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Noise Reduction Technologies for Turbofan Engines

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ABSTRACT

Significant progress continues to be made with noise reduction for turbofan engines. NASA has conducted and sponsored research aimed at reducing noise from commercial aircraft. Since it takes many years for technologies to be developed and implemented, it is important to have aggressive technology goals that lead the target entry into service dates. Engine noise is one of the major contributors to the overall sound levels as aircraft operate near airports. Turbofan engines are commonly used on commercial transports due to their advantage for higher performance and lower noise. The noise reduction comes from combinations of changes to the engine cycle parameters and low noise design features. In this paper, an overview of major accomplishments from recent NASA research programs for engine noise will be given.

1 INTRODUCTION

Significant progress continues to be made with noise reduction for commercial aircraft (Figure 1). NASA has conducted and sponsored research aimed at continuing this trend, especially as air traffic grows and the impact of noise on the community will increase if the noise levels are not reduced. Since it takes many years for the technologies to be developed and implemented, it is important to have aggressive technology goals that lead the target entry into service (EIS) dates. “Cum” is a term used to combine takeoff, cutback and approach certification margins relative to regulation noise levels (Stage 3 or Stage 4). Effective Perceived Noise Level (EPNL) in decibels is a certification metric used for aircraft. It evaluates both the noise amplitude and duration at a single measurement point during a flyover.

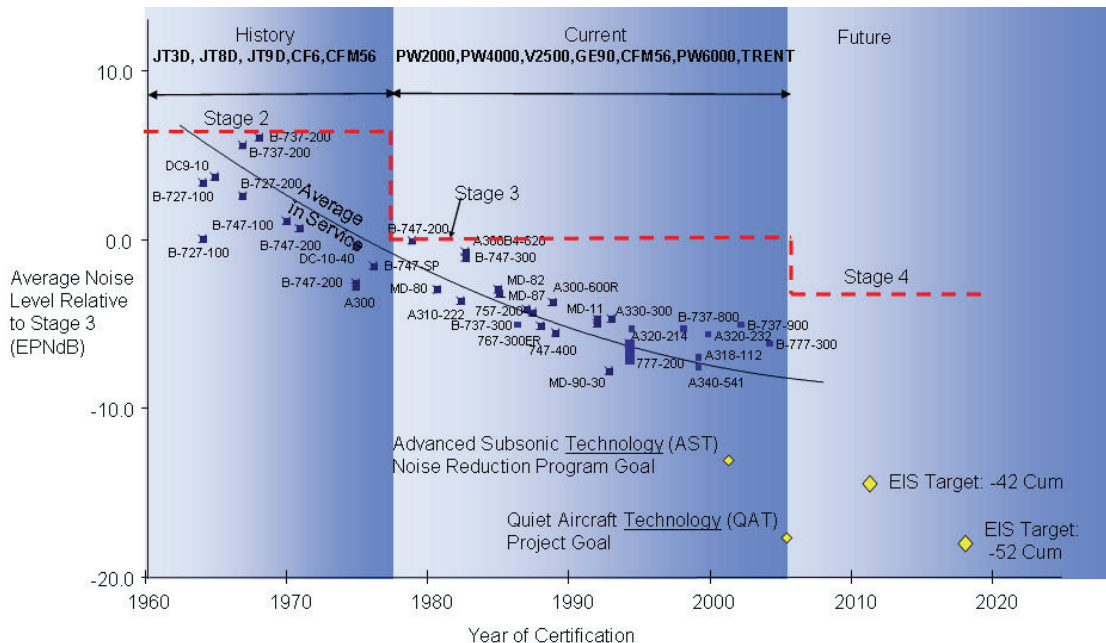


Figure 1: Progress in aircraft noise reduction.

Engine noise is one of the major contributors to the overall sound levels as aircraft operate near airports. Turbofan engines are commonly used on commercial transports due to their advantage for higher performance and lower noise. The noise reduction comes from combinations of changes to the engine cycle parameters and low-noise design features. Engine noise sources principally come from the fan (including the stator), the exhaust (also referred to as the jet), the compressor, the combustor, and the turbine (Figure 2).

