A Status Report on Turbulence Warning Technology

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A Status and Progress Report on Turbulence Warning Technology

Briefing Outline

- The Turbulence Hazard
  - Sources of Turbulence
  - Accident Statistics
  - Accident/Injury Characteristics
  - Cabin Accelerations
  - Costs
- Turbulence Issues
- Approach to Risk/Injury Reduction
  - Cabin Procedures/Training - Cabin Design
  - Warnings
- Warning Issues
  - Existing Warnings
  - Advanced Time

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Briefing Outline (cont.)

• Remote Warning Technology
  • General Principles/Operating Concept
  • Radar
    • Hardware/Testbed Aircraft
    • Operating Parameters
    • Warning Display
    • Flight Test Summary
  • Lidar
    • Hardware/Testbed Aircraft
    • Operating Parameters
    • Flight Test Display
    • Flight Test Summary

• Warning Technology Summary

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Sources of Turbulence

- **Natural Turbulence**
  - Convective Induced
  - Mountain-wave Induced
  - Jet-stream Induced

- **Man-Made Turbulence**
  - Enroute Wake Vortex

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Turbulence Accident Trends

Turbulence Accidents per Million Flights US Carriers, Based on Part 121 Definition
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Serious/Fatal Turbulence Injury History

- Serious Injury
- Fatalities

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Aspects of Turbulence Accidents/Incidents

- Few commercial aviation fatalities (1 each 1987, 1990, 1997)
- Many serious **Flight Attendant** and Passenger injuries and numbers growing
  - Average 6-7 accidents and 8 serious injuries per year, 1980 to 1995
  - Sudden rise, 1995-2000 to 12 accidents and 16 serious injuries per year
  - 70 minor injuries for every serious injury (est.)
- Negligible aircraft damage and hull loss
- Numerous shallow but few data-rich accident/incidents
- Successful avoidance or mitigation of turbulence is heavily dependent upon information that is often:
  - Unavailable,
  - Inaccurate, or
  - Unreliable
Example of Severe Turbulence Encounter Cabin Acceleration

The cockpit saw this one 34 seconds before it happened; it injured 22 people.

Negative Gs lasted 3/8th seconds

5.5 seconds 2.6 ΔGs

1/2 second
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Turbulence Costs
(Difficult to quantify)

- One Airline’s Experience
  “…on an annual basis it (AA’s turbulence costs) is in the double-digit millions of dollars….last year we had 235 workers compensation claims related to turbulence encounters; those claims resulted in some 7,000 days of injury-related disability or lost time…the equivalent of 21 work-years at American alone.”

- 50% of injuries are to Flight Attendants
  - Average 10,000 lost workdays/year through 1994
  - Average 15,000 lost workdays/year since 1994
  - For each injury, 11 workdays lost (est.)

- Estimated >$ 100M yearly

- One carrier averages 9 turbulence encounters resulting in 24 injuries per month

- Leading cause of in-flight injuries

- Major contributor to passenger’s fear of flying

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Turbulence Issues

• Challenges
  • Characterization
    • Buildup & Decay cycle
    • Persistence
  • In-situ testing
    • Finding turbulence
    • Measurement standardization (Eddy Dissipation Rate /Cabin Acceleration)

• Understood
  • Injury-producing motion
    • Vertical Acceleration (-g most dangerous)
    • Rear cabin most susceptible
  • Protection strategy
    • Fasten seat belt!!!
    • Heed Crew Warnings
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Coordinated Approach to Turbulence Injury Risk Reduction

2002 2006 2010

TIME

Improved Forecasting
Crew Training
Cabin Procedures
Reduce Exposure

Cabin Design
Avoidance

Look-ahead Detection

New Controls Technology
Reduce Cabin Accelerations

Injury Risk Reduction

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An End-to-End Turbulence Warning System

- Detection Hardware
- Signal processing algorithm
- Turbulence hazard tables
- Turbulence Alert criteria
- Display/Alert

Significant Gust

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Current Turbulence Warnings

- **Forecasts**
  - Broad, non-specific location
  + Substantial work on-going and accuracy improving

- **Visual Cues**
  - Vicinity of Convective activity
  - Cirrus cloud patterns
    - Jet Stream boundaries
    - Mountain Waves

- **Pilot Reports**
  - Observing/Ownship Dependent
  - Subjective
  - Spotty Capture & Dissemination
  + Direct Experience
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The Question of Warning Time

- Turbulence Severity?
- New Air Traffic Rules
- Improved Cabin Procedures
- Turbulence Persistence?

