JET NOISE REDUCTION TECHNOLOGY DEVELOPMENT AT GE AIRCRAFT ENGINES

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Abstract

Several years ago, GE Aircraft Engines realized that with the expected increased stringency of Stage 4 noise regulations, the continued thrust growth of engine families, and increasing environmental pressures, jet noise would become a restricting factor in aircraft operations. An internal research and development program, with some invaluable assistance from NASA, was started to investigate how to reduce jet noise while achieving acceptable impacts on performance, operability, manufacturability, weight, etc.… The chevron nozzle for separate flow exhaust systems was the outcome, reducing jet noise by enhancing mixing of the fan, core and ambient streams faster than conventional nozzles, with a minimal impact on performance. The chevron nozzle, consisting of cut-outs around the perimeter of the nozzle, generates stream-wise vorticity, enhancing the mixing between the two streams, reducing the peak velocity more quickly and therefore reducing peak noise. The physical blockage is very small with this concept, with relatively small impact on thrust and flow, attributed to the aerodynamic blockage of the streamwise vortices. This technology was developed in 1996, became part of a production exhaust system in 1999, and was first flown on an airplane in 2001. This paper provides a brief overview of this technology.

1 Introduction

In January of 2001 the proposal for a new aircraft noise certification standard (ICAO Annex 16, Vol. 1, Chapter 4) was announced, requiring 10 dB margin to Annex 16, Chapter 3, with the sum of any two certification points totaling at least 2 dB, and no trades between points. This new standard was anticipated, and some current engine aircraft combinations were known to require changes to remain in compliance. Trades were allowed in the past where at one certification point the noise could be above the certification limit. In cases where an aircraft had low noise at two certification points but exceeded the allowable limit at a high power setting associated with take-off, for example, it could still be compliant with certification rules, as long as the noise level did not exceed the rule by more than 2 dB. Also, over the years engine families have grown, in many cases with increased throttle settings to compensate for heavier or extended range aircraft, which raises the exit velocity of the jet. As a rule of thumb, jet noise correlates with V^8 [1]; thus any increase in jet velocity corresponds to a very fast increase in noise.

GE Aircraft Engines has a fairly extensive history in jet noise and jet noise reduction work, dating back to the late 1950’s. Figure 1 shows a time history of some of the major jet noise reduction initiatives GE Aircraft Engines has been involved with. Most of these focused on high speed jet noise, but in the late 1980’s NASA initiated the Advanced Subsonic Technology program (AST), with a component of this focused on jet noise reduction for commercial high bypass ratio engines [2,3]. The Supersonic Transport (SST) and the High Speed Civil Transport (HSCT) programs are good examples which show the difficulty of jet noise reduction, because both of these programs were canceled before making it to the product stage, and a large factor in each of these