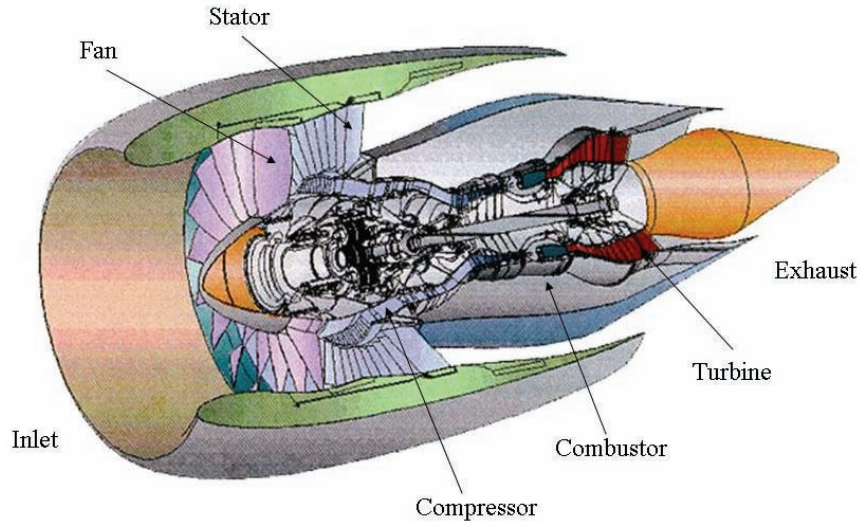


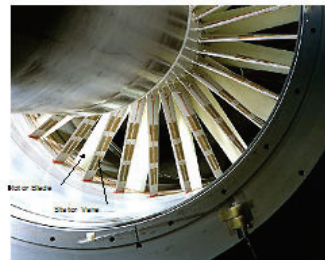
Figure 2: Dominant engine noise sources.



(a) Ultra-High Bypass Ratio



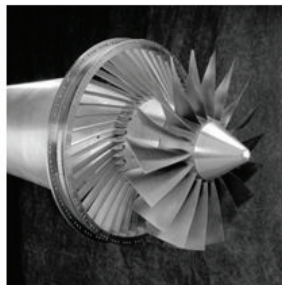
(b) Scarf Inlets



(c) Active Noise Control



(d) Forward-Swept Fans



(e) Swept/Leaned Stators



(f) Chevron Nozzles

Figure 3: Selected noise reduction concepts.

2 NOISE REDUCTION

A common development path for noise reduction concepts is to first explore an idea in sub-scale model tests. This is usually done in two steps: 1) Proof of concept experiments designed by either experimental intuition or guided by analyses, and 2) Higher fidelity experiments that faithfully model the flow conditions and geometry that is representative of a full scale application. For the latter, experiments have concentrated on engine components with emphasis on dominant sources such as fans and jets to quantify the amount of reduction that can be achieved from various noise reduction methods. Since simulating flight conditions is important, these tests are typically done in large wind tunnels and free jets with sufficient distance from the source to the microphones to project noise levels to the far field. NASA's role has been to conduct both the fundamental experiments (sometimes verifying results from other laboratories) and the higher fidelity experiments in cooperation with universities and aerospace organizations. It has been useful to the entire community to conduct experiments in common facilities to improve the quality of comparisons. A pictorial of selected noise reduction technologies that were developed in the 1990's during NASA's Advanced Subsonic Technology (AST) Noise Reduction Program is shown in Figure 3.

