Recent Progress In Engine Noise Reduction Technologies

ABSTRACT

Highlights from NASA-funded research over the past ten years for aircraft engine noise reduction are presented showing overall technical plans, accomplishments, and selected applications to turbofan engines. The work was sponsored by NASA's Advanced Subsonic Technology (AST) Noise Reduction Program. Emphasis is given to only the engine noise reduction research and significant accomplishments that were investigated at Technology Readiness Levels ranging from 4 to 6. The Engine Noise Reduction sub-element was divided into four work areas: source noise prediction, model scale tests, engine validation, and active noise control. Highlights from each area include technologies for higher bypass ratio turbofans, scarf inlets, forward-swept fans, swept and leaned stators, chevron/tabbed nozzles, advanced noise prediction analyses, and active noise control for fans. Finally, an industry perspective is given from General Electric Aircraft Engines showing how these technologies are being applied to commercial products. This publication contains only presentation vu-graphs from an invited lecture given at the 41st AIAA Aerospace Sciences Meeting, January 6-9, 2003.
Recent Progress in Engine Noise Reduction Technologies

Dennis Huff, NASA Glenn Research Center
Philip Gliebe, GE Aircraft Engines

41st AIAA Aerospace Sciences Meeting
January 6-9, 2003
Advanced Subsonic Technology
Noise Reduction

**SUBELEMENTS**

- Engine Noise Reduction
- Nacelle Aeroacoustics
- Acoustic/Aerodynamic Integration and System Evaluation
- Interior Noise Reduction
- Community Noise Impact
### Technical Working Group

<table>
<thead>
<tr>
<th>Company</th>
<th>Name</th>
<th>Company</th>
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<tbody>
<tr>
<td>AAAE</td>
<td>Morris*</td>
<td>Honeywell</td>
<td>Weir*</td>
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<tr>
<td>Allison</td>
<td>Dalton*</td>
<td>L&amp;Brown</td>
<td>Woosley</td>
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<td>ALPA</td>
<td>Davis*</td>
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<td>ATA</td>
<td>Young*</td>
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<td>Clark/Waitz</td>
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<td>Boeing</td>
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<td>Parente*/Schien</td>
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<td>Arman*</td>
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<td>Sikorsky</td>
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<td>Yu*</td>
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<td>Kastenhuber*</td>
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*Ad Hoc Steering Committee*
Engine Noise Reduction
Aerospace Vehicle Systems Technology Program

Engine Noise Reduction & Nacelle Aeroacoustics

GOAL: Provide technology for lowering engine noise while maintaining high performance for advanced turbofan engines.

Objectives
• 6 dB engine source noise reduction relative to 1992 technology
• ~2 dB from nacelle improvements (liners, etc.)
Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

ENGINE NOISE REDUCTION SUBELEMENT ROADMAP

<table>
<thead>
<tr>
<th>FY94</th>
<th>FY95</th>
<th>FY96</th>
<th>FY97</th>
<th>FY98</th>
<th>FY99</th>
<th>FY00</th>
</tr>
</thead>
</table>

1) Completed: shared with 3.2; Key to early success

Integrated Source/Duct Coupled Propagation/Radiation Prediction Codes Developed

3) 3 dB Fan Noise: P&W, GE, Allison, and Boeing:

Validate Generation One Concepts

7) Suite of Codes: TFaNS, BFaNS, LINFLUX, MBGK
   GE Fan Broadband/MPT & Core Noise

3) 3 dB Jet Noise: P&W, GE, Allison, and AlliedSignal

8) 6 dB Engine Noise: Low-Speed Fans, Swept Cut-On Stators, BPF ANC, Forward-Swept Fans, Chevron Nozzles

LEVEL 1 MILESTONES & DELIVERABLES:

- First integrated fan noise source and propagation prediction code
- Concepts validated for 3 dB jet noise for 1.5-6 bypass ratio engines and 3 dB fan noise reduction relative to 1992 technology
- Validated codes for fan/jet/core low noise design
- Technology to reduce engine noise 6 dB relative to 1992 technology
Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Engine Noise Reduction Research Plan

Source Noise Prediction
- CFD/CAA: ADPAC, TURBO, LINFLUX, Advanced TFANS using LINFLUX
- Fan Noise: VOF/TFANS, Broadband Analysis (GE, Glegg)
- Jet Noise: MGB, CFD → MGB, Semi-empirical model update