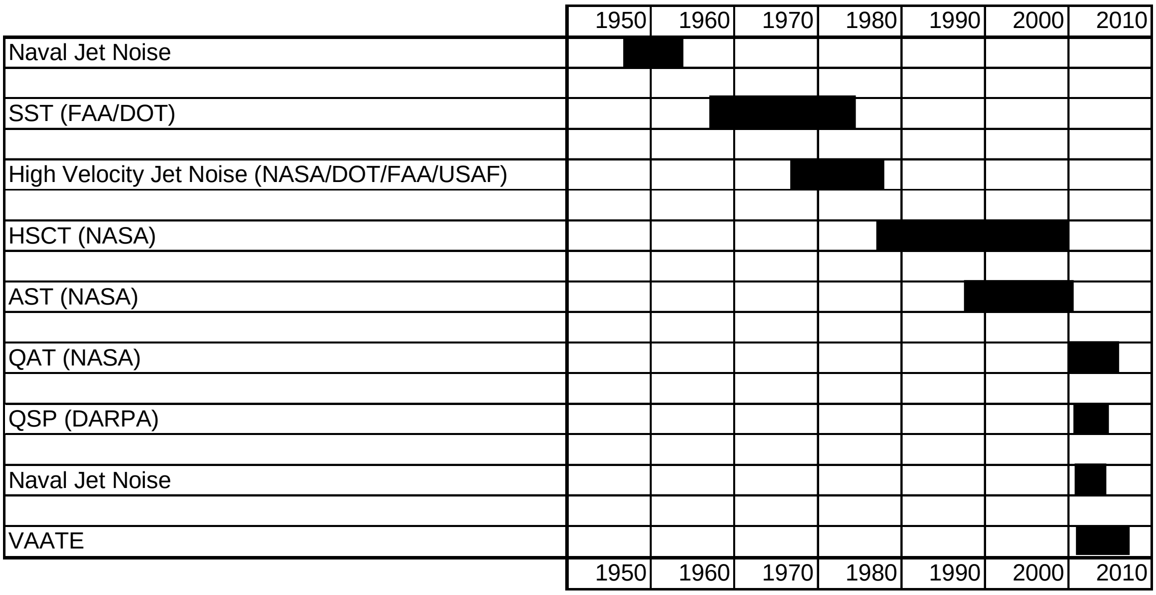

Figure 1 History of jet noise reduction programs GE Aircraft Engines has been involved in.

cancellations was the problem of high jet noise levels and the lack of a technically and economically acceptable means to reduce jet noise. In simplest terms, to reduce jet noise you must reduce the velocity of the jet plume. For example, the newest and largest turbofan engines have incorporated higher and higher bypass ratios, thus lower exhaust velocities for the same level of thrust and a corresponding lower level of jet noise (Bypass ratio is the ratio of the mass flow through the fan bypass stream to that through the core of the engine). With the turbofan a relatively high flow is generated through the fan and bypasses the engine core, exiting at a lower velocity compared to that exiting the core of the engine. Figure 2 shows the trend of noise levels for a number of commercial aircraft. In the late 1950's state of the art engine technology was the turbojet, which had very high noise levels, the majority of which was due to very high levels of jet noise. Over the following decades the turbofan was developed and the bypass ratio has been increasing steadily. Through the 1970's and 1990's turbofan engines typically had bypass ratios on the order of 4-5, with jet noise still remaining the dominant source of aircraft noise at take-off. Over the last few years, new turbofan engines have been developed with bypass ratios on the order of 6-9. In these newer designs, the other noise sources (fan and turbomachinery) are beginning to overtake that of jet noise. The noise level reductions seen in this figure are mostly attributed to the increase in bypass ratio, as well as advances in quiet fan and turbomachinery designs. The real question now becomes: How do you reduce jet noise, in an existing engine or if it's not practical to increase the bypass ratio further in a new engine? This is the question that the chevron nozzle technology was intended to address. To reduce the effective velocity exiting from the exhaust nozzle, the air must be encouraged to mix faster with the surrounding fluid and entrain more of this flow. In the case of very high-speed jets, the ambient flow is typically brought into the high velocity core stream with some type of ejector system, usually with a mixer [4]. However, this technique is not always the most aerodynamically efficient, and the performance, weight, and drag impacts can make them impractical for most commercial applications. The other associated byproduct of using a mixer to encourage strong mixing of two flows is the generation of high frequency noise. Related to enhanced mixing is the accompanying increase in smaller scale turbulence, and jet noise reduction has always been a careful balancing act between low frequency noise reduction (decreased mean velocity) and high frequency noise generation (increased turbulence/small scale mixing). For supersonic applications, a relatively long duct is used downstream of the mixer, sometimes lined with acoustic treatment to attenuate the excess high frequency noise generated by the mixing. This is also the type of configuration used for many older Stage 2 engines, which have incorporated 'hush-kits'. Also, long-duct, mixed-flow engines, which mix the core and fan streams with a lobed mixer, may incorporate this jet noise reduction design. However, this type of exhaust system has a relatively longer length, higher weight, and increased scrubbing drag. Alternatively, a properly designed chevron creates streamwise vorticity which enhances the mixing between the fan and core streams with little to no increase in high frequency noise.

