FAA Perspectives on Historical Wake Turbulence R&D to Recent Operational Implementations

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9th AIAA Atmospheric and Space Environments Conference,
Denver CO, June 3-9, 2017

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Acknowledgements – FAA Leadership Team

- Jeff Tittsworth
- Paul Strande
- Jillian Cheng
- Wayne Gallo
- Edward Johnson

Purpose

- A major intent of this presentation is to delineate why the many years of Wake Turbulence R&D are finally yielding beneficial operational implementations.
- Highlight lessons learned from past R&D.
- Going forward – NextGen and Beyond

Some Things to Keep in Mind

- Useful to note that wake turbulence separation minima is more than just the well known in-trail separation (FAA JO 7110.65W)
  - CSPR (Closely Spaced Parallel Runways)
  - Intersection Departures
  - Intersecting Runways
  - En-Route vertical separation (ICAO Doc 9574)
- Useful to recognize that in the terminal area, FAA has an unique culture of having both VFR and IFR flights
  - Wake separation minima is enforced on approach and at threshold crossings, under IFR
  - Visual approaches can be used in VMC, where pilots can assume wake avoidance responsibility
  - Wake separation minima is enforced when operating directly behind under VMC and IMC
  - However, wake solutions have been addressing both IFR and VFR operations

Highlights of Knowledge 1970-2000 (1/3)

- Sensors were developed to measure wake vortices in the airport environment, and with each sensor technology it leads to newer sensors and increasingly relevant knowledge[1,2]
- A wide array of sensors were designed and tested, but eventually three main sensor types became the work-horses at various times:
  - Anemometers (windline [3,4])
  - Acoustic systems (pulsed -- bistatic[5] and monostatic[6])
  - Lidar (CW[4,7] and pulsed[4,8])

Highlights of Knowledge 1970-2000 (2/3)

- Confirmed many fundamental theoretical frameworks such as initial circulation (weight, speed, wingspan relationship), transport[9], descent, rebound and vortex tilt[10]
- Recognized early from field measurements that vortices can at times last longer than separation standards[11]; therefore, the safety of a system does not solely rely on wake lifespan
- Established early on the sensitivity to atmospheric parameters[9]
- Determined departure vs arrival vortex behavior are essentially the same[12]

Highlights of Knowledge 1970-2000 (3/3)

- Introduced concept of $\Gamma[5\text{-}15]$ vs Γ total and a simple vortex model that later became known as the Burnham-Hallock model[13]
- Established rotorcraft wake characteristics – hover vs forward flight [14]
- Confirmed the onset of instability and breakup exists for OGE and NGE regions[15]
- Determined that vortices decay from the outside in (vorticity does not diffuse from inside out / high vs low Reynolds number influence)[16]
- Configuration effects[17]
- Proposed a range of wake severity metrics[18-19]

Prior to 2000 – R&D was Mostly R

- Historical Background: No Significant Operational Changes Benefitting the NAS Prior to 2000:
  - 30+ Years of R&D with most of that being R
  - Earlier efforts to change standards ineffectively coordinated between researchers and users/stakeholders
  - Separations overall got larger with increasing R&D [20]
    - "Add a Mile" for Small aircraft at threshold
  - However, resulting R&D yielded a safe system (when procedures and wake mitigation strategies were followed)

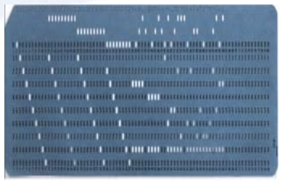
What Changed Over Time (1/4)

- Program Redirection (Since 2000)
  - Focused on operationally feasible solutions using well established Wake science to date
  - Focused R&D for each specific defined goal
  - Used phased approach – near, mid- to far-term goals
  - Developed airport specific solutions instead of "One Size Fits All"
  - Had insight that wake turbulence solutions to the National Airspace System (NAS) do not revolve solely on wakes from Heavy aircraft
  - Resulted on a steady evolution of solutions which increased in complexity and applicability as they were developed

What Changed Over Time (2/4)