Model Scale Tests
- First Integrated Fan Noise Analysis Level I
- Jet Noise Prediction Methodology Level 2
- Select 2nd Gen. Concepts based on Advanced Codes/Tests Level 2
- Validated Codes for Low-Noise Design Level 2

Model Scale Tests
- Low Speed Fan
  - GE UPS
  - Boeing Diag
- High Speed Fan
- Low BPR Jet
- UHB Jet
- P&W Mixers I
- P&W Mixers II
- P&W Nozzles
- GE E3 Mixers
- Allison Mixers I & II
- Allison Low-Noise Fan
- P&W ADP "Fan 1"
- P&W ADP "Fan 2"
- NASA Fan
- GE/Allison Fans
- Honeywell Fans

Active Noise Control
- Wall: Baseline ANCF, Grumman Active/Passive, GE Multiple Mode Test
- Stator Vanes: Purdue Cascade, P&W/BBN Active Vanes, Work Moved to Nacelle Aeroacoustics

Engine Validation
- Fan: GE UPS Scalability
- Jet: Allied Signal Mixers

Technology to Reduce Engine Noise 6dB Level
- Engine Tests - Honeywell, P&W

Moved to Propulsion Systems Base: Validated MGBK Predictions
Source Noise Prediction

TFaNS: Theoretical Fan Noise Design/Prediction System
Joint Development By P&W/UTRC/NASA For Fully Coupled Interaction Tone Prediction

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Code Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>Eversman Inlet/Aft Code</td>
<td>RADIATION</td>
</tr>
<tr>
<td>1996</td>
<td>Improved Eversman Code</td>
<td>RADIATION</td>
</tr>
<tr>
<td></td>
<td>Caruthers Inlet/Aft Code</td>
<td>RADIATION</td>
</tr>
<tr>
<td>1998</td>
<td>Asymmetric Code</td>
<td>RADIATION</td>
</tr>
<tr>
<td></td>
<td>Classical Flat Plate Theory</td>
<td>SOURCE</td>
</tr>
<tr>
<td></td>
<td>LINFLUX : 3D Linearized Euler Code</td>
<td>SOURCE</td>
</tr>
<tr>
<td></td>
<td>TURBO : 3D Navier–Stokes Code</td>
<td>SOURCE</td>
</tr>
<tr>
<td></td>
<td>Linear/Non–Linear</td>
<td>SOURCE</td>
</tr>
</tbody>
</table>
Engine Noise Reduction - Prediction Tools

Level 2 Milestone (2Q, 99): Validated codes for fan/jet/core low noise design

Fan Noise Source Models:
- V072, TFaNS(SOURCE3D, CUP3D)
- LINFLUX, TURBO, CFL3D => tone noise
- BFaNS, Envia/Mani/Glegg => broadband noise
- GE MPT Analysis

Jet Noise Models:
- MGBK Code, Empirical Codes

Directivity Predictions:
- Eversman, Caruthers, TBIEM3D, RDIFF/CDUCT, Rice

Combustion Noise:
- GE Model
Fan Noise Prediction

Can predict stator noise fairly accurately but not the rotor noise.

➢ Tone Noise: LINFLUX Code
   • Pros: 3D, Realistic flow & geometry
     Captures quantitative details
   • Cons: Separate computation for mean flow
     One frequency at a time

<table>
<thead>
<tr>
<th>Tone Power Level (dB)</th>
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<tbody>
<tr>
<td>Mode</td>
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<tr>
<td>------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

➢ Broadband Noise: BFaNS Code
   • Pros: Captures basic trends
   • Cons: Quasi-3D, simplistic flow & geometry
     Inaccurate details

<table>
<thead>
<tr>
<th>Total Power Level (1-50 kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
</tr>
<tr>
<td>Theory</td>
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<tr>
<td>121</td>
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</tbody>
</table>
Jet Noise Prediction

MODIFIED “MGB” CODE, now called “MGBK”

Combines CFD solutions with modeling of noise sources to predict far-field acoustics

- Small-scale turbulence noise
- External mixing noise only
- Accounts for both self and shear noise
- Non-isotropic turbulence
- Can be extended to a 3D geometry (assumes flow is locally axisymmetric)

Splitter Nozzle

12-Lobe Mixer

Isotropy: \( L_2 / L_1 = 1, \frac{u_2^2}{u_1^2} = 1 \)