2.1 Fan Noise Reduction

Fan noise is a strong function of the rotational tip speed and fan pressure ratio. The surest way to reduce fan noise is to reduce the tip speed and pressure ratio, but this causes the engine diameter to increase to recover thrust. Optimization studies show the best fan speed for takeoff is where the rotational tip speed is just under Mach = 1 to eliminate shock associated noise. Once this has been achieved in an engine design, the fan pressure ratio becomes the controlling factor for broadband noise. The source for this noise is the turbulence in the fan wakes striking the stators and the resulting unsteady pressure field that becomes acoustic waves and radiates from the engine fan duct. Another advantage to reducing fan tip speed and pressure ratio is the number of noise sources are reduced, which helps make noise reduction design features more effective.

The picture in Figure 3a shows a model scale fan, called the Advanced Ducted Propulsor (ADP) "Fan 1", of an Ultra-High Bypass Ratio (UHBR) engine concept by Pratt & Whitney. Results showed that significant noise reduction can be achieved by lowering the fan tip speed and pressure ratio (i.e. change engine cycle parameters). Several tests were done to quantify the benefits of adding combinations of acoustic treatment, casing treatment for stall control, and the effect of continuing to lower the fan tip speed while maintaining constant fan pressure ratio.¹⁻⁴ The results from these tests were used by Pratt & Whitney to design their "Geared Turbofan (GTF)" engine, which has the potential of meeting the "42 cum" EIS target shown in Figure 1, assuming additional noise reduction concepts are applied to both the engine and the airframe.

A "scarf inlet" (Figure 3b) can be used to reduce inlet fan noise by redirecting the forward radiated sound away from the community. Several tests were done on engines that showed significant noise reduction.⁵ As computational methods continue to improve, applications of scarf inlets are expected since optimizing the aerodynamic design for both cruise and takeoff will be possible.

Active noise control was investigated for fan noise reduction (Figure 3c). A special fan rig called the "Advanced Noise Control Fan" (ANCF) was built and used in a wide range of experiments.⁶⁻⁷ Actuators designed to cancel fan tones were mounted in fan duct walls and inside stator vanes. A series of tests were performed to show single and multiple duct mode cancellation from both the inlet and exhaust of the fan duct.⁵ Strategies evolved to selectively target modes that only affect directivity patterns that impact community noise during takeoff and

landing. Hybrid systems were also developed that integrate acoustic treatment. Practical applications of active noise control in turbofans remains a development issue. As newer engine cycles become less tone dominant, the incentive to use active noise control diminishes unless methods for broadband noise can be developed.

Forward-swept fans (Figure 3d) help reduce noise associated with shocks by delaying the onset of “multiple pure tones”. Many of the modern fan designs use fan sweep near the tip to reduce aerodynamic losses associated with shocks and improve stall margin. There is also evidence that additional mass flow through the fan can be achieved. NASA supported several tests in the late 1990’s of forward-swept fans.⁸⁻¹¹ The designs were aggressive and some experienced part-speed flutter problems.

Swept stators (Figure 3e) have been found to reduce fan noise by increasing the phase changes from hub-to-tip of the unsteady aerodynamics producing the sound and by increasing the effective distance from the fan to the stator vanes. A test performed with the Allison Engine Company (now Rolls-Royce) was one of the first fan noise tests done in the AST program where the design was guided by higher fidelity noise prediction methods.¹² The experiment conclusively showed about a 3 EPNdB fan noise reduction.¹³

In addition to the fan noise reduction concepts shown in Figure 3, there have been newer concepts investigated over the past five years as a part of NASA’s Quiet Aircraft Technology (QAT) project. A recent test using a scale model simulating a GE-90 engine showed that variable area nozzles can be used to reduce the fan noise and increase the thrust. Variable area nozzles have been suggested for many years as a way to reduce jet noise (lowers the jet exit velocity), but it also appears to reduce fan noise by controlling the incidence angle of the flow near the rotor and stator. Sound power level results highlighted in Figure 4 show the noise reduction benefits.¹⁴⁻¹⁶

