Quantification of Acoustic Scattering Prediction Uncertainty for Aircraft System Noise Assessment

Casey L. Burley, Russell H. Thomas
NASA Langley Research Center, Hampton, VA, USA
And
Yueping Guo
NEAT Consulting
Seal Beach, CA, USA

22nd AIAA/CEAS Aeroacoustics Conference
Lyon, France
June 1, 2016
AIAA Paper 2016-3041
Acknowledgement

The authors would like to thank

• The NASA Environmentally Responsible Aviation Project for funding this work
Outline

• Background and Motivation
  • ERA N+2 Vehicle Concepts
  • Assessment Objective
  • System Noise Assessment

• Acoustic Scattering Prediction: PAA-effect

• Quantification of Prediction Uncertainty
  • Reference data prediction test method
  • Results for system noise assessment

• Concluding Remarks
### ERA Project Goal

The ERA Project’s goal is to identify and mature technologies and advanced configurations that, when integrated, can simultaneously meet the N+2 noise, LTO NOx, and fuel burn reduction metrics.

### NASA Subsonic Transport Metrics

<table>
<thead>
<tr>
<th>TECHNOLOGY BENEFITS*</th>
<th>TECHNOLOGY GENERATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Technology Readiness Level = 4-6)</td>
</tr>
<tr>
<td>Noise (cum margin rel. to Stage 4)</td>
<td>-32 dB</td>
</tr>
<tr>
<td>LTO NOx Emissions (rel. to CAEP 6)</td>
<td>-60%</td>
</tr>
<tr>
<td>Cruise NOx Emissions (rel. to 2005 best in class)</td>
<td>-55%</td>
</tr>
<tr>
<td>Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)</td>
<td>-33%</td>
</tr>
</tbody>
</table>

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines.

** ERA’s time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015.

‡ CO2 emission benefits dependent on life-cycle CO2e per MJ for fuel and/or energy source used.
Noise Certification Measurement Points

- Lateral (Sideline) reference
- Flyover with Cutback
- Approach

Flight operation/trajectory simulation
Source noise modeling

Noise propagation to observers (accounting for spreading, atmospheric and lateral attenuation, ground effects, reflections)

Ground observer noise time history of PNLT metric (Frequency integration for each observer time accounting for tonal content with amplitude penalties)

PNLT = tone corrected perceived noise level

Effective Perceived Noise Level: EPNL

Time integration to Effective Perceived Noise Level: EPNL
ERA System Noise Prediction Process

ANOPP2

Aircraft Flight Definition

Source Noise (ANOPP-L31v3)
- Jet: Stone (ST2JET + AOA correction)
- Core: SAE (GECOR)
- Fan: modified Heidmann (HDNFAN-Krejsa), (ACD:GTF-measured)
- Duct Treatment: modified GE method (TREAT)
- Landing gear (nose & main): (Guo-LG)
- Flap-side-edge: Boeing (BAF-Flap)
- Leading edge (Krueger): (Guo-Krueger)
- Trailing edge: Fink (FNKAFM)

PAA Effects: engine noise installation effects (shielding, reflections) (GENSUP)

ITD noise technology: reduction through suppression of specific source noise (fan, gear, flap, Krueger) (GENSUP)

Flight profiles that meet CFR 36 Aircraft geometries

FLOPS MVL-aero

- Low speed aero (ITD 51A)
- Engine operating limits
- Airframe geometric definition
- Aircraft weights

Engine states and geometric parameters

NPSS

ITD 35A: Soft Vane fan noise reduction
- GTF source fan noise and ‘effects’ data for cut-off, bifurcation, sweep & lean, rotor-stator-spacing

ITD 50A: Flap side edge noise suppression data for RJ & 3.0 dB suppression for all other vehicles
- Partial main gear noise suppression data for all vehicles

Propagation

Noise Metrics

Propulsion/Airframe Aeroacoustic (PAA) Effects Prediction:
- 14x22 N2A data (Phase I)
- LSAF PAA data (Phase I)

EPNL predicted at locations defined by Code of Federal Regulations (CFR) Title 14 Part 36
Vehicle Assessment – Advanced N+2 (2025)  
Large Twin-Aisle Concepts