Anisotropy: \( L_2 / L_1 = 0.8, \frac{u_2^2}{u_1^2} = 0.7 \)
Model Scale Tests
LOW NOISE CYCLE/CONCEPT DEFINITION STUDIES

CONCEPTS SELECTED (1994)

P&W 2nd Generation Advanced Ducted Propulsor (ADP)
- Variable pitch
- Low tip speed
- High loading

GE Extensions of GE-90 Technology for Lower Noise
- Fixed pitch
- High tip speed
- Long duct, mixed flow
- Blade sweep

ALLISON Ultra High Bypass for Short-Haul Applications
- Fixed pitch
- Low tip speed
- Swept stator
Fan Tests in the 9’x15’ Wind Tunnel

Comprehensive Tests of Many Model Fan/Nacelles Obtaining Aerodynamic, Acoustic & Structural Data

GE Universal Propulsion Simulator (1994)


Detailed Flow Measurements

NASA Alternate Low Noise Fan (1997)
ASTT Noise Reduction Program

LOW-NOISE SWEPT AND LEANED STATORS DESIGN

- Numerical predictions indicate that interaction tones can be reduced to broadband noise levels of a fan.

- Optimal sweep/lean designs predicted to meet 3 EPNdB fan noise reduction LI Milestone (1Q97).

- 22 inch model fan hardware tested in 9 x 15 Wind Tunnel, results verify predictions.
NASA/Allison Low-Noise Fan in 9x15 Wind Tunnel (1996)

Baseline

Swept Stators

Swept/Leaned Stators
GE/Allison/NASA High Speed Fan Test (1998)

Objectives
- Demonstrate benefits of swept/leaned stators with high tip speed fans
- Determine "buzz saw" noise reduction using a forward-swept fan
- Supports 6dB engine noise reduction milestone in AST Noise Reduction Progr

9x15 Wind Tunnel Installation

Wide-Chord Baseline Fan

Forward-Swept Fan

Shrouded Fan (GE Proprietary)

Swept & Leaned Stators
Engine Noise Reduction
Aerospace Vehicle Systems Technology Program

Honeywell Quiet High Speed Fan (2000)

Baseline Fan  QHSF Fan
Engine Noise Reduction
Aerospace Vehicle Systems Technology Program

Noise Comparisons: 1500' Flyover, 30.7'' Diameter Fan, Matched Thrust

![Graph showing noise comparisons between Honeywell Baseline (731-60) and Honeywell Forward-Swept Fan](image-url)
Boeing 18-Inch Fan Rig Test Results (1995)

Components of Fan Broadband Noise

Graphs showing the relationship between RPM and scaled dB(A) PWL for Inlet-radiated Far-field and Aft-radiated Far-field, with different configurations of stators and rotors.
Engine Noise Reduction
Aerospace Vehicle Systems Technology Program

Source Diagnostics Fan Test in 9’x15’ Wind Tunnel (1999)

Joint effort w/ Glenn, Langley, GE & Boeing
2 Fans/3 Stator Combinations
• “R4” Early GE-90 Design
• “M5” Higher Tip Speed, Matched P(r)
• Radial “Cutoff” Stators
• Radial “Cuton” Stators
• “Cuton” Swept Stators

Rotor-Alone Tests
• Self-Centering Nacelle Suspension System
• Maintained Stringent Fan Tip Clearances

Comprehensive Data Base
• Aerodynamic Performance
• Unsteady Surface Pressures on Stators
• LDV & Two-Point Hot Wire Flow Measurements
• Wall & Rotating Microphone Duct Mode Measurements
• Sideline Acoustics
Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Jet Noise - Full Scale Mixer Demonstration

- Showed 3 EPNdB jet noise benefit
- Validated design from MGB Code
- Attempted source separation using three-signal coherence technique
- Characterized exhaust plume T/P profile using the NASA Glenn rake
- Evaluated engine performance

Three Test Configurations

- TFE731-40 nozzle
- Advanced Solid Mixer
- Advanced Porous Mixer

Baseline Configuration

<table>
<thead>
<tr>
<th></th>
<th>Compound nozzle with C-D exit</th>
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<tbody>
<tr>
<td>Takeoff Bypass Ratio</td>
<td>3.48</td>
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<tr>
<td>Primary jet Velocity</td>
<td>1600 ft/sec</td>
</tr>
<tr>
<td>Primary Jet Temperature</td>
<td>1120F</td>
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<tr>
<td>Secondary Jet Velocity</td>
<td>920 ft/sec</td>
</tr>
<tr>
<td>Secondary Jet Temp.</td>
<td>160F</td>
</tr>
</tbody>
</table>

