter for GA aircraft and helicopters are exacerbated by the circumstances of their use. First, they are more susceptible as a consequence of low airspeed and wing (or rotor-disk) loading. They often are flown out of unimproved airfields with minimal meteorological instrumentation and terrain-induced wind shear. Helicopters often are used on emergency or otherwise urgent missions in poor weather, so frequency of exposure to hazardous wind shear is relatively high.

Because the cost of equipment is so much lower, because the operators of such aircraft routinely accept the risks, and because the potential loss of life (per accident) is less, few studies of the wind-shear hazard to GA aircraft and helicopters have been conducted. Furthermore, when amateur or low-time pilots are involved, it often is concluded that "pilot error" is the probable cause; hence, accident statistics may not give an accurate portrayal of the extent of the wind-shear problem. Nevertheless, the potential severity of the consequences suggests that added attention should be given to the unique wind-shear encounter problems of these classes of aircraft.

GUIDANCE-AND-CONTROL AIDS

Perhaps the most treacherous aspect of wind-shear encounter is that counter-intuitive piloting may be the key to survival. With the onset of strongly increasing tail wind or decreasing head wind, an aircraft loses airspeed and, therefore, lift. The pilot's normal reaction of adding power is appropriate, but the time for thrust to build and for this to integrate to increased airspeed and lift may exceed the time available for recovery. In such instance, the only way to increase lift quickly is to increase the angle of attack; however, raising the nose in response to decreasing airspeed is contrary to everything that the pilot has learned for flight in constant-speed air masses. This training effect is so strong (and so right under normal circumstances) that it is unrealistic to expect pilots to pull the nose up without added information and guidance.

Of course, the pilot's principal worry is that the aircraft will stall, but stalling represents the maximum amount of lift that can be squeezed out of the aircraft at a given airspeed. The trouble is that airspeed or altitude or both decay rapidly if the stall angle of attack is held for any length of time, lateral-directional flying qualities may be unfamiliar if not unacceptable, and visual ground contact may be lost at high pitch angle.

Successful wind-shear penetration may require a higher level of airmanship than could be expected from the average pilot unless proficiency can be maintained through continual practice in high-fidelity ground simulators. (Even then, there is some question about the value of simulation, as exposure to one wind shear profile may provide negative training for an equally hazardous but different profile.) With the understanding that wind-shear encounters are rare but violent events, the practicality and cost-effectiveness of keeping all pilots current in the proper procedures is questionable.

A better approach is to assure that pilots receive adequate warning and real-time guidance when the wind shear occurs. Modern instrumentation and avionics make various levels of protection against the wind-shear hazard possible for all classes of aircraft. Instruments that sense vertical acceleration or specific energy rate (the rate-of-change of kinetic and potential energy, divided by aircraft weight) are available; with proper desplays, they can indicate that the aircraft has penetrated wind shear and can give rudimentary guidance for evasive action. An angle-of-attack display can let the pilot maneuver up to the stall with increased confidence.

At the next level of sophistication, multisensor packages plus minimal amounts of computer logic can sense wind shear with increased reliability and can issue visual or aural warnings. Integrating such information into the logic that drives an advanced flight director provides more specific guidance for penetration of mild wind shears and for abort in severe wind shears. The same signal that drives the flight director can drive an auto-takeoff or auto-land system; this removes the pilot from the "inner" control loop, which may or may not be desirable.

Optimal Trajectories and Control Laws

While there is an increasing body of "folklore" regarding the "best" control strategies for wind-shear penetration or avoidance, there is a singular lack of hard information regarding the subject. It would be useful to know not only where the "edges of the envelope" lie but what the optimal control strategies are.

Two classes of optimality are of interest. Deterministic optimal trajectories and control histories for specific wind profiles would furnish insights about the phasing and magnitude of control inputs, and they could identify the relative value of initial condition variations, e.g., the "airspeed pad" or height above the nominal glide slope that would be necessary for successful encounter. It is conceivable that a guidance law based on dynamic programming could use pre-computed trajectories and controls in real time, although the practicality of such an approach must be determined.

Nevertheless, wind-shear encounter is a random event, and it seems likely that stochastic optimal control laws would provide increased margins of safety. In this approach, prior knowledge of aircraft dynamic characteristics and of the statistics of the disturbance environment and measurement uncertainties is combined to maximize the expectation of safe passage. The better the knowledge of the wind field, the more effective the stochastic optimal control will be. The mathematical tools for implementing optimal control laws in real time exist; it remains for them to be applied to the problem.

Predictive Estimates of the Wind

Of course, the problems of guidance and control would be reduced materially if there could be some detailed knowledge of the wind field before the aircraft enters it. Because the wind field is varying in time, there always will be some uncertainty about the disturbances that the aircraft will experience, but wind measurement that is predictive in some sense could reduce the uncertainty.

Here, "predictive" simply means that an estimate of the wind field exists prior to encounter; a measurement that is a few seconds old is itself a prediction which could be improved by taking account of time and space correlations. The wind sensors could be located either on the ground or in the aircraft, and there are many pros and cons to each approach [1]. For warning and avoidance, current estimates of the wind field that are one to five phugoid wavelengths ahead of the aircraft would provide enough time to frame guidance strategies, and they probably would be sufficiently "fresh" for making "go-no go" decisions. This corresponds to wavelengths of about a quarter to one nautical mile for GA aircraft and about five times that for jet transports. Corresponding lead times for GA aircraft are about 15 seconds to one minute and one-half to two-and-a-half minutes for the jet transport. For control during penetration, current wind estimates should extend from one to five short-period wavelengths ahead of the aircraft, roughly reducing the above numbers by a factor of five.

Predictions of the uncertainty of the wind as well as of the wind itself are useful. If the wind shear is predicted to be too great on the glide slope, that is grounds for abort; however, if the predicted uncertainty in wind inputs exceeds the aircraft's capabilities, that also provides a reason for go-around. Given such predictions, it would be possible to compute a projection of the desired nominal path; the desired path could be generated using concepts of "dual control", which combine prediction with optimal estimation and control.

Application of Artificial Intelligence

The computer power that can be packaged economically for use in flight has reached the point that artificial intelligence (AI) methods could be applied to the guidance-and control problem. In engineering application, AI generally refers to the process of making a computer emulate the rational behavior of a human expert.

In the context of wind-shear encounter, "DI methods" can be interpreted as storing all rational policies for pilot response to wind shear and retrieving that information which is appropriate for the case at hand. It also might connote decision-making and presentation of alternatives to the pilot, including alternatives for manual or automatic control. Behaving like an intelligent advisor to the pilot, the AI logic for the flight computer would provide an interface between the optimal control laws suggested above and strategic planning of the aircraft's flight.

CONCLUSION

Wind shear is not a new phenomenon, but there is heightened interest in minimizing the hazard it presents to aircraft of all classes. This is the result of many factors, not the least of which is that technical solutions to the problem are becoming more practical as a consequence of continued meteorological, aeronautical, and electronic research and development. Furthermore, there is increased awareness that aviation safety is not only humanitarian but that it constitutes a direct benefit to our society. While there are important unresolved technical issues, approaches to resolving many of these issues can be identified. What remains is the commitment of sufficient resources to turn these solutions into reality.

REFERENCES

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