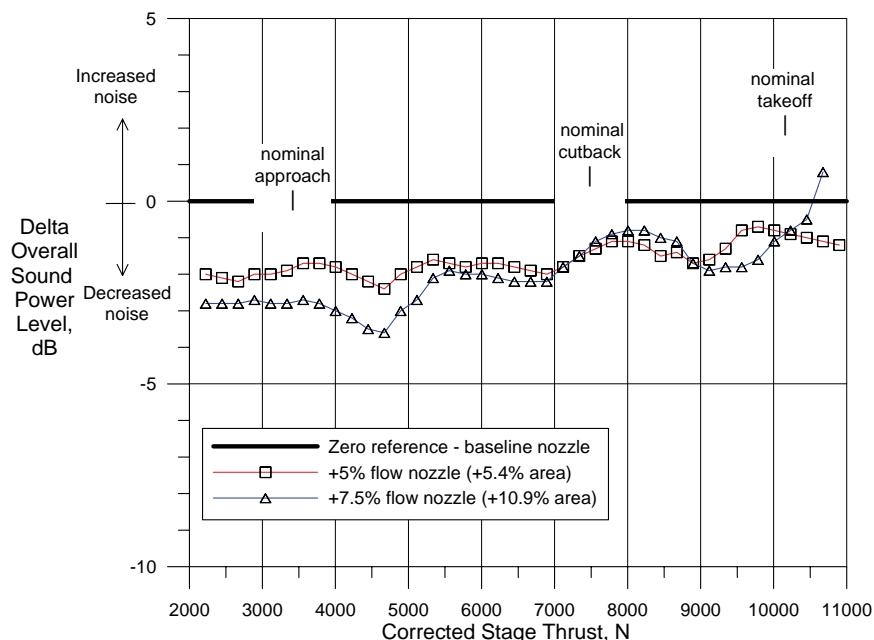


Figure 4: Change in overall sound power level as a function of fan stage thrust for two nozzle areas.

An extensive investigation of fan trailing edge blowing was done to see if filling the fan wakes by injecting air at the trailing edge of the fan blades could reduce noise. Predictions with computational methods (aerodynamics and acoustics) showed that filling the fan wake reduces

both the wake defect (which impacts tones) and the turbulence intensity (which impacts broadband noise). Proof-of-concept tests were done by MIT¹⁷ and NASA in the ANCF rig.¹⁸ In 2005, a test on a fan similar to the ADP “Fan 1” was completed. The results show successful filling of the fan wakes over portions of the span, as evident by fan wake measurements taken of the flow field downstream of the fan. Both tone reductions and low frequency broadband noise reduction were observed.¹⁹ Figure 5 shows how air was pumped within the hub of the fan, through specially designed passages within each blade, and injected at the trailing edge.

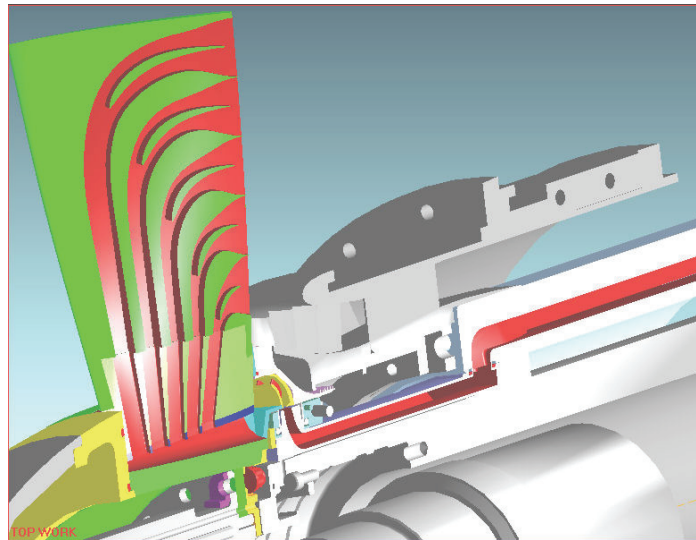


Figure 5: Fan trailing edge blowing concept.