Honeywell San Tan Acoustic Test Facility
Jet Noise Reduction Research
1997 NASA/GE/P&W Separate Flow Nozzle Test

Nozzles of the Future
Fan Chevrons with Core Alternating Chevrons

Flow Field Measurements

GE CF34 Engine
Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Noise Reduction From Separate Flow Nozzle Concepts

~3 EPNdB Noise Reduction, Minimal Thrust Loss

<table>
<thead>
<tr>
<th>Configuration #</th>
<th>( \Delta \text{EPNL (EPNdB)} )</th>
<th>( \Delta C_{fg} ) (point)</th>
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<tr>
<td>1</td>
<td>2</td>
<td>1</td>
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<tr>
<td>2</td>
<td>1</td>
<td>0.5</td>
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<td>14</td>
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Jet Noise Source Measurements

Particle Image Velocimetry, Phase Arrays

2-Component PIV Measurements of Chevron Nozzles

Finally getting turbulence data for hot, high-speed flows!

Source Location Using Phased Arrays

Tabs reduce classic jet noise at low frequency at end of potential core

Tabs produce noise at high frequencies near nozzle
Active Noise Control
Active Noise Control Fan (ANCF)
## Fan Active Noise Control – ANCF Tests

<table>
<thead>
<tr>
<th>Concept</th>
<th>Contractor</th>
<th>Targeted Mode(s)</th>
<th>Freq.</th>
<th>Direction</th>
<th>Test Date</th>
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<tbody>
<tr>
<td>Wall Actuators, Plate Radiators in ring</td>
<td>GE, CR&amp;D</td>
<td>(6,0)</td>
<td>2BPF</td>
<td>Ex.</td>
<td>6-9/95</td>
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<tr>
<td>Active Resonators</td>
<td>HAE (Hersh Acoustical Engineering)</td>
<td>(4,0), (4.1), (2,0)</td>
<td>2BPF, 1BPF</td>
<td>In.</td>
<td>1/96</td>
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<tr>
<td>Control Near Source, Wall Actuators up &amp; downstream of Vanes</td>
<td>HAE</td>
<td>(4,0), (4,1)</td>
<td>2BPF</td>
<td>In. + Ex. (global)</td>
<td>3/96</td>
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<tr>
<td>Hybrid Active/Passive</td>
<td>Northrop Grumman/HAE</td>
<td>(4,0), (4,1)</td>
<td>2BPF</td>
<td>In.</td>
<td>3-4/96</td>
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<td>On Scale Model P&amp;W Fan</td>
<td>Grumman/HAE</td>
<td>(9,0), (9,1)</td>
<td>2BPF</td>
<td>In.</td>
<td>11/96</td>
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<tr>
<td>Control at the Source &quot;Active Vanes&quot;</td>
<td>BBN (UTRC, P&amp;W, Purdue)</td>
<td>(4,0), (4,1)</td>
<td>2BPF</td>
<td>In. + Ex. (global)</td>
<td>7/97</td>
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<tr>
<td>Wall Actuators (high radial orders)</td>
<td>GE, CR&amp;D, HAE, BYU</td>
<td>(2,0), (2,1), (2,2), (2,0), (2,1), (2,2), (2,3)</td>
<td>2BPF</td>
<td>In./Ex. In.</td>
<td>6-9/98 +1/99</td>
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<tr>
<td>Wall Actuators (high order, global)</td>
<td>HAE, CEST</td>
<td>(2,0), (2,1), (2,2), (2,0), (2,1), (2,2), (2,3)</td>
<td>2BPF</td>
<td>In. + Ex. (global)</td>
<td>3/99</td>
</tr>
<tr>
<td>Active Vanes (high order, global, control simplification)</td>
<td>BBN, HAE</td>
<td>(2,0), (2,1), (2,2), (2,0), (2,1), (2,2), (2,3)</td>
<td>2BPF</td>
<td>In. + Ex. (global)</td>
<td>5-6/01</td>
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</table>
Fan Noise Reduction Research
1996 NASA/Northrop Grumman Active Noise Control Fan Test

**Uniform Passive**
Near Grazing Incidence Fan Noise; Modest Overall Attenuation.

**Two Segment Passive**
Initial Segment Scatters Modes into Higher Order Radial Modes. Limited Bandwidth of Attenuation Since Liner is Efficient only near Design RPM.