<table>
<thead>
<tr>
<th></th>
<th>T+W301-GTF</th>
<th>MFN301-GTF</th>
<th>HWB301-GTF</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOGW (lbs)</td>
<td>570,533</td>
<td>540,837</td>
<td>534,491</td>
</tr>
<tr>
<td>Payload (lbs)</td>
<td>118,100</td>
<td>118,100</td>
<td>118,100</td>
</tr>
<tr>
<td>Design Range (nm)</td>
<td>7500</td>
<td>7500</td>
<td>7500</td>
</tr>
</tbody>
</table>

Same mission, different configuration and aero-performance
Aircraft Cumulative Noise Results

N+2 includes:
- UHB GTF or DD engines
- Light weight structures
- Single element trailing edge flap
- Leading edge Krueger flap
- Configuration dependent PAA effects
- Multi-degree of freedom duct liners (MDOF)

Integrated Technology Demonstration Noise Reduction (ITDNR) adds:
- Soft Vane (SV)
- Flap Side Edge Treatment (FSET)
- Partial Main Gear Fairing (PMGF)

ITDNR combined 0.9 to 2.5 dB noise reduction

N+2 includes:
- UHB GTF or DD engines
- Light weight structures
- Single element trailing edge flap
- Leading edge Krueger flap
- Configuration dependent PAA effects
- Multi-degree of freedom duct liners (MDOF)

Integrated Technology Demonstration Noise Reduction (ITDNR) adds:
- Soft Vane (SV)
- Flap Side Edge Treatment (FSET)
- Partial Main Gear Fairing (PMGF)

ITDNR combined 0.9 to 2.5 dB noise reduction

42 dB Goal

N+2
N+2 w/ITDNR

Quieter

CUM EPNL Below Stage 4

T+W301
MFN301
HWB301

19.8
22.1
31.4
38.4
33.9
38.4
40.3

T+W301
MFN301
HWB301

18.2 dB quieter

11.8 dB quieter

42 dB Goal

T+W301

18.2 dB quieter

11.8 dB quieter

42 dB Goal
Acoustic Scattering Prediction of Propulsion Airframe Aeroacoustic (PAA) Interaction Effects

- Multi-parameter analysis of the most closely matched datasets coupled with theoretical analysis, computational and analytical modeling.

- Datasets
  - LSAF and 14x22 aeroacoustic test campaigns
  - HWB and conventional tube-and-wing configurations with variations in source noise definition: distributed and point broadband sources, jet
  - Operational parameters defined for approach and takeoff conditions
  - Acoustic data as function of configuration, power condition, frequency and both polar & azimuthal directivity.

- Computational and analytical modeling
  - Account for effects not fully represented in the datasets such as reflections from horizontal tails, or specific full aircraft configurations with multiple engines
  - Extend frequency and directivity angle definitions to required full-scale ranges
Shielding Characteristics

• Angular zones
  – Insonified: slight noise increase due to edge diffraction
  – Partially insonified: noise reduction by half of the direct radiation but slight increase due to diffraction
  – Shadow: no direct radiation and diffraction as noise floor

• Boundaries of angular zones predicted by geometry and vary with engine/wing configuration

• Diffraction amplitudes determined by source/edge distance and frequency
Noise Scattering Map Prediction

![Diagram of noise scattering map prediction with various angles and frequency levels.

ΔSPL, dB

- Noise increase
- Noise decrease

[Legend showing different color codes for ΔSPL values from -13 to 3 dB.]

[Graph showing log frequency (Hz) vs. θ (Degrees), with marked angles of 57°, 108°, 135°, and 153°.]
• Modification to engine source noise components
  - “Suppression/Attenuation”

\[
S(f, \theta, \phi) = \frac{P_{rms}^2(f, \theta, \phi)_{shielded}}{P_{rms}^2(f, \theta, \phi)_{unshielded}} = 10^{(\Delta dB / 10)}
\]

• Applied to engine source noise to account for installation effects due to
  • Shielding / reflection from airframe
  • Modification of source level and directivity due to change in flow field from free stream

Shielding is dependent on noise source characteristics and directivity, source/airframe positioning, airframe shape, control surface deflection, and frequency
• Companion paper presents framework and process for establishing aircraft noise prediction uncertainty

• The uncertainty on EPNL prediction is computed in a direct Monte Carlo process
  • 10,000 EPNL simulations: \( \text{EPNL}_i = f(\text{prediction element}_i) \)
  • Source prediction elements: Engine (fan, jet, etc.), airframe (gear, etc.), PAA-effects

