Session X. Flight Management Research

Wind Shear Related Research at Princeton University
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Wind Shear-Related Research at Princeton University

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Real-Time Decision Aiding:
Aircraft Guidance for Wind Shear Avoidance

Target Pitch Angle and Optimal Recovery
from Wind Shear Encounter

Dynamic Behavior of an Aircraft Encountering a Wind Vortex
Real-Time Decision Aiding: Aircraft Guidance for Wind Shear Avoidance

D. Alexander Stratton and Robert F. Stengel
Princeton University

Presentation Outline

• The Microburst Hazard to Aviation

• Processes of a Wind Shear Advisory System

• Simulated Microburst Encounters
The Low-Altitude Wind Shear Threat

- Microburst phenomenon
  - Short-lived, powerful outflow
  - Aircraft performance, control
- Microburst research
  - Wet, dry environments classified
  - Frequency, characteristics determined
  - Guidance and control strategies
An Advisory System for Wind Shear Avoidance

- Support crew decision reliability
  Monitoring and estimation, data link
  Risk assessment
  Provide decision alternatives
  Recovery procedures

- Define computational structure
  Summarize relevant information
  Incorporate meteorological data
  Declarative structure, convert to real-time

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Reducing the Wind Shear Threat

- Flight crew training
  FAA Windshear Training Aid

- Ground-based detection systems
  LLWAS, TDWR
  Weather services, forecasting

- Airborne detection technology
  Doppler radar, lidar, infra-red
  Radar reflectivity, lightning

- Integration, information transfer
Energy-Based Hazard Model

One-dimensional energy model:

\[ E_s(t) = \left(\frac{1}{2g}\right)V_a^2 + h \]
\[ \frac{dE_s}{dt}(t) = P_s - \mathcal{F}(t)V_a \]

- \( \mathcal{F} \) - "F-factor" (Bowles)

\[ \mathcal{F}(t) = \left(\frac{1}{g}\right)\frac{dw_x}{dt}(t) - \frac{wh(t)}{V_a} \]

Specific excess power (P) variation

Airspeed variation

NASA Langley - 0.1 average \( \mathcal{F} \) over 1 km

- Energy deviation across shear

\[ \Delta E_s = -\mathcal{F}_{ave}\Delta x = -\frac{V_{an}}{g}\Delta w_x + \frac{wh_{ave}}{V_{an}}\Delta x \]
Forward-Look Sensor Measurement of Wind Shear

Relative Speed of the Air Masses = Remote Wind Speed with respect to Aircraft Speed with respect to Local Air Mass

\[ \Delta W_{jk} = z_{jk} - V_a \]

- Aircraft Specific Energy Loss

\[ \Delta E_s = -F_{ave} \Delta x = -\frac{V_{an}}{g} \Delta w_x + \frac{w_{ave}}{V_{an}} \Delta x \]
Stochastic Prediction Algorithm

- Coupled Kalman filters
  "Random walk" stochastic model
  Sensor platform motion - state propagation
  Parallel processing
  Optimize design gain parameter

- Coupled predictive-reactive detection

- Positive detection - threshold exceedence
Probability-Based Decision Strategy

• Predictive measurements $z_p(t)$

• Probability-based decision-making

$$\Pr\{\exists t_i \in [t,t_f]: \mathbf{w}(t_i) \in \mathcal{U} \mid z_p(t), u_d(t) = u_{d1} \} < T \Rightarrow u_d(t) = u_{d1}$$

• Bayesian inference

$$\Pr\{H \mid z_p(t)\} = \frac{\Pr\{z_p(t) \mid H\}}{\Pr\{z_p(t)\}} \Pr\{H\}$$

• Joint probability computation
Computational Processes for Decision Aiding

- Identify Knowledge, Structure

- Rule-Based Logic
  Declarative, back-chaining inference
  Top-level monitoring, assessment, planning, guidance functions