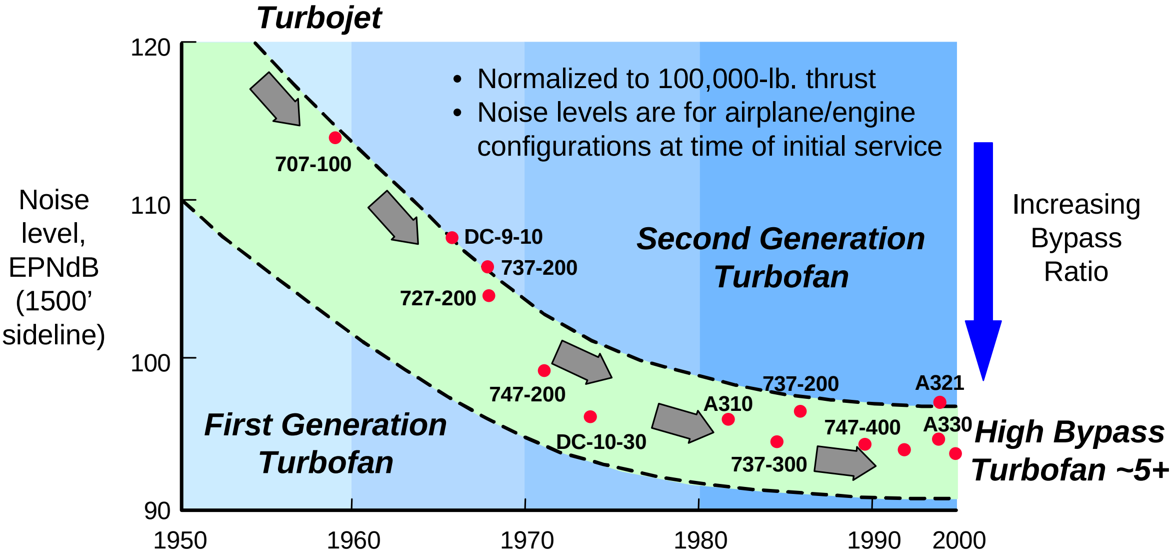

Figure 2 History of commercial aircraft noise levels and progression of engine type and bypass ratio.

2 The Chevron Nozzle

2.1 Chevron Nozzle Development Program

A program was started in early 1999 to develop a noise reduction upgrade package for the CFM56-5B engine. This engine was developed jointly by GE Aircraft Engines and Snecma Moteurs, to power the A321 narrow body aircraft, and has been in passenger service for many years. The upgrade package was envisioned to ensure that this aircraft would meet the new Chapter 4 noise certification requirements and allow this widely utilized aircraft to continue to operate without noise restrictions.

The chevron nozzle is a major element of this upgrade package, forecast to provide a significant amount of noise reduction. The specific goal was to maximize the noise reduction with the chevron while minimizing any negative impacts on the rest of the engine/aircraft system. This has been a very successful program and the remainder of the paper summarizes the test results obtained at the GE Aircraft Engines acoustic test facility, Cell 41.

The overall chevron development program contained many elements that resulted in an excellent noise reduction design. The approach started with computational fluid dynamic studies (CFD) of different chevron designs, a number of which were built and tested on a 1/11th linear scale model of the exhaust system. These tests were used to determine the jet noise reduction compared to the current production exhaust system both for static conditions as well as for simulated forward flight. This test was used to downselect to a smaller number of viable acoustic designs and then tested for performance (flow and thrust coefficient). After another round of down-selecting, taking into account the noise reduction and effect on flow and thrust, the scale model was tested at the CEPRA 19 acoustic facility at ONERA with a 1/11th scale model of the A321 wing. This test ensured that there were no major installation or integration effects on the acoustic performance of the chevron nozzle.

2.2 Facility

The acoustic results discussed in this paper were obtained at GE Aircraft Engines test facilities. The GE Aircraft Engines Cell 41 anechoic free-jet noise facility, shown in Figure 3, is a cylindrical chamber 43 feet in diameter and 72 feet tall. The inner surfaces of the chamber are lined with anechoic wedges made of fiberglass wool to render the facility anechoic above 220 Hz. The facility can accommodate single and dual flow model configurations, the dual flow representing the core and fan stream of a typical high-bypass ratio, separate flow exhaust system. The two streams of heated air for the dual flow arrangement, produced by two separate natural gas burners, flow through silencers and plenum chambers before entering the test nozzle. Each stream can be heated to a maximum temperature of 1960 ^{o}R with nozzle pressure ratios as high as 5.5, resulting in a maximum jet velocity of 3,000 ft/sec, with throat areas of 22 in^2 and 24 in^2 for the core and fan streams, respectively. For the tests discussed in this paper, the nozzle temperature, nozzle pressure ratio, and mass flow requirements are well within the capabilities of the facility.

