Sonic Boom Prediction and Measurement Analysis Methods for Certification of Quiet Supersonic Aircraft

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Industry is pursuing civil supersonic products

Two regulatory issues for civil supersonic flight: limiting terminal noise during subsonic flight and sonic boom during supersonic flight

For sonic boom, formulating an international standard for low-boom capable, supersonic designs to potentially amend ban on civil supersonic overland flight worldwide

- Noise-based certification standard for supersonic en route (sonic boom) noise
- Standard would include noise metric, test procedures, and noise limits

NASA is building the X-59 QueSST low-boom demonstrator to support standards development

- Prediction tool validation for shaped booms
- Community response testing
Overview of International Standards Development

- **International Civil Aviation Organization (ICAO)**
  - Works through Committee on Aviation Environmental Protection to create global harmonized aviation environmental standards (e.g., aircraft noise and emissions)
  - Standards and Recommended Practices (SARP) are developed in working groups
  - Working group members include national aviation authorities, international non-governmental orgs, regional state orgs, subject matter experts
  - Structured process to review and propose SARPs for adoption by ICAO

- **Concept of fairness (“level playing field”)**
  - Reference day atmosphere adjustments
  - Already implemented for subsonic aircraft noise standard

- **Other necessary criteria**
  - Robust and repeatable
  - Easily implemented and cost effective
Notional Certification Procedure

- Reference Procedure Must Characterize Noise Performance at Reference Conditions

**Notional Certification Procedure Steps**

1. Predictions to plan flight test
2. Test measurements
3. Test day predictions
4. Validation or comparison of measurements and predictions
5. Reference day adjustment
6. Calculate cert level and compare to limit
Develop procedures using existing measured (N-wave) sonic boom data

- Procedures will be tested with X-59 data when available

NASA SonicBAT summary

- Flight test procedure:
  - Fly F-18 at Mach 1.4 at 10.4 km over microphone array through various levels of atmospheric turbulence (July 11-22, 2016)
  - 20 flights (69 passes) at Edwards AFB, CA
- Flight test goal:
  - Understand turbulence effects on ground measurements of sonic booms
  - Turbulence effects model validation
- Use low-turbulence data from this test
Analyses of Measured Data

- Develop procedures using existing measured (N-wave) sonic boom data
- Distribution of measured data (N=106)
  - Distributions vary by metric and by pass

Six metrics under consideration
Alternate statistical representations of data

Empirical Cumulative Distribution Function

- 78% of data at or below 100 dB

Box Plot

All Passes

Analyses of Measured Data
Analysis of Aggregate or Individual Measurements

- All 6 passes combined (N=106)
  - Standard deviation of 1.1 dB

- Calculations conducted for each separate pass (N=17)
Distributions vary by pass

- Meteorological conditions
- Flight conditions
  - Mach number, altitude, trajectory, weight
- Amount of variation also depends on metric
Boom Propagation Predictions

- **Propagation methods**
  - Ray tracing
  - Implement the nonlinear wave equation
    - Nonlinearity, absorption/dispersion, geometrical spreading

- **Inputs**
  - F-18 nearfield pressure from CFD
  - Measured F-18 trajectory
    - Altitude, heading, lat/lon, Mach, derivatives
  - Measured atmospheric profile from weather balloon
    - Temperature, relative humidity, and winds as a function of altitude
    - One profile per flight

- **Output**
  - Ray landing positions closest to microphone array
  - Ground waveforms at these positions
Can a single ray represent the microphone array?

- Propagation predictions completed for a set of ground intersection points bounding the microphone array
- For a single stratified atmosphere without turbulence, differences in modeled PL at these points are ≤0.04 dB

<table>
<thead>
<tr>
<th>Δt</th>
<th>ΔPL across predictions</th>
<th>φ = 0°</th>
<th>φ = −1°</th>
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</thead>
<tbody>
<tr>
<td>−1.0 sec.</td>
<td>+0.00 dB</td>
<td>+0.00 dB</td>
<td></td>
</tr>
<tr>
<td>−0.5 sec.</td>
<td>−0.01 dB</td>
<td>−0.02 dB</td>
<td></td>
</tr>
<tr>
<td>T_{AC} = 56660.0 sec.</td>
<td><strong>106.32 dB</strong></td>
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<tr>
<td>+0.5 sec.</td>
<td>−0.01 dB</td>
<td>−0.03 dB</td>
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</tbody>
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Comparing Predictions and Measurements

- Certification procedure will include both measurements and predictions
  - Helpful to investigate both with N-wave dataset
- Test day predictions for N-wave signatures without atmospheric turbulence effects show much less variation than measurements
- Comparisons and adjustments to reference conditions are larger than preferred
- Hence this may require statistical approach
Comparing Predictions and Measurements

- Potential need to include turbulence in predictions
  - Propagation through many realizations of turbulence based on measured meteorological parameters
  - Ground boom variability is increased and approaches that of measured data
  - Increasing the turbulence level lowers the mean metric value

[Graphs showing ECDF of PL (dB) vs. ABL thickness ($h_{ABL}$) and Turbulence intensity ($\sigma_v$)]
Recognize that there is a large variability in test data for N-wave noise
- Shaped booms predicted to have smaller variation\(^1\), but there will still be some variation

Whether to compare individual measurement points, passes, or in aggregate

What is an acceptable level of disagreement or adjustment to reference conditions?
- For subsonic aircraft, 14 CFR Part 36 sets minimum sample sizes and associated confidence intervals, establishes a window on temperature, relative humidity, wind/crosswind velocities, and requires “No anomalous meteorological or wind conditions that would significantly affect the measured noise levels…”

How many microphones and passes are needed?
- Do we need predictions at each microphone location?
- Recognize that procedure needs to be simple and cost-effective

How might we consider refining our approach? How might scatter be reduced?
- Introduce test day meteorological limits
- ANOVA and other statistical tests

Summary

- **Existing dataset being used to exercise proposed certification procedure methods**
  - Real-world data presents challenges due to variability, even in “low-turbulence” conditions
  - Limited dataset with only two flights of an N-wave aircraft configuration
  - Will be able to exercise procedure methods with X-59 test data when available

- **It is not reasonable to expect very close agreement between predicted noise levels and measured ground data**
  - More work required to compare data statistically
  - May have to account for atmospheric turbulence effects in predictions