**Hybrid Active/Passive**
Initial Active Control Segment Compensates for Changing Parameters Resulting from Mode Mixture Variations with Fan Speed. High Bandwidth of Attenuation.

- Superior Performance Relative to Conventional Uniform Passive Liners Over Extended Fan Speeds
- 3 to 10 dB Attenuation Increase Over Uniform Passive Liners for ADP Fan over the Speed Range of 5200 to 6000 RPM

Northrop Grumman Hybrid Active/Passive Liner Installed in the NASA ADP Fan Rig at the NASA LeRC 9'x15' Wind Tunnel
Fan Noise Reduction Research
1998 NASA/BBN Active Noise Control Fan Test

- 4 ft Fan (16 Blades)
- Stator Vanes (28)
- Control Microphones
  fore & aft spool sections
  (16 each row, 96 total)
- PZT (THUNDER) Actuators
  6 per vane, 4 Channels of Control

Rotating Rake
mode measurements
inlet & exit plane
Engine Validation
Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Validate Noise Reduction Technology Through Large-Scale Component Testing (Milestone No. 1A3.1; Due 4Q, FY01)

Milestone met through two static engine tests:
1.) Pratt & Whitney PW4098 tested in 1999 and 2001
2.) Honeywell TFE731-60 tested in 1999
Engine Noise Reduction
Aerospace Vehicle Systems Technology Program

PW4098 Engine Test

Active-Passive Liner

Scarf Inlet

Advanced PW Fan Case Treatment

Fan Blade # Change and Low Number/Cuton FEGV

Treated Primary Nozzle

Pratt & Whitney
A United Technologies Company

BOEING
Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Honeywell TFE731-60 Engine Test

Chevron Nozzles

Rotating Microphone

TFE731-60 Engine with Inflow Control Device (ICD)

Variable Area Nozzle

Scarfed Inlet
Engine Noise Reduction
Aerospace Vehicle Systems Technology Program

Honeywell EVNRC Flight Demonstration of Noise Reduction Concepts

Objectives
- Demonstrate concepts from static tests will work in flight
- Obtain performance and diagnostic data for QAT concept development

Benefit
- Concepts fully demonstrated at flight conditions

Approach
- Conduct flight tests of TFE731-60 engine on Honeywell Falcon 20
- Perform comparisons with existing static data
- Share resources with Glenn, Langley and Boeing

Variable Nozzle Chevron Nozzle Scarf Inlet
Engine Noise Reduction
Aerospace Vehicle Systems Technology Program

Engine Noise Reduction Technologies Entering QAT

- Higher BPR Propulsion
- Scarfed Inlets
- Forward-Swept Fans
- Swept/Leaned Stators

Chevron Nozzles
Noise Prediction
Active Noise Control
NASA AST Noise Reduction Technology

Applications to Product Engines
Philip R. Gliebe
GE Aircraft Engines

AIAA 41st Aerospace Sciences Meeting
January 6-9, 2003
Reno, Nevada
Engine Noise Reduction Technology Programs - Approach

Three - Pronged Approach:

- Detailed *Scale Model and Engine* Experimental Investigations

- *Prediction Model and Code Development* To Describe Noise Generation and Reduction Physics - Develop Design Tools

- *Propulsion System Acoustic Modeling*
  - Concept Benefit Analysis
  - Screening of Most Promising Noise Reduction Concepts
Basic Physics of Engine Noise Generation

Steady Flow

Unsteady Flow
- Rotor Flow Hits a Stator
- Stator Flow Hits a Rotor
- Turbulence - Jets, Boundary Layers, Combustion, etc.