- Advancements of Sensor and Information Technologies
  - 24 x 7 data collection
  - Statistically large amount of data collection now routine, including
    - Seasonal and diurnal effects
    - Aircraft ID details down to M/M/S
    - Detailed aircraft speed profiles [21]
  - Ability to collect a much rawer form of the data for subsequent post-processing and reprocessing
  - Ability to provide data-driven safety evidence
  - Entire flight region of interest for safety argument/consideration can be addressed via direct measurements
    - Arrival: From Stabilized Approach Point to Runway Threshold
    - Departure: From Rotation Point to Point of Divergence

What Changed Over Time (3/4) -- Evolution of Measurement Tools



1970s

1980s and 90s

2000+

Tower Visualization and Measurements

Aircraft Smoke Visualization

CW Lidar

Windline

Acoustic Radar – Bi-Static

Acoustic Radar – Mono-Static

Pulsed Lidar

FAA

NextGEN

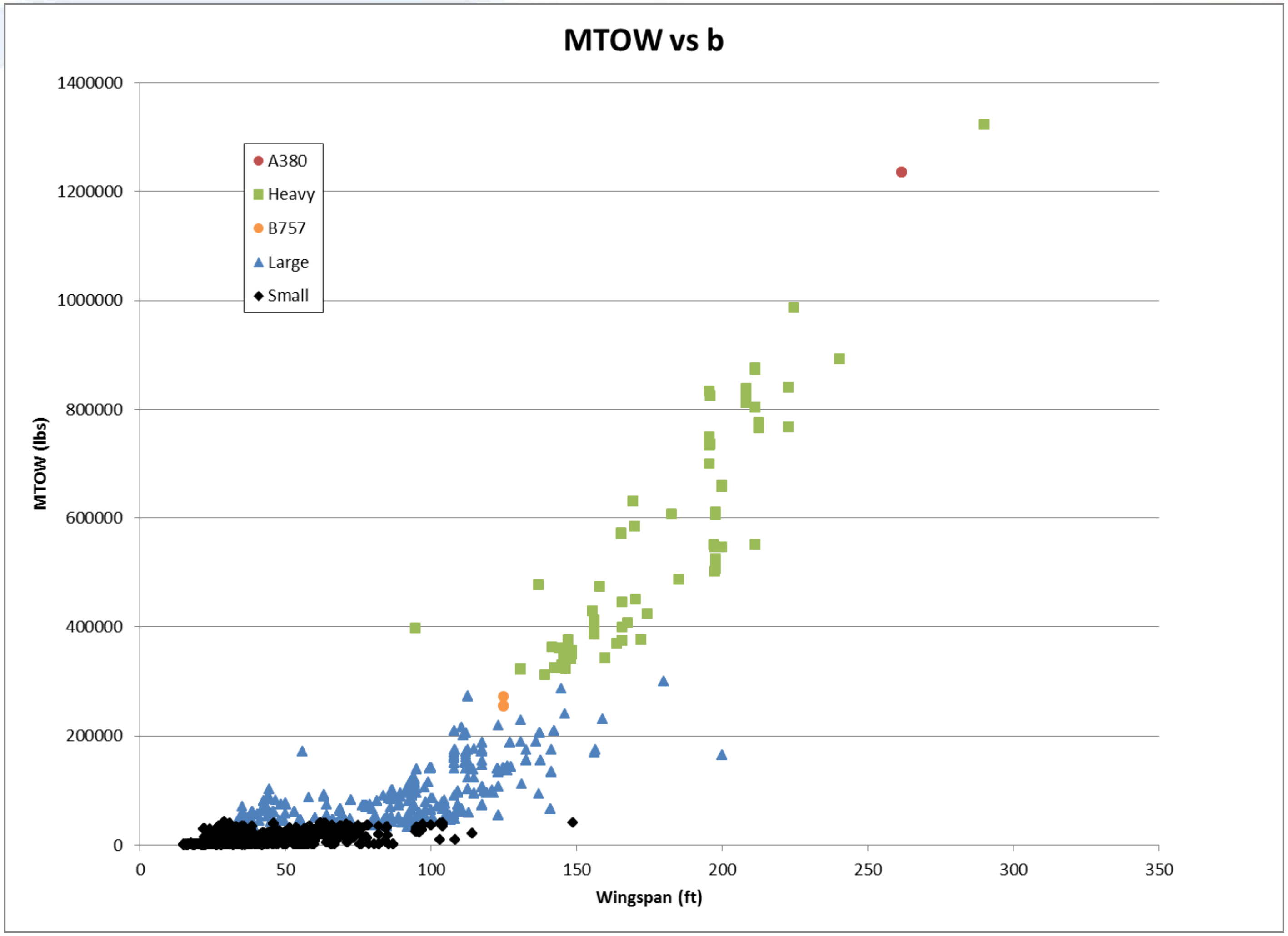
What Changed Over Time (4/4)