- Bayesian Logic
  Statistical model, data-driven inference

- Multivariable Estimation
  Stochastic model
Bayesian Network Risk Assessment

- Assign link probabilities, priors
- Probabilities updates, Bayes's theorem
Spatial and Temporal Factors

- Likelihoods weigh timeliness, nearness
  - Dual-doppler data (Hjelmfelt, 1988)

![Bar chart showing probability of microburst enduring over duration time in minutes.](chart)

- Network time-dependant, re-initialize

- Repeated evidence, downgrade relevance
Risk Assessment Benchmarks

- Windshear Training Aid Guidelines
  - 12 Weather Evaluation Exercises
  - Risk Assessed by WTA authors
    Example: moderate convection results in Medium risk

- Bayesian Network Calculations
  - Monotonic relationship
  - Subjective levels assigned
Robustness of Predictive Wind Shear Detection

- Robustness issues
  - Variation in microburst structure
  - Vertical winds unmeasured
  - Bandwidth limitations

- Detection robustness metrics
  - Probability of Correct Warning, \( \Pr\{A \mid WS\} \)
  - False Warning Probability, \( \Pr\{A \mid \neg WS\} \)

\[
\Pr\{WS \mid A\} = \frac{\Pr\{A \mid WS\}}{\Pr\{A\}} \Pr\{WS\}
\]

\[
\Pr\{A\} = \Pr\{A \mid WS\} \Pr\{WS\} + \Pr\{A \mid \neg WS\} [1 - \Pr\{WS\}]
\]

- Accuracy metrics
  - Mean-Square Prediction Error
  - Mean Advance Warning Time
Prediction Algorithm Refinement

- Probability of Correct, Missed Detection
  Monte Carlo analysis

- Design parameter optimization
  Mean-Square Hazard Prediction Error

- False Warning Probability

\[
N(T_d) = \frac{\sigma_y'}{2\pi\sigma_y} e^{-\left(\frac{T_d^2}{2\sigma_y^2}\right)}
\]

- Benchmark Statistics for Bayesian Network
Selection of Design Threshold

- Fixed design threshold
  Tolerance for false warning rate
  Tolerance for wind shear encounter

\[ \lambda = \frac{P_{CW}}{P_{FW}} \]

\[ \lambda = \frac{\Pr\{WS | A\} \cdot [1 - \Pr\{WS\}]}{[1 - \Pr\{WS | A\}] \cdot \Pr\{WS\}} \]

- Variable or multiple threshold
**Benefit of Integrated Warning**

- **CASE 1**
  
  Prior $\Pr(H) = 1/20,000$
  
  Likelihood ratio $= 200$ (0.075 radial F)
  
  Posterior $= 1/100$

- **CASE 2**
  
  Prior $\Pr(H|E) = 1/1000$
  
  Likelihood ratio $= 8$ (0.05 radial F)
  
  Posterior $= 1/100$
Wind Shear Safety Advisor Determines "High" Risk

<table>
<thead>
<tr>
<th>Princeton Wind Shear Safety Advisor</th>
<th>Guidance Information and User Interaction Window</th>
<th>Rule Monitoring Window</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WINDSHEAR ADVISORY ALERT</strong></td>
<td>* RISK OF WIND SHEAR ENCOUNTER DURING</td>
<td>so the hazard is now displayed</td>
</tr>
<tr>
<td>* TAKEOFF AT DENVER IS HIGH, DUE TO:</td>
<td>* DRY-SURFACE</td>
<td>PLANNING: A hazard is to be displayed to the flight crew, so the hazard is now displayed.</td>
</tr>
<tr>
<td>* VIRGA</td>
<td>* TDWR, WS-ADVISORY</td>
<td>PLANNING: An avoidance strategy is required for the next flight phase.</td>
</tr>
<tr>
<td>* AVOIDANCE STRATEGY: DELAY OPERATIONS</td>
<td></td>
<td>so the recommended avoidance strategy is to delay</td>
</tr>
<tr>
<td>Will the next flight phase be delayed?</td>
<td></td>
<td>YES</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor Information Window</th>
<th>Status Information Window</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WEATHER ADVISORY INFORMATION</strong></td>
<td><strong>WEATHER ADVISORY INFORMATION</strong></td>
</tr>
<tr>
<td>* A report has been received from data link.</td>
<td>* Awaiting takeoff from DENVER.</td>
</tr>
<tr>
<td>* A TDWR WS-ADVISORY was reported near the</td>
<td>* Takeoff scheduled to begin</td>
</tr>
<tr>
<td>TAKEOFF path at DENVER</td>
<td>in 0.7 MINUTES.</td>
</tr>
<tr>
<td>0.2 minutes ago.</td>
<td>* Risk of Wind Shear Encounter is MEDIUM.</td>
</tr>
<tr>
<td></td>
<td>* Risk of Heavy Precipitation is LOW.</td>
</tr>
</tbody>
</table>
Conclusions