• New uncertainty framework/process outlines four methods for determination of prediction element uncertainty
  I. Reference data prediction test method
  II. Formulation method
  III. Fixed by aircraft level method
  IV. Inferred method

• Reference data prediction test method: “Reference Dataset” hierarchy
  1. Full-scale, full-fidelity aircraft flight data
  2. Model-scale, higher fidelity integrated system experimental data
  3. Model-scale, high fidelity sub-system experimental data
  4. Isolated component experimental data
Full-Scale Propulsion Airframe Aeroacoustic (PAA)  
“Reference Dataset”

PAA integration effects from a similar engine installed on similar sized but different aircraft configurations – likely PAA effects are acoustic shielding by wing and fuselage for tail mount while the under-wing mounting increases noise from reflection and jet-flap interaction (Ron Olsen, Boeing)

<table>
<thead>
<tr>
<th>Boeing MD-90-30</th>
<th>Airbus A319-133</th>
<th>(relative to MD-90-30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine IAE 2528-D5</td>
<td>Engine IAE 2527M-A5</td>
<td></td>
</tr>
<tr>
<td>Thrust (lbs) 28,000</td>
<td>Thrust (lbs) 26,500</td>
<td>−1,500 lbs</td>
</tr>
<tr>
<td>MTOW (lbs) 166,000</td>
<td>MTOW (lbs) 166,400</td>
<td>+400 lbs</td>
</tr>
<tr>
<td>MLW (lbs) 142,000</td>
<td>MLW (lbs) 137,800</td>
<td>−4,200 lbs</td>
</tr>
</tbody>
</table>

**Noise Certification (EPNdB):**

<table>
<thead>
<tr>
<th>Boeing MD-90-30</th>
<th>Airbus A319-133</th>
<th>(relative to MD-90-30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach 91.9</td>
<td>Approach 94.4</td>
<td>+2.5</td>
</tr>
<tr>
<td>Lateral 91.0</td>
<td>Lateral 92.5</td>
<td>+1.5</td>
</tr>
<tr>
<td>Flyover 82.6</td>
<td>Flyover 84.2</td>
<td>+1.6</td>
</tr>
</tbody>
</table>

Cumulative Margin Relative to Stage 3 = −23.5 EPNdB

Cumulative Margin Relative to Stage 3 = −17.9 EPNdB

Data from www.faa.gov and ICAO noisedb website
Certification Noise Margins Relative to Stage 3

- Noise certification data (ref. EASA (European Aviation Safety Agency))
- Nearly linear function with Max Takeoff Weight
- Difference in EPNL invariant with MTOW

**Approach**

- Stage 3 Margin, EPNdB
- Max Takeoff Weight, 1000lbs
- 2.5 EPNdB

**Lateral**

- Stage 3 Margin, EPNdB
- Max Takeoff Weight, 1000lbs
- 1.5 EPNdB

**Flyover**

- Stage 3 Margin, EPNdB
- Max Takeoff Weight, 1000lbs
- 1.6 EPNdB
PAA-Effect Prediction Uncertainty Process

• Simulate configurations of MD-90-30 and A319-133 with NASA model of 737-800 with CFM56 engines

<table>
<thead>
<tr>
<th></th>
<th>Boeing MD-90-30</th>
<th>Airbus A319-133</th>
<th>Boeing 737-800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine/airframe</td>
<td>Empennage-mounted</td>
<td>Under-the-wing</td>
<td>Under-the-wing</td>
</tr>
<tr>
<td>Configuration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine</td>
<td>IAE 2528-D5</td>
<td>IAE 2527M-A5</td>
<td>CFM56-7B</td>
</tr>
<tr>
<td>Thrust</td>
<td>28,000</td>
<td>26,500</td>
<td>26,000</td>
</tr>
<tr>
<td>BPR</td>
<td>4.8</td>
<td>4.7</td>
<td>5.2</td>
</tr>
<tr>
<td>MTOW (lbs)</td>
<td>166,000</td>
<td>166,400</td>
<td>174,000</td>
</tr>
</tbody>
</table>

• Predict PAA-effect for the both configurations
  • Broadband engine noise scattering
  • Jet noise scattering

• Compare difference in EPNL at each certification noise point to Reference Dataset differences