- Stakeholder and Intra-Agency and International Involvement
  - Intra-Agency: FAA NextGen, AFS, ATO, AOV, NATCA, ALPA, etc. all involved from the onset
  - International: for example, international WG established the process and method of evaluation for addressing A-388 and B-748 wake turbulence separation minima
  - Safety Management System (SMS) Process – provides a rational, documentable and repeatable safety assessment
  - Dedicated and frequent workshops for solicitation of end-user/stakeholder feedback

Separation Standards

- When the first wake turbulence separation standards were promulgated in 1970, the maximum certificated takeoff weight (MTOW) was used to form weight categories. Wingspan was acknowledged to be a better criterion, but its use was considered to be more complicated and MTOW was already in use by ATC.
- MTOW has served as a surrogate metric for both the wake turbulence severity generated by the lead aircraft as well as the wake encounter vulnerability of the trailing aircraft.

MTOW vs Wingspan



Recent Operational Implementations by the FAA

There are a number of recent operational implementations addressing the efficiency/capacity aspect of wake turbulence without compromising safety:[22]

- Dependent Staggered Approaches to Closely Spaced Parallel Runways with 1.5 NM Diagonal Minima
  - FAA Order JO 7110.308 Ch3 (later consolidated with WTMA-P and re-designated as JO 7110.308A)
- RECAT (Recategorization)
  - FAA Order JO 7110.659C (for RECAT I)
  - FAA Order JO 7110.123 (for RECAT II)
- WTMA-P (Wake Turbulence Mitigation for Arrivals)
  - FAA Order JO 7110.308A
- WTMD (Wake Turbulence Mitigation for Departures)
  - FAA Order JO 7110.316

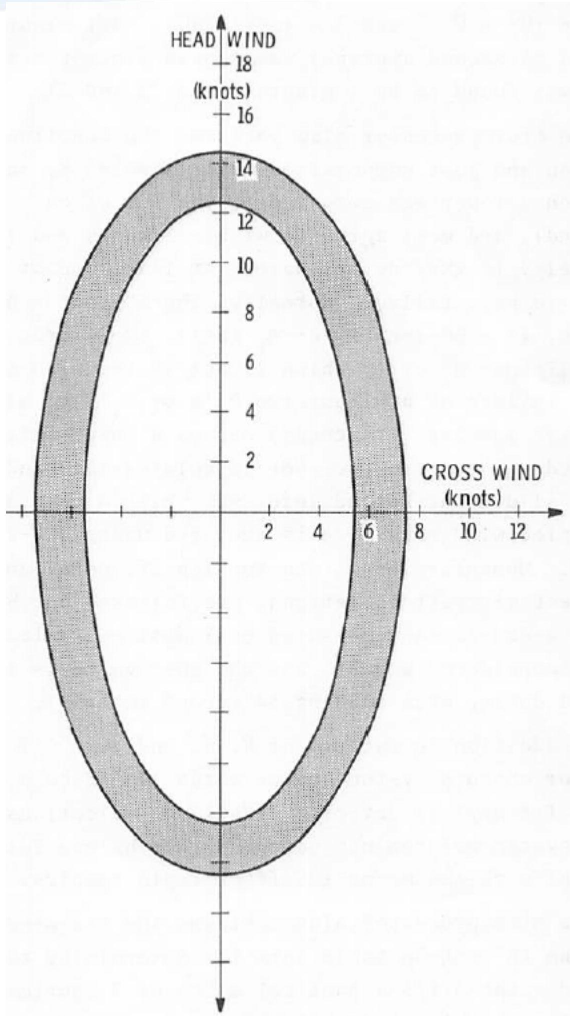
Design/Analysis

- RECAT – the design/analysis uses more than landing weight. In design, the lead aircraft is characterized by landing weight, wingspan and TAS at threshold and the following aircraft consideration included speed profile on approach, wake strength exposure and roll moment coefficient. [23]
- WTMA-P and WTMD – the designs/analyses use local wind and in WTMD, forecast wind.