Since the fan wake/stator interaction noise is the dominant fan noise source, methods for reducing the noise directly at the source have been developed. A “soft” vane concept has been developed that reduces the unsteady pressure response on the stator surface and absorbs energy that would eventually become sound radiating from the stator. It is possible to tailor the design for specific frequency ranges. Tests have been done in the ANCF rig that used prediction codes like V072 (presented in section 3.1) to design the vanes.

Another promising fan noise reduction technique is to increase the acoustic treatment area over the tip of the rotor. Existing engines only use acoustic liners in the inlet and aft fan ducts, and sometimes in the inter-stage region. They usually use honeycomb materials with porous or felt metal face sheets to provide maximum insertion losses around a desired target frequency. It has been known for many years that bulk materials provide better noise reduction over a range of frequencies, but the materials used are not suitable for engine applications due to harsh environments. NASA has found that metal foams can be used to provide favorable bulk liner properties that also meet engine requirements over a range of temperatures for either the core or fan ducts. A material known as “Haynes 25” metal foam has been tested acoustically in the ANCF rig at NASA Glenn and shows significant noise reduction over a range of frequencies and fan speeds. The foam was mounted over the fan rotor to increase the effective treatment area and serve as a multifunctional acoustic treatment/rub strip. Studies have also shown that fan containment structures can be integrated with the metal foam. Lighter weight, alternative metal foams are currently being developed. Figure 6 shows the noise spectra for sample inlet and aft angles (labeled “mic loc” and measured from the inlet engine axis) with and without the metal foam acoustic treatment. Results show that significant noise reduction can be achieved. In fact

the amount of noise reduction with just the treatment located over the rotor exceeds inlet and aft insertion losses with the treatment located in just the inlet or aft fan ducts. Combining treatment over the rotor with conventional inlet and aft treatment is expected to increase the overall noise reduction.

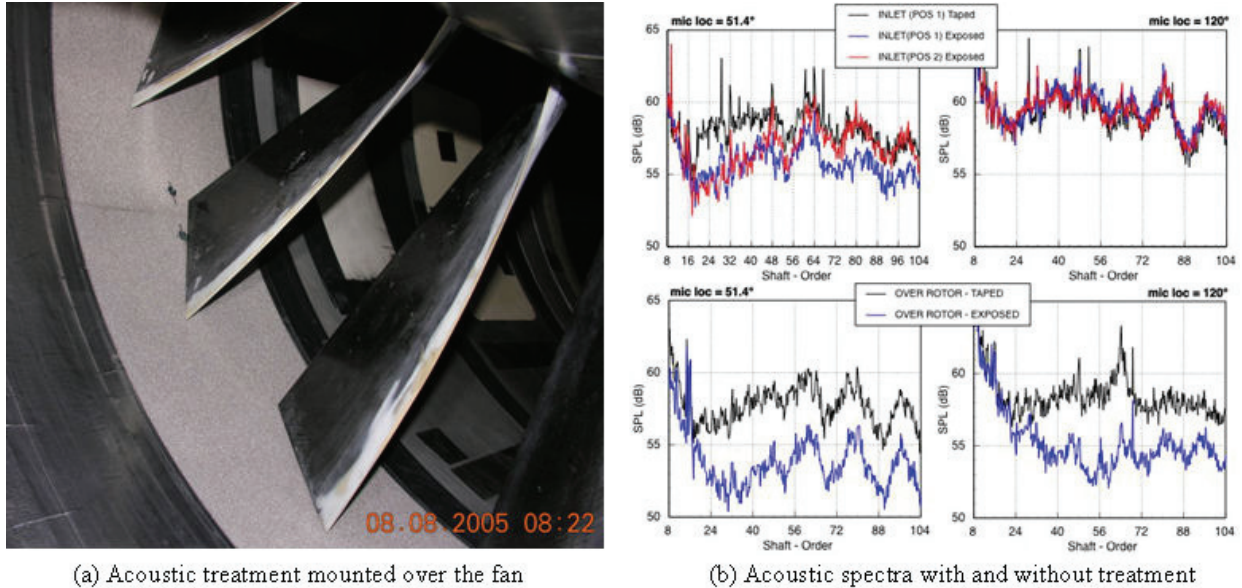


Figure 6: Over the rotor acoustic treatment.