Pressure Waves

"When the source is Clear, the Solution is near" - NLR
### Fundamentals of Noise Generation

Source Sound Power -

\[ W \propto \rho \cdot L^2 \cdot V_{\text{char}}^N \]

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Component</th>
<th>Velocity Dependence</th>
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</thead>
<tbody>
<tr>
<td>Volume displacement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forces on the fluid</td>
<td>Fluctuating Mass</td>
<td>Combustor</td>
</tr>
<tr>
<td>Fluctuating Force</td>
<td>Fan, LPC, LPT</td>
<td>4th-power</td>
</tr>
<tr>
<td>Fluctuating Shear Stress</td>
<td>Fan, Jet, Boundary Layers</td>
<td>6th-power</td>
</tr>
</tbody>
</table>

**Characteristic Velocity Is a Key Parameter In Determining Noise Source Strength – Reducing Jet Velocity is a Strong Driver For Reducing Engine Noise**
Advanced Cycle & Core Technology Engines

The GE90

Represents the application of:

• Proven technologies
  – Demonstrated by CF6 and CFM56 engines

• Demonstrated new technologies
  * Composite fan blades
  * E^3 23:1 HP compressor
  * Dual annular combustor
  * High Bypass Ratio
  * Fan Optimized for Low Noise
  * Advanced Liner Designs
  * High Bypass Ratio ~ 9:1
  * Low Jet Velocities

Unique GE90 Noise Technologies ...
London QC 0.5 at Arrival,
QC 1 to 2 at Departure
Jet Noise Reduction Technology

Focus on Jet Noise Reduction Through Development of Mixing Enhancement Devices with Minimal Performance Loss
Advanced Chevron Exhaust Nozzles

Initial Concept Benefits
Demonstrated in NASA AST-Sponsored Tests

Work Continuing .....  

- Increase Noise Reduction
- Scale model tests show modest improvements
- Minimizing performance loss is a significant challenge

Over 50 Chevron Nozzle configurations Tested in the GE Scale Model Jet Acoustics (Cell 41) Facility
Advanced Chevron Exhaust Nozzles

Chevrons Create Vortices Which Enhance Jet Exhaust Gas Mixing

Chevron Nozzle Development
- CFD to rapidly screen potential designs
- High quality acoustics and performance testing for design optimization
- Establish Link Between Flow and Noise
Validation on Full-Scale Engines

Static Engine Tests of Chevron Nozzles

Chevron Nozzle Benefits:
- Engine Tests Confirm Model Test Results
- Up To 2.5 EPNdB Cumulative System benefit for a BPR=5 engine
- Minimal Performance Impact
Jet Noise Reduction Technology

Future Chevron Nozzle Development and Challenges

• Second Generation Chevron Designs
  ➢ A project has been initiated to develop effective Fan nozzle Chevrons
  ➢ Current Chevron designs have been optimized for engines with bypass ratios of ~6 and are less effective for higher bypass ratios cycles with lower jet velocities
  ➢ Work is underway to develop Second Generation Chevrons that perform well for high bypass ratio engines
  ➢ Development of low-loss Chevron Designs Underway
    - Smart Materials Chevrons
    - Fluidic Chevrons
Fan Noise Reduction Technology

- GE Universal Propulsion Simulator (UPS) has produced:
  - invaluable fan noise design database
  - improved aero/acoustic understanding of fan/OGV interaction
- Recent NASA AST-Funded Tests:
  - High Tip Speed CF6 type fans (HSF)
  - Source Diagnostic test of GE90 type fans (SDT)
- Joint GE/Boeing UPS test of Growth GE90-115B Fans
  - 3 Fan Rotor configurations
  - Acoustic liner Studies

The GE UPS is an Invaluable Tool for the Development of Low Noise, High-Performance Fan Technology
Fan Noise Reduction Technology

NASA AST High Speed Scale Model Fan Test

Rotors

- **SH**: 34-Blade Shrouded Rotor Baseline ~CF6-80E1
- **WC**: 24-Blade Wide Chord Radial Rotor
- **FS**: Forward-Swept Wide Chord Rotor Allison Design

OGV's

- **80R**: 80 OGVs - Modest Sweep Baseline ~CF6-80E1
- **80SL**: 80 OGVs - Swept & Leaned
- **52IV**: Integral Vane-Frame (52 Vanes) a'la GE90

**CF6-Size Engine Swept & Leaned OGV Reduces Fan Noise by 3-EPNdB Without Aerodynamic Performance Loss - Great Achievement!**
Fan Noise Reduction Technology