• Diverse information aids hazard avoidance

• Explicit models easier to refine, validate
  – explicit conditions
  – statistical data, analysis

• Architecture for strategic decision-making
  – Mission planning, vehicle guidance
  – Failure detection, reconfiguration

• WSSA logic applications
  – Pilot training aid
  – Automated detection, recovery guidance
Reducing the Threat: Manual Recovery Strategies

• After liftoff/on approach technique
  - Aggressive application of thrust
  - Pitch toward 15° attitude
  - "Respect Stick Shaker"
  - Higher attitude, thrust if necessary

• On the runway
  - Aggressive application of thrust
  - Below V1, abort takeoff
  - Above Vr, rotate toward 15°
  - With less than 2000 ft runway, rotate toward 15° (possible tail scrape)

• Pilot Report
Target Pitch Angle for the Microburst Escape Maneuver

Sandeep S. Mulgund and Robert F. Stengel

Overview

- The Wind Shear Problem
- Previous research
- Effect of wind shear on airplane performance
- Recovery strategies for inadvertent encounters with wind shear
- Present Research
  - Recovery technique for commuter-class aircraft
  - Trajectory Optimization
- Conclusions
Recovery Technique for Inadvertent Encounter

**FAA Wind Shear Training Aid**
- Apply maximum thrust and rotate aircraft toward initial pitch target of 15°, while respecting "stick shaker"
- Maintain aircraft configuration

**Why Constant Pitch?**
- Attitude indicator is one of few major aircraft instruments not affected by microburst environment
- Easily recalled in emergency

**Why 15° as the target?**
- Easily recalled in emergency
- 15° mark on attitude indicator can be targeted even in heavy turbulence
- Provides good recovery performance for *jet transports* in a wide spectrum of shear encounters
Application to Commuter/General Aviation Aircraft

Issues
- Lower takeoff and approach speeds than jet transports
- Lower wing loading
- Lower specific excess power

Objective
- Apply FAA recovery strategy to this class of aircraft
- Methodology for identification of Target Pitch Angle (TPA)

Commuter Aircraft Model
- Simulation model representative of light twin prop - 6300 lb g.w.
- Point Mass dynamics
Maximum Climb Capability in Wind Shear

- Rate of Climb:
  \[ \dot{h} = V \sin \gamma + w_h \]

- Maximize steady-state rate of climb under an imposed F-Factor
  \[ F = \frac{\dot{w}_x}{g} - \frac{w_h}{V} \]
  
  (a) \[ F = \frac{\dot{w}_x}{g} \]
  
  (b) \[ F = -\frac{w_h}{V} \]

- Aircraft in initial approach configuration: 45° flaps, gear retracted
Effect of Wind Shear on Maximum Rate of Climb

- **Rate of Climb (ft/min)**
  - Y-axis:
    - Minimum: -500
    - Maximum: 2000
  - X-axis:
    - Minimum: 0
    - Maximum: 0.25