2.2 Jet Noise Reduction

Jet noise reduction is usually achieved by lowering the jet exhaust velocity. Newer engine designs such as the GE-90 take advantage of this by using the engine cycle to extract energy from the engine core and reduce the mixed velocity of the core and fan ducts. Just as with fan noise research, model scale tests are used to evaluate new exhaust nozzles and noise reduction concepts. For the UHBR engine cycle mentioned in section 2.1, tests were performed with nozzles simulating the separate flow exhaust. Significant jet noise reduction was verified in tests performed at the United Technologies Research Center.²⁰

It is highly desirable to reduce the jet noise without changing the engine cycle. Over the years, this has proven to be a challenging problem. In 1996, a jet noise reduction concept using “chevron nozzles” was tested at NASA that reduces the jet noise by mixing the core and bypass flows in a way that reduces low frequency mixing noise from highly turbulent flows. This was a major breakthrough for separate flow exhausts and one of the first successful tests where a jet noise reduction concept did not significantly impact thrust. Model scale tests using chevron nozzles shown in Figure 3f have shown reduction in jet noise by about 2.5 EPNdB without changing the engine cycle. The thrust loss was shown to be less than 0.50%.²¹ There are chevron nozzles in production today on several commercial aircraft as a result of these tests (Figure 7).



Figure 7: Chevron nozzle on General Electric's CF34-8C engine.

3 NOISE PREDICTION

Noise prediction methods for engine systems typically rely on empirical correlations for engine components. Overall sound pressure/power levels and directivity information is characterized as a function of engine operating parameters for each component. Data bases from engine and model scale tests are used to update the correlations, which means the noise estimates are less reliable when made outside of the design envelope. Higher fidelity models have been developed that use Computational Fluid Dynamics (CFD) and Computational AeroAcoustics (CAA) to predict the noise spectra from first principles. While these codes take days or months to complete a limited number of design points, they provide insight into the physics of the noise generation process and can be used to improve the faster empirical methods through reduced order modeling. NASA has concentrated engine source noise prediction development on fan and jet components.

3.1 Fan Noise Prediction

Improvements have been made in fan noise prediction in the development of the V072²², TFaNS²³, BFaNS²⁴, and LINFLUX²⁵ codes. The V072 code predicts inlet and aft fan duct sound power levels as a function of engine speed for rotor stator interaction noise sources. It is computationally efficient since it relies on classical unsteady aerodynamic methods, but does not reliably predict the correct distribution of sound power over a range of propagating duct modes. It also does not predict noise for supersonic tip speed fans that typically need a model for the rotor self noise. The TFaNS code couples the inlet, fan rotor, stator, and nozzle and accounts for duct liners using impedance models in the frequency domain. The LINFLUX code solves the linearized Euler equations and can be used to replace the rotor/stator source model in TFaNS to model more realistic steady flows (blade geometries, swirl). It has been shown that these codes provide a better prediction of the duct power levels on a mode by mode basis and proper trends in tone levels with varying geometric parameters such as stator vane number (Figure 8). In the future, time marching methods will be used for simultaneous broadband and tone noise prediction. A CAA code called "BASS" has been under development for several years.²⁶