Warning Time Requirement?

Projected Technology Capability

- Reliability
- Forecast/Nowcast

Time

30 Sec 1 Min 5 Min 10 Min 30 Min 1 hour

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General Principle of Doppler Radar/Lidar Turbulence Measurement

Relative wind induces a Doppler frequency shift in the backscattered light; this frequency shift is detected by the sensor.

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Doppler Radar/Lidar Operating Concept

Aircraft Skin
Laser Transceiver
Transmitted Beam

Doppler Shifted Backscattered Signal
Aerosols

Airspeed measured along this axis

Transmitted frequency
Backscattered frequency

\[
A = \lambda \Delta f \quad T = \Delta A = \lambda \delta f
\]

Note: At long ranges L is determined by pulse length. 
\(\delta f\) is an index of airspeed variation over length L.
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NASA Langley B757 Radar Testbed Aircraft

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Research Weather Radar

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g-Loading (rms g) Event 191- 06

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Radar Flight Test Summary

- 4 flights totaling 15 hours on NASA 757
- Flight Conditions Encountered
  5,000-30,000 ft MSL altitude operation
  Mostly clear, occasional clouds
  Encountered moderate to severe turbulence
  18 Convective Events
  1 Severe Event with - g’s
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NCAR Electra
Lidar Testbed Aircraft

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NASA Dryden DC-8 Lidar Testbed Aircraft

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Lidar on DC-8

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DC-8 Outside Periscope

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LIDAR Airspeed Results in Turbulence Encounter

- "Isolated" moderate turbulence region in light turbulence
- Detected ahead and observed as aircraft approached
- Moderate turbulence observed aboard aircraft (25 sec later)
- Aircraft traversed through turbulence and into smoother air

Sample Turbulence Encounter

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Lidar Flight Test Summary

- 5 flights totaling 15 hours on NCAR Electra
- Flight Conditions Encountered
  5,000-25,000 ft MSL altitude operation
  Mostly clear, occasional clouds
  Encountered light to moderate turbulence
    Mountain-wave-induced
    Convective
    Cloud/Virga

- 13 flights totaling 83 hours on NASA DC-8
- Flight Conditions Encountered
  - 24,000-39,000 ft MSL altitude operation
  - Mostly convective conditions, occasional dry air
  - Encountered light to severe turbulence in/out of cloud
Lidar Flight Test Summary (Cont.)

- Sensor readily capable of detecting light or stronger turbulence ahead of the aircraft
  - Measures apparent strength of turbulence as well as time to encounter
  - Positive correlation with on-board in-situ sensors
  - Range performance compares favorably with expectations
    - 4-6 miles for 11,000-15,000 ft MSL
    - 2 miles for 25,000-39,000 ft MSL and cloudless conditions
Turbulence Hazard Summary

- Turbulence is the leading cause of in-flight injuries and is estimated to cost the airline industry > $100M/year
- The turbulence hazard is not completely characterized from an atmospheric perspective but understanding is improving
- The approach to risk reduction includes cabin design, cabin procedures, improved forecasting as well as warning technology development
- Progress is being made with warning technology
  - Enhanced Weather Radar
    - Implemented with software change in existing Weather Radar sets
    - Most mature technology, Available 2-3 years
  - Lidar
    - Implemented with Lidar transceiver and signal processing hardware
    - Hardware integration an issue for existing fleet aircraft
    - Requires increased transmitted pulse energy
    - Available est. 5-7 years
Out-of-Scope “Turbulence”
Out-of-Scope “Turbulence” (cont.)