The tertiary air system (for flight simulation) consists of a 250,000 scfm (at 50” of water column static pressure) fan driven by a 3,500 horsepower electric motor. The transition ductwork and silencer route air from the fan discharge through a 48” diameter free-jet nozzle. The silencer reduces the fan noise by 30 to 50 dB. Tertiary airflow at its maximum delivery rate permits flight simulation up to a free jet Mach number of approximately 0.4. Mach number variation is achieved by adjusting the supply air fan inlet vanes. The combined model, free-jet, and entrained airflow is exhausted through an exhaust ‘T’ stack silencer aligned directly over the model in the ceiling of the chamber. The exhaust ‘T’ stack is acoustically treated to reduce noise transfer from the facility to the surrounding community.

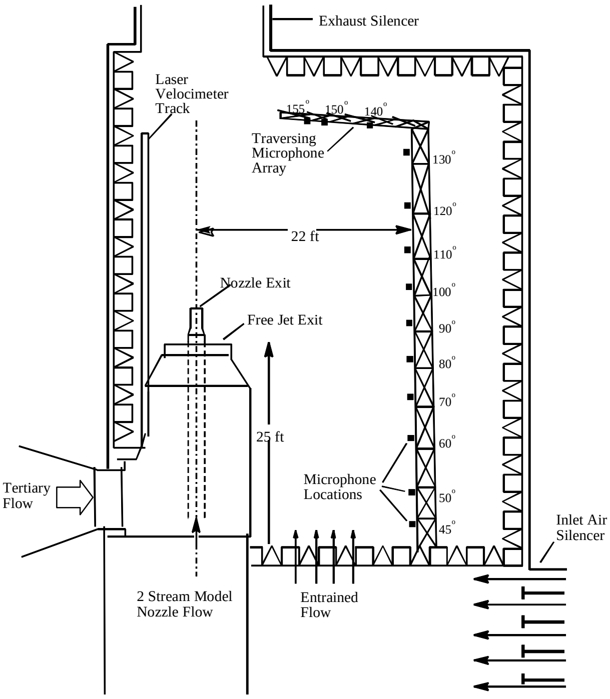

Figure 3 Side-view schematic of Cell 41.

The facility is equipped with a traversing tower containing 13 microphones, mounted at polar angles from 45^o to 155^o, seen in Figure 3, and provides measurements at a minimum distance of 22 feet from the nozzle reference location, (see Figure 4) to measure the acoustic characteristics of the test models in the far-field. Figure 4 also shows a layout of the facility, indicating the orientation of the model hardware and the microphone locations. The tower can be physically positioned at any azimuthal angle noted in Figure 4. However, to ensure non-interference from close proximity to wedges in its extreme positions, data acquisition is normally limited to the 0^o to 90^o locations identified on Figure 4. An azimuthal angle of zero is defined as the 45° (N-E) position. Acoustic microphone data is typically acquired at two azimuthal angles to simulate the sideline and community noise measurements required for FAR 36 certification. For these experiments the sideline noise measurements were made at 34 degrees and the community noise or cutback noise was measured at 90 degrees, (microphones aligned with the model such that the pylon is on the far side of the exhaust system model) identified on Figure 4.

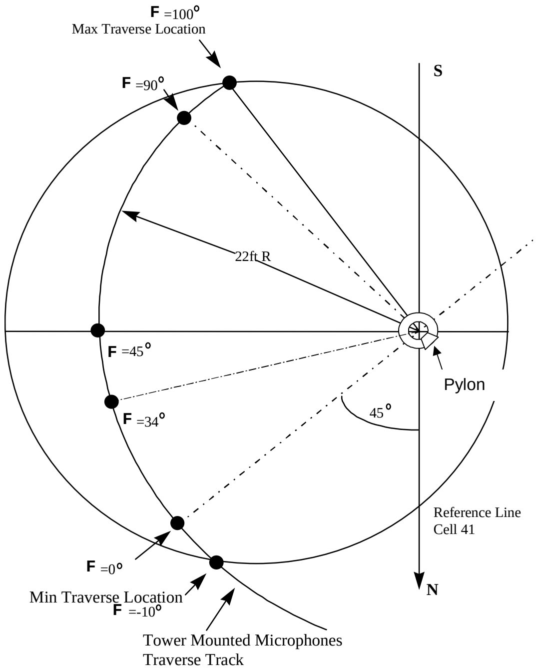

Figure 4 Plan view of Cell 41 showing microphone locations and measurement orientations.

2.3 Chevron Description and Design

Chevron nozzles were first tested at GE Aircraft Engines in 1996 during an internally funded program, which looked at a variety of different jet noise reduction concepts. The chevrons proved to be the most promising concept developed in terms of noise reduction and performance impact, and were further developed in testing at NASA Glenn Research Center under the AST program [2,3]. The idea for chevrons came from a myriad of sources, including work done on tabbed nozzles [5-8], nozzles with cutouts [9-12], mixer nozzles [13-15], and general knowledge and experience developed over the years at GE Aircraft Engines.