Best Configurations Comparisons - CF6 Size

NASA AOI 14
Comparison of Best Configurations With Baseline

Altitude = 2200 ft
Flight Velocity = 284 ft/sec

2-Engine Level Flyover, EPNdB

Fan Corrected Tip Speed, ft/sec

Approach
Cutback
Sideline

SH 80R
SH 80SL
WC 80SL
WC 52IV
## Acoustic Benefits Summary (Fan Noise Only)

**CF6 Size - Cumulative Margin Improvement**

<table>
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<tr>
<th>Rotor Type</th>
<th>WC</th>
<th>SH</th>
<th>FS</th>
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<tr>
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<td>80SL</td>
<td>-3.4</td>
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</table>

OGV Type: 52IV, 80R, 80SL
Fan Noise Reduction Technology

**NASA AST Source Diagnostic Test**

**Two Rotor Designs:**
- **R4** - Alternative to M4 (Early GE90 Design)
  - 1215 ft/sec Design Tip Speed
  - 1.5 Fan Pressure Ratio
  - 22 Blades
- **M5** - Higher Speed Version of M4
  - 1350 ft/sec Design Tip Speed
  - 1.5 Fan Pressure Ratio
  - 22 Blades

**Three Vane Designs:**

- **Baseline**
  - 54 Vanes, Integral Vane-Frame Design
  - Cut off Blade Passing Tone
  - Similar to GE90 Architecture

- **Low Vane Count**
  - 26 Vane Version of Baseline
  - Low Vane Count Introduced to Reduced Broadband Noise
  - Cut on Blade Passing Tone

- **Low Noise Vane**
  - 26 Vanes Swept Version of Low Vane Count
  - Cut on Blade Passing Tone
  - Sweep Introduced to Reduce BPF
Fan Noise Reduction Technology

Effects of OGV Design - R4 Blade
Nominal Tip Clearance
Scaled to Full Size

OGV Type
Tip Clearance
- BL
- LVC
- LN

Percent Speed

EPNL

40 50 60 70 80 90 100 110

394 ft Altitude
2600 ft Altitude
Fan Noise Reduction Technology

Acoustic Benefits Summary (Fan Noise Only)
Full Size - Cumulative Margin Improvement

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OGV Type

54BL  LVC  LN
Fan Noise Reduction Technology

Development of Fan Noise Reduction Technologies through Scale Model Fan/Nacelle Wind Tunnel Demonstration and Prediction/Design Tool Validation Tests
Fan Noise Reduction Technology

Joint Boeing/GEAE UPS GE90-115B Acoustic and Performance Testing in Boeing LSAF

Acoustic Evaluation Of Three Different Fan Blade Types

Fwd Swept

High Flow Swept

Radial
Fan Noise Reduction Technology

Joint Boeing/GEAE UPS GE90-115B Test in Boeing LSAF

Test Evaluation of Acoustic Treatment Designs:
• 3 For The Exhaust Duct
• 2 For The Pylon

Data Used to Optimize the GE90-115B Treatment Design and Validate Treatment Design Tools
Acoustic Liner Technology

Current Technology
Two Layers of Impervious Honeycomb

New Technology
Single Layer of Permeable Honeycomb

New Acoustic Liner Technology Promises Improved Noise Suppression & Reduced Manufacturing Costs
Fan Noise Reduction Technology

Advanced Tools Development

Establish linkage between fan flow field and noise through:

- Diagnostic Flow Field Measurements
- CFD Analysis
- Advanced Aeroacoustic Computational Modeling
- Validation With High-Quality Controlled Experimental Fan Data
Better Codes & Databases for Acoustic Design

Fan & Nacelle Noise Evaluation Tools

Aeroacoustic Computer Codes & Models

Scale Model Fan Test Vehicle

Scale Model Testing Validates Analysis Prior to Full Engine Test
Multiple Pure Tone Noise Analysis

Better Codes - MPT Noise Analysis

Wide Chord Radial Rotor

Forward-Swept Wide Chord Rotor

Delta MPT Noise Radial - Forward Swept Wide Chord Rotor

Corrected Speed

Data

Analysis

CFD Prediction of Fan Blade Bow Shocks

CFD-Based Analysis Method Developed in AST Program Being Used to Assess Fan Designs for MPT (Buzzsaw) Noise
Better Codes - Turbine Acoustic Analysis

3D CFD Being Used to Assess Acoustic Cut-off for LP Turbines
In-Service Engine Noise Upgrade Packages