Lessons Learned from R&D – VAS (1/2)

- The Vortex Advisory System (VAS) [24] was developed in the mid-1970s. It was a single-runway system that indicated when it was safe to reduce all wake separations for arrivals to 3 nm at the runway threshold. The algorithm was an ellipse with the semi-major axis of 12.5 knots in the headwind or runway orientation and a semi-minor axis of 5.5 knots in the crosswind orientation.

Vortex Advisory System Ellipse



Lessons Learned from R&D – VAS (2/2)

- A 2-knot guard band is employed to preclude rapid change of state.
- The VAS was rejected because of:
  - All stakeholders were not fully engaged from the start
  - Short duration of reduced separations (no forecast for availability and persistency)
  - Use in VMC would reduce capacity
  - Misinterpretation of events
- The SMS process could likely have resolved these issues.
- Wake systems developed recently and under development by the FAA include forecast as well as an extensive human factors element.

Lessons Learned from R&D – B-757 (1/3)

- Flight tests in Idaho Falls (1990) of aircraft flying past an instrumented tower [25] led to incorrect operationally relevant results.
- The B-757 was in landing configuration but flew past the tower at constant altitude. The data yielded vortices with very high core-edge tangential velocities. In addition, the attendant weather conditions were not representative of an airport operational environment.
- Regardless, the high tangential velocity results were publicized more so than the circulation, even though circulation behavior was consistent with the B-757 weight and wingspan.

Lessons Learned from R&D – B-757 (2/3)

- However, B-757's measured tangential velocities as well as circulation history when on a 3-degree glideslope yielded different results – the B-757 behaved similar to other Large aircraft at the time (i.e., B-727 and the lighter variant of the DC-8).
- Regardless, the B-757 was labeled a special aircraft needing special treatment.
- The accidents that occurred behind the B-757 were in VFR and the B-757 was flying higher than a normal 3-degree approach and the trailing aircraft were inside of 2.5 nm in trail and below the glide path of the B-757.
- After many years (proper analysis of airport measurements from 1999 to 2015), the additional separation behind the B-757 has been slowly reduced toward that used today behind other Large aircraft.

Lessons Learned from R&D – B-757 (3/3)

- Two major lessons: (1) The key is to collect data in as close to the operational configuration and conditions as possible. (2) The relevant safety metric is important.
- The NTSB recommended [26] that future turbojet*, transport category aircraft should be assessed for wake turbulence characteristics during certification. The FAA pointed out that the wake characteristics are not a certification issue but are now part of analysis prior to aircraft entry into service.
- These lessons learned were carried over to the design of recent international efforts (A-388 and B-748 flight test assessments), as well as smaller wake generators.

* In the FAA vernacular "Turbojet" essentially means gas turbine engines (which includes turbojets and turbofans)

Going Forward (Partial Topics)

- RECAT Phase III (dynamic pairwise separations)
- CSPO enabled concepts
- Efforts to assess wake turbulence risk (i.e., frequency and severity of encounters) in a more absolute framework
  - Progress made to date is in a relative safety framework -- new procedures and systems need to be as safe as an existing system/procedure that has extensive operational experience
- ADS-B enabled weather messages for wake turbulence (ADS-Wx), such as wind, turbulence and stratification
- En-route wake turbulence mitigation

Closing Comments (1/2)

- Wake turbulence is a rich subject that involves multiple disciplines: fluid mechanics, meteorology, flight mechanics/applied aerodynamics, instrumentation, remote sensing, human factors, etc. However, one must keep in mind that it is fundamentally an ATC/transportation and aviation safety and capacity problem.
- Even though it is a transportation problem, it still has a technical component whose current success is partially based on the collective progress over the years of researchers such as those from the AIAA community.

Closing Comments (2/2)

- Wake Turbulence solutions are not solely a US or EU or other regional concern, rather a Global Aviation concern
- For the Global Success / Impact
  - **Manufacturers** have a role in providing aircraft performance data
  - **Airlines and other Operators** have a role in describing the importance of an operational change and acting as an advocate
  - **Regulators** have the role of assessing the safety of a proposed change
  - **ANSPs** have the role of implementation of the proposed change in an acceptably safe manner
  - **Researchers** have a role in developing proposed changes that are operationally achievable, and responsive to the technical needs of the aviation authority

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Common Error: FAA test – Not NASA