- **Airspeed (knots)**
  - Y-axis:
    - Minimum: 55
    - Maximum: 75
  - X-axis:
    - Minimum: 0
    - Maximum: 0.25
Angle of Attack and Pitch Attitude for Best Climb in Wind Shear

- Horizontal Shear
- Downdraft

Graphs showing the relationship between F-Factor and Angle of Attack (deg) as well as Pitch Attitude (deg) for different conditions of wind shear.
Implications

- Pitch attitude for climb rate depends on source of threat.
- Actual environment contains regions of both downdraft and horizontal shear.
- Single target pitch angle is a compromise.
- Nature of trade-off may be ascertained through simulation of microburst encounters.
- Require a mathematical microburst model.
Simulation of Encounter During Final Approach

- Microburst core placed directly along flight path.
- Aircraft tracks glide slope prior to shear entry.
Effect of Initial Altitude on Minimum Recovery Altitude

- $V_o = 95$ knots
- $\delta F = 45^\circ$
- $R = 3000$ ft
- $U_{max} = 80$ ft/s
- $Z_{max} = 150$ ft

Shear Parameters:

- $h_o = 1400$ ft
- $1200$ ft
- $1000$ ft
- $800$ ft
- $600$ ft

Initial Distance from Core: 10,000 ft

Target Pitch Angle (degrees)

Minimum Recovery Altitude (ft)
Effect of Shear Strength on Minimum Recovery Altitude

- $U_{max} = 60$ ft/s
- $V_o = 95$ knots
- $\delta F = 45^\circ$
- $h_o = 1400$ ft

Shear Parameters:
- $R = 3000$ ft
- $Z_{max} = 150$ ft

Initial Distance from Core: $10,000$ ft

Minimum Recovery Altitude (ft) vs. Target Pitch Angle (deg)
Trajectory Optimization in Wind Shear

- Find $x(t), u(t)$ to minimize

$$J = \phi[x(t_f), t_f] + \int_{t_0}^{t_f} L[x(t), u(t), t] dt$$

- What is optimal?
- Successful recovery $\Rightarrow$ Avoiding ground impact
- Maximize minimum altitude $\Rightarrow$ Minimize maximum deviation from a high reference altitude: [Miele]

$$l = \max_t (h_{ref} - h(t)) \quad t_0 \leq t \leq t_f$$

- Equivalent Lagrangian problem:

$$J = \int_{t_0}^{t_f} (h_{ref} - h(t))^q dt \quad q \gg 2 \text{ and even}$$
Altitude and Angle of Attack vs. Time for TPA and Optimal Recovery

\[ R = 3,000 \text{ ft} \]
\[ U_{\text{max}} = 80 \text{ ft/s} \]
\[ z_{\text{max}} = 150 \text{ ft} \]
Pitch Attitude and Airspeed vs. Time for TPA and Optimal Recovery

- Recovery at 17° Pitch Target
- Glideslope Tracking
- Escape Maneuver
- Optimal Escape Trajectory
Comparison of Trajectories

- Performance

<table>
<thead>
<tr>
<th>TPA Recovery</th>
<th>Optimal Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Altitude (ft)</td>
<td>403</td>
</tr>
<tr>
<td>Min. $E_s$ (ft)</td>
<td>596</td>
</tr>
<tr>
<td>Min. Airspeed (kts)</td>
<td>65</td>
</tr>
<tr>
<td>Max. Alpha (deg)</td>
<td>11.0</td>
</tr>
</tbody>
</table>

- Qualitative features
  
  Optimal trajectory involves initial reduction in pitch attitude
  
  Positive climb rate established earlier in optimal recovery
Conclusions

- Aircraft attitude for best climb rate depends on source of threat
- TPA simulation results - no single attitude stands out
- Optimal trajectory analysis - TPA not optimal, but reasonable
Computation of Optimal Trajectories