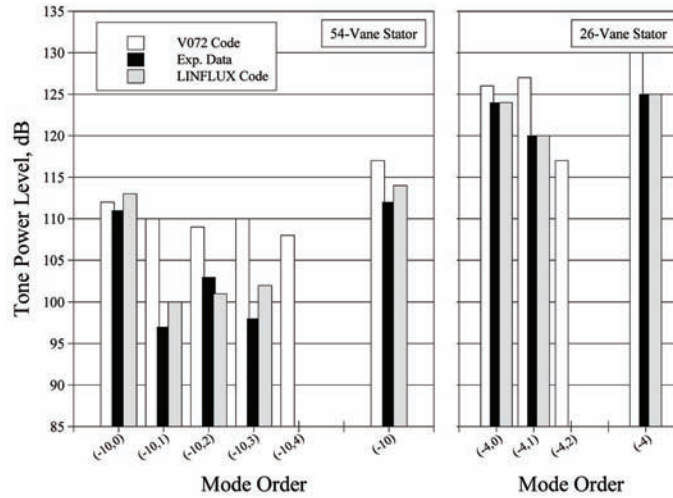


Figure 8: Fan noise prediction, (circumferential, radial) duct modes.

3.2 Jet Noise Prediction

For jet noise, the MGBK²⁷ and JeNo²⁸ codes have been shown to provide good acoustic spectra directivity predictions for cold single and dual flow nozzles over a range of nozzle pressure ratios representative of subsonic vehicles. Improvements are still needed for hot jets. Figure 9 shows how the level of agreement has improved using the JeNo code for a conical nozzle. In recent years, predictions have been reliably used to guide noise reduction experiments. The JeNo code has been applied to chevron nozzles and “offset” nozzles and has predicted the proper trends for noise reduction on a spectral basis.

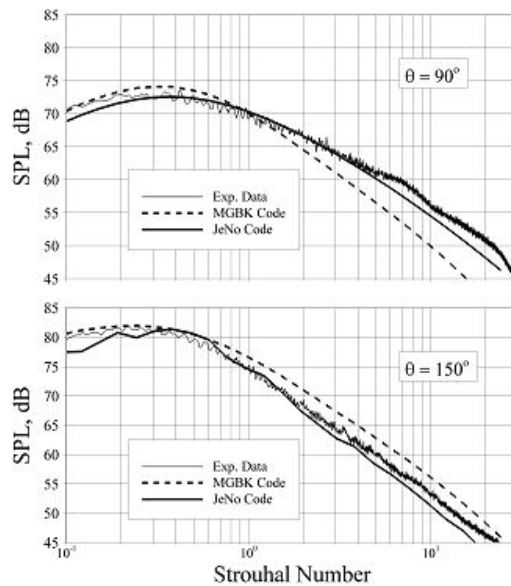


Figure 9: Jet noise prediction, theta measured relative to inlet axis.

4 FUTURE OPPORTUNITIES

While there has been significant progress toward noise reduction for commercial aircraft, further noise reduction is needed before all of the objectionable noise is contained within airport boundaries. NASA estimates that this will require another 10 EPNdB reduction (30 cum) beyond the goals shown in Figure 1. It is likely that future aircraft will need to look much different from the “tube and wing” configurations flown today. Strategies for mounting the engines above or within the wings will provide additional shielding. Distributed propulsion systems integrated with the wing show promise for better performance and lower noise, and will be a major research topic over the next decade in NASA’s new Subsonic Fixed Wing project in the Fundamental Aeronautics program.

5 SUMMARY

A review of recent research conducted and sponsored by NASA for turbofan engine noise reduction has been presented. Engine systems where cycle changes lower the fan tip speed, lower the fan pressure ratio, and lower the jet exhaust velocity are the best way to achieve significant noise reduction. Further noise reduction can be realized by applying design features that reduce noise with minimal impact to performance. Examples of these technologies have been presented and include scarf inlets, active noise control, chevron nozzles, forward swept fans, swept and leaned stators, variable area nozzles, fan trailing edge blowing, “soft” stator vanes, and acoustic treatment placed over the fan. Progress has been made developing fan and jet noise prediction tools. Methods available today combine CFD and acoustic analyses, and do a better job of predicting changes in geometric parameters than the traditional empirical methods. Future work is needed developing technologies for both engine and airframe noise in order to meet more stringent noise standards near airports.

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