• Match Reference Dataset result by “adjusting” PAA-effect prediction
Noise Simulations of PAA Configurations

- Engine represented by NPSS NASA model of CFM56-7B
- Airframe and certification flight path determined from FLOPS aero-performance analysis of NASA 737-800 like aircraft
- Noise Scattering (PAA-effect) Prediction

**Under-the-wing**
- Aft engine sources: wing reflection
- Jet: reflected from wing
- Observers directly in sight of both engines

**Empennage-mounted**
- Inlet engine sources: wing shielding
- Jet: reflected from horizontal tail
- Sideline observers: one engine shielded, but engine noise reflected from fuselage
### Prediction Compared to Reference Dataset

<table>
<thead>
<tr>
<th></th>
<th>Under-the-wing engine</th>
<th>Empennage-mounted engine</th>
<th>ΔEPNL Prediction</th>
<th>ΔEPNL Reference Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Approach</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(EPNdB)</td>
<td>96.4</td>
<td>94.8</td>
<td>1.6</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Lateral</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(EPNdB)</td>
<td>95.1</td>
<td>91.4</td>
<td>3.7</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Flyover</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(EPNdB)</td>
<td>86.3</td>
<td>85.5</td>
<td>0.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>

- Discrepancy between ΔEPNL results from prediction and Reference Dataset is indirect measure of prediction uncertainty
  - Approach and Flyover: *underprediction* of shielding effect
  - Lateral: *overpredict* noise shielding
Noise Scattering Prediction Map Adjustment ($\Delta$SPL, dB)

- Engine noise scattering prediction uncertainty
  - Dependent on engine source, geometry, flight condition & data available
    - Representative jet source: nozzle geometries, flow and cycle conditions
    - Turbomachinery (broadband) source: representative nacelle with ‘impinging-jet’ source

- Empennage-mounted engine configuration PAA-effect prediction adjusted
  - Uniformly applied spectrally at each polar and azimuthal directivity angle
    - Lateral: reduced “shielding” effect
    - Approach and Flyover: increased “shielding” effect

<table>
<thead>
<tr>
<th>Engine Source/ PAA map source</th>
<th>Approach</th>
<th>Lateral</th>
<th>Flyover</th>
</tr>
</thead>
<tbody>
<tr>
<td>fan &amp; core / Broadband (dB)</td>
<td>-1.0</td>
<td>+3.3</td>
<td>-1.5</td>
</tr>
<tr>
<td>Jet / Jet (dB)</td>
<td>0.0</td>
<td>+1.5</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Predicted PNLT and EPNL
With Adjusted Noise Scattering Maps

Under-the-wing engines

Lateral
ΔEPNdB=1.5

Empennage-mounted engines

Flyover
ΔEPNdB=1.6
Acoustic Scattering Prediction Uncertainty

- Established through deductive inference and additional considerations

- If Reference Dataset quantifies the PAA-effect between aircraft configurations
- And the PAA-effect difference can be computed through simulation whereby only change is the engine noise scattering prediction
- Then the discrepancy between results from Reference Dataset and simulation is measure of prediction uncertainty

- Additional considerations include fidelity of PAA-effect prediction method datasets and modeling, and their range of validity for vehicles in flight

<table>
<thead>
<tr>
<th>Engine Source/ PAA map source</th>
<th>95% Confidence Level</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan &amp; Core / Broadband (dB)</td>
<td>± 4</td>
<td>2</td>
</tr>
<tr>
<td>Jet / Jet (dB)</td>
<td>± 2</td>
<td>1</td>
</tr>
</tbody>
</table>
Concluding Remarks

• Described a process to quantify the uncertainty of the “acoustic scattering prediction element” utilized in full-scale, full-fidelity aircraft system noise simulations

• Scattering prediction element uncertainty quantified using the “Reference data prediction test method” with full-scale, full-fidelity aircraft flight data

• Quantification of the “acoustic scattering prediction element” is a valuable contribution to establishing aircraft noise prediction uncertainty for both conventional and unconventional configurations.

• Acoustic scattering prediction uncertainty can be improved, particularly for installed turbomachinery sources, through dedicated campaigns:
  • Higher fidelity flight acoustic “Reference Dataset”
  • Large-scale wind tunnel PAA tests with representative source
  • Development and validation of physics-based computational methods