Analytical Approach for Quantifying Noise from Advanced Operational Procedures

Jacqueline Thomas  
thomasj1@mit.edu

Professor John Hansman  
rjhans@mit.edu

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Motivation

- Significant reductions in population exposure to airport noise have been made over the past 25 years
  - Reduced engine noise
  - Noise abatement procedures
- Further noise footprint reduction may be possible through operational adjustments

Note: 65db DNL is FAA’s designation of significant noise exposure.

Source: Massport
Potential for Continued Noise Improvements

- **Advanced operational departure procedures**
  - Flight path adjustments
  - Derated takeoff thrust
  - Thrust cutback scheduling

- **Advanced operational approach procedures**
  - Continuous descent/steep approaches
  - Delayed deceleration approaches
  - RNAV/RNP approach trajectories

- **New Aircraft Configurations**
  - Cleaner Airframes
  - Engine Noise Shielding Effects

*Figure: The Orange County Register*

*Figure: D8 Aircraft Concept, from NASA.gov*
Project Goal

- Current industry standard noise analysis methods do not fully capture noise impacts from aircraft configuration or other operational techniques.
- Traditional aircraft noise analysis assumes that engine noise dominates aerodynamic noise.
  - Assumption may have been valid for earlier generation jet engines.

Project Goal: to expand analysis capabilities to enable the modeling the noise impacts of advanced operational procedures and aircraft configuration.
Current Analysis Methods: Aircraft Environmental Design Tool (AEDT)

- Industry standard model that evaluates aircraft noise impacts in the vicinity of airports
  - Normally used for DNL analysis
- Simple physics model
  - Low resolution
    - Not intended for high-fidelity single event modeling
  - Considers “Average Annual Day”
  - Assumes consistent sound energy dissipation with distance
  - Only considers atmospheric noise propagation
  - Does not capture shielding effects well
- Noise-Power-Distance (NPD) based

Figure: INM Technical Manual
Noise-Power-Distance Approach

- Single-event noise exposure calculated for each arrival/departure segment
- Requires thrust and distance interpolation from limited flight test data
- Crude accounting for different flap, landing gear settings
  - High-power approach curves assume dirty landing configuration
  - Ignores velocity effects on aerodynamic noise

![Noise Power Distance (NPD) Curves GE CF6-50 (Airbus A300)](image)

- Sound Exposure Level (dBA)
- Distance from Source (feet)

- 40,000lb Departure
- 25,000lb Departure
- 10,000lb Arrival
- 25,000lb Arrival
TASOPT and ANOPP Noise Modeling Approach

Transport Aircraft System OPTimization (TASOPT)

- Written by Prof. Mark Drela (MIT)
- Physics-based optimization program
- Based on mission requirements, generates an optimal transport aircraft design, including:
  - Engine performance and geometry
  - Aircraft performance and geometry

Aircraft NOise Prediction Program (ANOPP)

- NASA-developed program
- Computes far-field engine and airframe noise at an observer grid given various flight profile and configuration metrics
  - Semi-empirical calculations require detailed engine/aircraft performance inputs
    - e.g., Engine mass flow, areas, and temperatures, airframe geometry, etc.
- Models shielding, propagation effects
TASOPT - ANOPP Noise Analysis Framework

**TASOPT Inputs:**
- Operating/mission parameters
- Aircraft sizing/performance parameters
- Engine sizing/performance parameters

**TASOPT Outputs:**
- Aircraft/engine performance & geometry

**Flight Procedure Type:**
- Flight Path Angles
- Velocity
- Configuration

**Flight Procedure:**
- Thrust, velocity, position, gear/flap settings per time

**ANOPP Control Inputs:**
- Propagation settings
- Observer locations

*Flight Procedure Generator* a force-balance model to determine required thrust levels given:
- User flight profile requirements
- TASOPT aircraft performance characteristics

**ANOPP Outputs:**
- Noise contours for each observer location
Noise Certification Data
Comparison Overview

- Effective Perceived Noise Level (EPNL) of known aircraft computed in ANOPP
  - Results compared to FAA certification noise data (reported in 14 CFR Part 36) for those aircraft for validation
- EPNL reported at 3 observer locations: Flyover, Approach and Sideline
- Flight profile requirements:
  - Flyover:
    - **Thrust:** Max TO to altitude 300m, then reduced to maintain 4% climb grad
    - **Velocity:** V2+10kt to V2+20kt
  - Approach:
    - **Thrust:** required to maintain 3° glide slope
    - **Velocity:** Vref+10kt
  - Sideline:
    - **Thrust:** Max TO
    - **Velocity:** V2+10kt to V2+20kt
**Current Validation Results**

- *Sideline noise error likely due to jet exhaust temperature over-prediction in TASOPT (required input for the ANOPP jet noise calculation) for max thrust conditions
- Calculated sideline noise error is reduced to within +/- 1 dB EPNL for each aircraft with an 8% reduction in TASOPT outputted jet exhaust temperatures