- Aircraft subject to two constraints:
  \[-20^\circ \leq \delta_E \leq 20^\circ\]
  \[V \geq 125\text{ knots}\]
- Airspeed constraint imposed using a penalty function:
  \[L(x,u) = L(x,u) + L_V(V)\]
  where
  \[L_V(V) = \begin{cases} 
  0 & V > V_{\text{min}} \\
  K_V [V - V_{\text{min}}]^2 & V \leq V_{\text{min}}
  \end{cases}\]
- Contribution of \(L_V\) to cost grows quadratically with magnitude of constraint violation
Altitude vs. Time for Optimal Paths through 4 Different Downbursts

- $U_{max} = 60$ ft/sec
- $U_{max} = 70$ ft/sec
- $U_{max} = 75$ ft/sec
- $U_{max} = 80$ ft/sec

Increasing $U_{max}$

Range from Core (ft)

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Rate of Climb vs. Time for Optimal Paths through 4 different Downbursts

Increasing $U_{max}$

- $U_{max} = 60$ ft/sec
- $U_{max} = 70$ ft/sec
- $U_{max} = 75$ ft/sec
- $U_{max} = 80$ ft/sec
Qualitative Features of the Optimal Flight Paths

- Rapid transition from descending to level or ascending flight
- Targeted rate of climb during escape depends on wind shear severity
  - Weak to moderate $\Rightarrow$ Aircraft reaches 5 ft/sec climb rate
  - Severe to very severe $\Rightarrow$ Aircraft reaches a lower climb rate
- Lower climb rate in severe microbursts results in reduced violation of minimum airspeed constraint

*OK, but...*

- Global knowledge of flowfield required for optimization
- Results not immediately applicable to real-time feedback control
Future Work:
Neural Networks for Real-Time Flight Guidance

- Train neural network with results of trajectory optimization
- Can parametrize microbursts according to size and severity
- Network generates flight path angle commands according to position within flow field
- Availability of forward-look information could assist in flight-path planning
Neural Networks for Aircraft Control

Benefits and Limitations of Trajectory Optimization

- Provides insight into the nature of control action required to most effectively achieve a specified goal
- Require global knowledge of microburst
- Optimal performance can only be approximated in real-time

Enter Neural Networks!

- Objective: Teach a neural network to fly an airplane through windshear using the results of trajectory optimization as training data
- Families of optimal trajectories through a broad spectrum of microbursts must be developed
- Robust optimization technique needed - cost functions weights themselves need to be optimized
DYNAMIC BEHAVIOUR OF AN AIRCRAFT ENCOUNTERING A SINGLE AXIS VORTEX

Darin R. Spilman

Princeton University
FLIGHT PATH

intended flight path

roll, yaw right

pitch attitude near vertical

Xr
Yr
xr
yr
z
WIND ROTOR MODEL

Vt : tangential velocity
Vc : core velocity
rc : core radius

0 < r/rc < 1: Vt/Vc = r/rc
1 < r/rc < 3: Vt/Vc = 1.15 - .15(r/rc)
3 < r/rc < 7: Vt/Vc = .88 - .06(r/rc)

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WIND EFFECTS ON AIRCRAFT

1. Equations of Motion

   Translational kinematics
   \[ \dot{r}_E = L_{EB} \vec{v}_B + \vec{w}_E \]

   Translational dynamics
   \[ \dot{v}_E = \frac{F_B}{m} - H^B_l g - \dot{w}_B v_B - \dot{w}_B \]

2. Force & Moment Coefficients

   \[ (C_{RL})_{ROLL} = (C_{RLP})p - (C_{RLP_{wing}} + C_{RLP_{htail}})w_y + (C_{RLP_{vtail}})v_z \]
CONCLUSIONS?

TBD
Wind Shear Related Research at Princeton University  
Questions and Answers

Unknown - I would like to comment that Rob’s work is independent of the accident investigation on the Colorado Springs accident which is still far from complete. We appreciate the efforts that they are doing, but you should not leave here with any conclusions based on it.

Rob Stengel (Princeton University) - No certainly and we have not made any conclusions either.
Session XI. Regulation, Certification and System Standards