Noise Reduction Upgrades Under Study For CF6-50-Powered Aircraft

Evaluations of the noise reduction packages shows the ability to achieve Chapter 3 with 5 EPNdB Cumulative Margin
In-Service Engine Noise Upgrade Packages

Potential Noise Reduction Upgrades
For CF6-50 Powered Aircraft

Hardwall Fan Case Panel
- Benefits Approach and Cutback

Fan case & reverser lining changes
- Benefits all conditions

Improved Core Nozzle Acoustic Treatment
- Reduces LPT Noise
- Major Benefit at Approach, some at Cutback

Cutoff Turbine (optional)
- Benefits Approach and Cutback

Chevron Exhaust Nozzle *
- Benefits Sideline and Cutback

Upgrade Package Will Improve Noise Margin at All 3 Certification Points
Engine Validation

Noise Reduction Technology Validation

Engine Noise, Noise Reduction Features, and Diagnostic Measurements Evaluated at GE's Peebles, Ohio Outdoor Acoustic Test Site
Engine Validation

Noise Reduction Technology Development

Barrier Testing to Isolate Engine Sources, Evaluate Noise Reduction Concepts

- Jet Noise
- Fan Noise
- Combustor Noise
- Turbine Noise
- Liner Suppression

Swept/Leaned OGV Design Tested On CFM56 Engine

Chevron Nozzle Tested on CF6 Engine
Noise Reduction Technology Transition

Example of noise benefit change during research program

3 Proof of concept
4 Laboratory test
5 Rig Test
6 Engine Test
7 Flight Test

Feasibility studies demonstrate worthwhile benefit

Validation test with artificial noise source confirms noise benefit

Potential Variation in Benefit for Technology Readiness Level X

Benefit significantly reduced for realistic engine sources

Implementation delayed by need to develop associated technology

System adjusted to meet real aircraft environment

Research

Time
AST Noise Reduction Technology

Summary & Future Prospects

- Considerable Progress Has Been Made in Noise Reduction Technology
- New Products likely to Have "GE90-Like" Cycles - an inherent noise advantage
- Some concepts are maturing - Chevron Nozzles, Advanced Inlet Acoustic & Exhaust Treatment, Swept Vanes - available for potential application to existing products and product derivatives
- Introduction of noise reduction technologies takes time:
  - Concept Demonstration to production readiness - 5+ years
  - Realization - Some Benefit is lost in the transition - 20 to 25%
  - Time for new products to significantly penetrate the fleet and have a significant community noise impact
- New Concepts/Technologies Have to be Mature and Cost Effective!
- Future Focus - Noise Reduction Technologies which provide benefits to both Industry and the Environment
Engine Noise Reduction for Large Quad-Sideline
Comparison of GE and P&W Studies, BPR=5, Source Reduction Only
(Tabs/Chevrons, Swept Stators)

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Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Engine Noise Reduction for Large Quad - Approach
Comparison of GE and P&W Studies, BPR=5, Source Reduction Only
(Tabs/Chevrons, Swept Stators)

- GE '92 Tech.
- GE Source Red.
- P&W '92 Tech.
- P&W Source Red.

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EPN/A
Engine Noise Reduction
Aerospace Vehicle Systems Technology Program

Engine Noise Reduction for Large Quad - Sideline
Results From P&W Study

P&W '92 Tech.  BPR=5+Source Red.  BPR=5+Source+Nac.
ADP Cycle Only  ADP+Source  ADP+Source+Nac.

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Engine Noise Reduction for Large Quad-Approach
Results From P&W Study

- Engine Noise Reduction for Large Quad-Approach
- Results From P&W Study

- Engine Noise Reduction
- Aerospace Vehicle Systems Technology Program

- P&W '92 Tech.
- BPR=5+Source Red.
- ADP Cycle Only
- ADP+Source
- BPR=5+Source+Nac.
- ADP+Source+Nac.

- Airframe
- Combustor
- Fan Exhaust
- Fan Inlet
- Jet
- **Engine Sum

- EPNdB

- 98.1
- 94.94.94.94.94.1
- 99
- 96.7
- 96.5
- 100.65
- 96.1
- 93
- 89.8
- 89.5
- 93
- 85.5
- 89.8
- 73
- 73
- 73
- 73
- 98.9
- 96.2
- 93.2
- 91.7

- P&W Technology Program Logo

- NASA Logo