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>TO/AP Wt:</th>
<th>Engine:</th>
<th>ANOPP Calculated Effective Perceived Noise Levels (dB)</th>
<th>FAA Certification Noise Data (dB)</th>
<th>Error (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boeing 737-800</td>
<td>172300/146300 lbs</td>
<td>CFM56-7B26</td>
<td>Flyover: 87, Approach: 96.11, Sideline*: 97.61</td>
<td>86.7, 96.8</td>
<td>+0.3, -0.69</td>
</tr>
<tr>
<td>Boeing 777-300</td>
<td>636100/524000 lbs</td>
<td>RR Trent 892</td>
<td>Flyover: 94.87, Approach: 101.3, Sideline*: 99.88</td>
<td>94.2, 100.4</td>
<td>+0.61, +0.9</td>
</tr>
<tr>
<td>Embraer 195</td>
<td>111970/99200 lbs</td>
<td>CF34-10E5</td>
<td>Flyover: 87.46, Approach: 92.55, Sideline*: 98.72</td>
<td>86.5, 92.8</td>
<td>+0.96, -0.25</td>
</tr>
</tbody>
</table>

*Sideline*
Example Application: Thrust Cutback Location on Departure

- Typical takeoff procedure uses constant takeoff thrust throughout initial climb segment
  - Safety & efficiency benefits
- Thrust cutback after takeoff during initial climb can be used to reduce noise for nearby communities
  - Specific location of cutback determines overall noise impact of procedure
Impact of Thrust Cutback Location on Single-Observer Departure Noise

Boeing 737-800 Departures with Varying Thrust Cutback Location
Measurement Location: Extended Runway Centerline, 6.5km from Start of Takeoff Roll
Takeoff Weight: 172,300 lbs
Engine: CFM56-7B26

EPNL at Observer (dB)

Cutback Distance from Start of Takeoff (ft)

- No Cutback
- Cutback Location for Minimum Noise
- Observer Location

Preliminary
Impact of Thrust Cutback Location on Departure Noise Contour Geometry

Boeing 737-800 Departure Profiles

Takeoff Weight: 172,300 lbs
Engine: CFM56-7B26

Effective Perceived Noise Level (dB), Boeing 737-800 Departure

Minimum Noise Cutback
No Cutback

Preliminary
Example Application: Delayed Deceleration Approach

- In conventional approaches, aircraft decelerate early in the approach
  - Often commanded by air traffic control for spacing traffic flows
- In DDA approaches, initial flap speed velocity held as long as possible during approach to lower drag and thrust requirements
  - Lower thrust levels and reduce engine noise
  - Higher velocities increase airframe noise
Delayed Deceleration Approach Profile: Glideslope Intercept from Level Flight

Boeing 737-800 Flight Profile
Landing Weight: 146,300 lbs
Engine: CFM56-7B26
Impact of Delayed Deceleration Approach on Noise Contour Geometry

Boeing 737-800 Flight Profile
Landing Weight: 146,300 lbs
Engine: CFM56-7B26
Effective Perceived Noise Level (dB), Boeing 737-800 Approach

Observer X Locations (nmi)
-20  -18  -16  -14  -12  -10  -8  -6  -4  -2  0

Observer Y Locations (nmi)
-2.5 -2  -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5

Delayed Deceleration Approach
Constant Speed Approach

Preliminary
Example Application: Modeling New Aircraft Configurations

- New aircraft configurations, compared to existing baseline aircraft with the same passenger number and range requirements, may feature:
  - Cleaner, lighter airframes, engine noise shielding
  - Reductions in fuel burn, emissions, community noise
Boeing 737-800 vs. D8.2 Concept
Aircraft Approach Profile

Boeing 737-800 vs. D8.2 Concept
Landing Weight: 146,300 lbs (B738) vs. 102,000 lbs (D8.2)
Boeing 737-800 vs. D8.2 Concept

Aircraft: Noise Contour Comparison

Boeing 737-800 vs. D8.2 Concept

Landing Weight: 146,300 lbs (B738) vs. 102,000 lbs (D8.2)

Effective Perceived Noise Level (dB), Boeing 737-800 vs. D8.2 Approach

Preliminary
Moving Forward

- Continue developing flight procedure generator
- Continue validating the TASOPT/ANOPP program noise results with FAA data for more aircraft types
- Use TASOPT/ANOPP program for computation of noise for more aircraft types and operational procedures
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Appendix
TASOPT Calculation Flow

TASOPT Inputs (user defined):
- Aircraft sizing/performance parameters
- Operating/mission parameters
- Engine sizing/performance parameters

TASOPT Calculation Flow:
- Fuselage/Wing/Tails sizing and weight computations
- Drag build-up
- Engine sizing, weight, performance computations
- Trajectory computations
- Mission fuel computations
- Final weight computation

TASOPT Outputs:
- Aircraft Performance
- Airframe geometry
- Engine performance
- Engine geometry
ANOPP Calculation Flow:

TASOPT Outputs:
- Aircraft Performance
- Engine Performance
- Airframe Geometry

Flight Profile Generator:
- Thrust, velocity, position, gear/flap settings

User Inputs:
- Observer array

ANOPP Calculation Flow:
- Flight profile definition
- Source to observer geometry
- Engine and airframe noise computations
- Propagation and ground effects
- Wing shielding effects

ANOPP Outputs: Noise contours for each observer location
Flight Profile Generator: Detailed Methodology

- **Goal:** to generate position, velocity, and thrust of an aircraft flight profile from a combination of user specified requirements at each profile segment, including:
  - Flap and gear settings: \( \delta_{\text{flap}}, \delta_{\text{gear}} \)
  - Segment end velocity: \( V_{\text{end}} \)
  - Deceleration: \( a \)
  - Thrust: \( T \)
  - Glideslope: \( \gamma \)
  - Segment end position: \( x_{\text{end}} \) or \( z_{\text{end}} \)

- **The user initially specifies:**
  - Aircraft weight, wing area, air density: \( W, S, \rho \)
  - Drag coefficients: \( C_D(\delta_{\text{flap}}, \delta_{\text{gear}}, C_L) \)
  - Initial position, altitude, velocity: \( x_{\text{start}}, z_{\text{start}}, V_{\text{start}} \)
  - Number of profile segments
Flight Profile Generator: Computation Methodology

- At each segment:

  The user specifies:
  \[
  \delta_{\text{flap}}, \delta_{\text{gear}}
  \]
  One of: \(a, V_{\text{end}}, \text{ or } T\)
  & two of: \(x_{\text{end}}, z_{\text{end}}, \text{ or } \gamma\)

  The generator computes:
  remaining three variables not yet specified, using the equations below:

  \[
  a = \sum_{m}^{F} m = \frac{T + W \sin(\gamma) - D}{W / g}
  \]
  \[
  \frac{(V_{\text{end}})^2 - (V_{\text{start}})^2}{2a} = \frac{x_{\text{end}} - x_{\text{start}}}{\cos(\gamma)} = \frac{z_{\text{end}} - z_{\text{start}}}{\sin(\gamma)}
  \]
  \[
  D = \frac{1}{2} \rho V^2 S C_D (\delta_{\text{flap}}, \delta_{\text{gear}}, C_L)
  \]
  \[
  C_L = \frac{W \cos(\gamma)}{\frac{1}{2} \rho V^2 S}
  \]

- \(x_{\text{end}}, z_{\text{end}}, V_{\text{end}}\) of one segment become \(x_{\text{start}}, z_{\text{start}}, V_{\text{start}}\) of the next segment

Segment sign conventions; negative value of \(\gamma\) indicates climb
Flight Profile Generator: Computation Methodology

• To get thrust (or reverse thrust) profile $T$ ($T_{\text{reverse}}$) on the runway, the user specifies (with $V_{\text{start}}$ the velocity upon liftoff or upon touchdown):
  - Takeoff/Landing roll length: $L_{\text{Roll}}$
  - Runway coefficient of friction: $\mu$

\[
\frac{(V_{\text{start}})^2}{2L_{\text{Roll}}} = a \quad a = \sum_{m} \frac{F}{m} = \frac{-T + T_{\text{reverse}} + D + \mu(W - L)}{W / g}
\]

\[
D = \frac{1}{2} \rho V^2 SC_D(\delta_{\text{flap}}, \delta_{\text{gear}}, C_L) \quad L = \frac{1}{2} \rho V^2 SC_{L,\text{start}} \quad C_{L,\text{start}} = \frac{W}{\frac{1}{2} \rho (V_{\text{start}})^2 S}
\]

• Lastly, the user specifies the lateral aircraft position profile $y(s)$ with $s = \sqrt{x^2 + z^2}$

Sample Approach Profile: Boeing 737-800 including Landing Roll
Drag Coefficients for Flight Profile Generator

- Drag coefficients for existing aircraft currently obtained from Base of Aircraft DAta (BADA)

- BADA provides aerodynamic drag coefficients for various flap and gear configurations of supported aircraft types:

\[ C_D = C_{D0}(\delta_{flap}, \delta_{gear}) + C_{D2}(\delta_{flap})^2 (C_L)^2 \]
Delayed Deceleration Approach Profile: Continuous 3-degree Glideslope

Boeing 737-800 Flight Profile
Landing Weight: 146,300 lbs
Engine: CFM56-7B26

Aircraft y Position (ft)

Aircraft x Position (nmi)

Velocity (knots)

Flaps 5
Flaps 15
Flaps 30
Flaps 30

Aircraft x Position (nmi)

Reverse Thrust Onset
10000

Thrust (lbs/eng)

Aircraft x Position (nmi)

2000 Idle Thrust
Impact of Delayed Deceleration on Noise Contour

Boeing 737-800 Flight Profile
Landing Weight: 146,300 lbs
Engine: CFM56-7B26

Effective Perceived Noise Level (dB), Boeing 737-800 Approach

Delayed Deceleration Approach
Constant Speed Approach

Observer X Locations (nmi)
-20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0

Observer Y Locations (nmi)
-2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5

65 75 85 95

Preliminary