System Noise Prediction of the DGEN 380 Turbofan Engine

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Introduction

• The DGEN 380 is a small, twin-spool, separate-flow, unboosted, geared turbofan manufactured by Price Induction
  – 570lb static thrust
  – 14in diameter fan
  – 7.6 bypass ratio

• Promoted for a small, 4- to 5-place twinjet application in the emerging personal light jet market

• Designed for aircraft operating in the regime currently dominated by propeller-driven airplanes under 25,000ft and 250ktas

• DGEN engine on promotional U.S. tour in July, 2014; arrangements made for one-day acoustic test in NASA Glenn’s Aero-Acoustic Laboratory dome on July 25

• NASA has interest in purchasing a DGEN to test propulsion technologies in a relevant engine environment; thus, interest in DGEN system noise
System Noise Prediction

- Flight conditions
- Spectra propagation
- Ground effects
- Noy-weighted frequency summation
- Tonal content penalties
- Result: Ground observer noise vs. time history

Concept airplane used in this study is a jet-powered variant of Cirrus Aircraft’s propeller-driven SR22

Observer PNLT, PNdB
Observer Time, s

Time integration to Effective Perceived Noise Level
Method of Analysis

• Most expedient method for computing EPNL is to use measured engine spectra directly with a system noise analysis and propagation tool:
  – Measured spectra analytically “flown” on a trajectory past ground observers
  – Propagation and ground effects applied, EPNL computed for each observer
  – Convection and Doppler flight effects applied to improve accuracy

• Issues with this approach:
  – Engine behavior is different in flight than at ground level
  – Noise measured statically on ground not wholly representative of noise in flight
  – Jet mixing noise is a distributed source radiating along the axial plume of exhaust

• Approach used in this study:
  – Semi-empirical noise prediction methods are derived; used in place of measured noise
  – Noise surrogate models functions of engine state variables; react with flight conditions
  – Surrogate models are calibrated to static spectra measured at NASA
  – Physics-based models are relied on to project spectra to arbitrary flight conditions
  – Surrogate models in place of actual spectra allows for removal of extraneous or spurious portions of the spectra not believed to be genuine engine noise
  – Each noise source can easily be manipulated mathematically
DGEN 380 Test in NASA’s Aero-Acoustic Propulsion Laboratory

Overhead microphone array (32ft to 57ft)

12ft microphone array

DGEN 380
Engine Source Modeling and Calibration (1)

- One-day static engine test in NASA Glenn dome
- Six throttle settings (47% to 96% N1max)
- 24-microphone overhead array; 32ft to 57ft radius
- Narrowband sound pressure levels collected @12.2Hz BW

Lossless spectra, 138 deg from inlet axis, 96% N1max
Fan noise:

- Based on empirical Heidmann formulation (1979), recalibrated for modern, wide-chord fans (2014)
- Acoustic power proportional to mass flow, stage temperature rise, and relative tip Mach
- Doppler and convection terms relied on to project source to flight conditions
- Calibration variables
  - $x_1$ amplitude
  - $x_2$ curvature
  - $x_3 - x_6$ discrete interaction tone levels

Fan noise model (after Heidmann, et al.):

$$L_{Fan}(f, \theta) = 10 \log_{10} \left\{ x_1 \frac{m}{m_{Ref}} \left[ \frac{\Delta T_{Fan}}{T_{Ref}} \right]^2 G(M_{r}) \frac{D(\theta) S(f, x_{2-6})}{1 - M_f \cos \theta} \right\}$$
Shaft noise:

- Homebrew empirical function
- High- and low-pressure spool speeds used as independent variables
- Filtered at shaft passage frequencies
- Doppler and convection terms relied on to project source to flight conditions
- Calibration variables
  - $x_7$ low-spool tone
  - $x_8$ high-spool tone

Shaft noise model:

$$L_{Shafts}(f, \theta) = 10 \log_{10} \left\{ x_7 x_8 H(N_L, N_H) \frac{D(\theta) S(f)}{1 - M_f \cos \theta} \right\}$$
Core noise:

- Based on 1976 SAE method
- Acoustic power proportional to burner mass flow, temperature rise, and density
- Difficult to tell when, or if, jet noise is masquerading as core noise or vice versa
- Source signal separation coherence techniques
- Use low engine power settings as a guide
- Calibration variables
  - $x_9$ amplitude
  - $x_{10}$ curvature

Core noise model (after Matta):

$$L_{Core}(f, \theta) = 10 \log_{10} \left( x_9 \frac{\dot{m}}{\dot{m}_{Ref}} \left[ \frac{\Delta T_{Comb}}{T_{Ref}} \right]^2 \left[ \frac{\rho_{Comb}}{\rho_{Ref}} \right]^2 \frac{D(\theta) S(f, x_{10})}{1 - M_f \cos \theta} \right)$$
Jet noise:

- Based on 2009 Stone method
- Jet mixing noise modeled as three virtual sources
- Each spectrum is adjusted to the microphone distance to exploit model’s convection/refraction features
- Calibration variable: $x_{11}$ amplitude

Jet noise model (after Stone):

$$L_{Jet}(f, \theta) = 10 \log_{10} \left[ x_{11} \left( \frac{V_e}{c_{Ref}} \right)^{n} \left( \frac{\rho}{\rho_{Ref}} \right)^{\rho} \frac{D(\theta_c) S(f, \theta_c)}{(1 + M_c \cos \theta)^2 + \alpha^2 M_c^2} \right]$$
Engine Source Modeling and Calibration (6)

- Optimizer used to aid fitment of noise models to measurements
- Imperfect models, imperfect data… composite objective:
  - Sound pressure levels
  - Perceived noise level with tone penalty correction
- Minimum, nonzero $O(x)$ does not result in a unique solution
- Values of $x$ should not stray too far from their nominal values, set limits

\[
O(x) = \frac{\sum_i (L_{i,\text{data}} - L_{i,\text{model}})^2}{\sum_i (L_{i,\text{data}} - \overline{L}_{\text{data}})^2} + w_2 \left( L_{\text{TPN, data}} - L_{\text{TPN, model}} \right)^2
\]

Lossless spectra, 138 deg from inlet axis, 96% $N_{1max}$
Wing Planform Shielding

- Maekawa diffraction loss method
- Implemented as function of Fresnel number
- Applied to fan and core noise sources
- Not subject to shielding:
  - Airframe noise sources
  - Jet noise: A distributed source generated downstream throughout axial exhaust plume

Maekawa diffraction expression:

\[ L_I = 20 \log_{10} \left( \sqrt{2\pi|F|} \right) \cdot \left( \tanh \sqrt{2\pi|F|} \right) + 5 \]
Airplane Trajectory

- Cirrus SR22 takeoff at 3400lb gross weight, 50% flaps
- Noise abatement power cutback; climb gradient:
  - 4%, all engines operating
  - Zero, one engine inoperative
- Approach at 2790lb
- Three-degree approach glide slope, with flaps fully extended, gear down
Noise Prediction Results

- Chapter 4 cumulative margin: 53.1 EPNdB
- Chapter 14 cumulative margin: 27.4 EPNdB

Meets NASA’s “N+3” noise goal, albeit at a much smaller size!
Monte Carlo Uncertainty Analysis

- Real engine, notional airplane… Uncertainty analysis needed!
- Modeling unknowns chosen by top-down decomposition of problem
- Variables categorized into trajectory, source levels, environmental & installation classes
- Variables chosen to represent effects that would cause values to stray from benchmark during airplane development
- Benchmark noise model transformed into stochastic model
- Variables randomly permuted around benchmark case

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Approach</th>
<th>Lateral</th>
<th>Flyover</th>
<th>Cumulative</th>
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</thead>
<tbody>
<tr>
<td>Benchmark case</td>
<td>77.0</td>
<td>74.2</td>
<td>66.8</td>
<td>217.9</td>
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<td>70.6</td>
<td>64.4</td>
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<td>74.6</td>
<td>66.8</td>
<td>218.7</td>
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<td>Standard deviation</td>
<td>0.9</td>
<td>1.2</td>
<td>0.8</td>
<td>2.3</td>
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</tbody>
</table>

Uncertainty statistics (in EPNdB)

Histogram and normal distribution generated from 8000 samples (bin span 0.1 EPNdB)
Summary

- Static noise measurements of a Price Induction DGEN 380 turbofan were collected at NASA Glenn Research Center.
- Noise source models were calibrated and used to analytically project static spectra to flight conditions.
- Embedded physics-based behavior allows noise source models to react properly to changing engine state and flight conditions.
- The DGEN is a quiet turbofan, owing not only to its small size, but also to its design.
- Cumulative margins to Chapter 14 and Chapter 4 limits are predicted to be 27.4 and 53.1 EPNdB, respectively.
Backup Slides
Simulated Engine Cycle Data

- Empirical noise models require engine cycle data for noise level scaling
- Engine cycle data not measured during acoustic test
- Price Induction’s “Virtual Engine Test Bench,” a DGEN 380 digital engine control unit
- Engine data response surfaces generated for steady pressures, temperatures and airflows (ISA+18°F) at all major engine flowstations as function of airspeed, altitude and low-spool shaft speed
Noise Prediction Results

- **Approach EPNL, EPNdB**
- **Lateral EPNL, EPNdB**
- **Ryover EPNL, EPNdB**
- **Cumulative EPNL, EPNdB**

- **Chapter 3 limit**
- **Chapter 14 limit, twins**

- **Notional DGEN twinjet**

- Cessna 510 Mustang
- Embraer Phenom 100
- Eclipse 500

Maximum Takeoff Gross Weight, 1000lb
## Monte Carlo Uncertainty Analysis

### Variables perturbed in Monte Carlo experiment

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mode</th>
<th>Model</th>
<th>Min</th>
<th>Max</th>
<th>Std. Dev.</th>
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<tbody>
<tr>
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<td>Triangular</td>
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<td>Approach $N_L$ setpoint</td>
<td>60%</td>
<td>Triangular</td>
<td>58%</td>
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<td>5°</td>
<td>7°</td>
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<tr>
<td>Lateral angle of attack</td>
<td>6°</td>
<td>Triangular</td>
<td>5°</td>
<td>7°</td>
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<tr>
<td>Flyover angle of attack</td>
<td>6°</td>
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<td>5°</td>
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<td>-</td>
<td>1.5dB</td>
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<td>Ground specific flow resistance</td>
<td>291sl/s-ft$^3$</td>
<td>Triangular</td>
<td>233sl/s-ft$^3$</td>
<td>349sl/s-ft$^3$</td>
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<td>Lateral attenuation adjustment</td>
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<td>2dB</td>
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<td>Wing area (shielding)</td>
<td>155ft$^2$</td>
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<td>200ft$^2$</td>
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