Figure 5 shows a photograph of a 1/11th-scale model of the CFM56-5B exhaust system. This engine model powers the A321 narrow-body aircraft. The chevron nozzle, shown in Figure 6, was chosen after testing a number of design concepts with various permutations of the design parameters of the chevron nozzle. Some of these parameters are: number of chevrons or cut-outs, length, width, aspect ratio, sweep angle, penetration, shape, azimuthal contouring, relative axial location, etc.... Initial design screening was done using computational fluid dynamics (CFD) analysis to qualitatively compare the mixing characteristics of the jet plume for different chevron designs relative to the baseline configuration. The chevron nozzle used for discussion in this paper has 8 chevrons that alternate penetration into and away from the engine centerline. In general the chevron design selection must consider acoustic benefit, performance, operability, manufacturability, maintainability, etc.... Unfortunately, acoustics and performance usually have an inverse relationship; that is, what's good for acoustics generally is bad for performance. The art is in designing a nozzle that maximizes acoustic benefit and minimizes negative performance impact, while meeting the remaining system requirements.

An important and often unrecognized aspect of the chevron nozzle is their inherent difference to tabbed nozzles. Tabbed nozzles, like mixers, shift the frequencies of noise generated. They move energy from low frequencies to high frequencies. Chevrons, on the other hand, are designed with an aim to reduce low frequencies while leaving the high frequency acoustic characteristics essentially the same as a conventional nozzle. There may be some very slight increases in noise at some moderate to high frequencies, but in efficient chevron designs, it is usually insignificant when taking into account other engine sources, which are typically usually higher than the jet noise at these frequencies.

Figure 5 Photograph of CFM56-5B conventional exhaust system scale model.

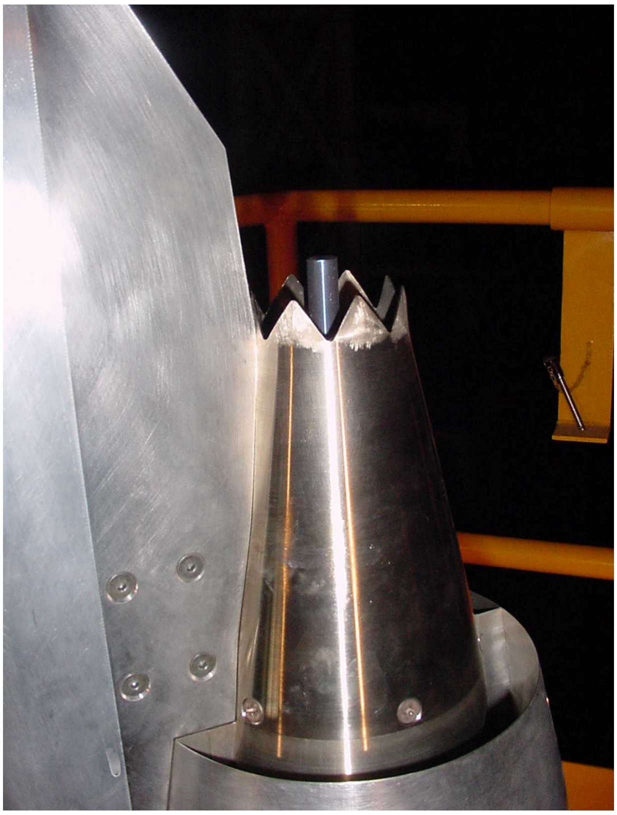

Figure 6 Photograph of scale model chevron for CFM56-5B exhaust system.

2.4 Acoustic Results

All of the results shown and discussed in this section were obtained during a joint GE Aircraft Engines/Snecma scale model development program.

The discussion of the acoustic results begins with the Effective Perceived Noise Level (EPNL). This is the noise metric that determines if an aircraft is in compliance with FAR 36 noise regulations. The EPNL is a measure of the cumulative noise measured as an aircraft flies by a specific location. This is constructed from the perceived noise level (PNL) time history. The PNL value at each measured directivity angle is calculated from the integrated sound pressure level (SPL) spectra, weighted for human annoyance. The SPL spectrum is the measured noise level at each directivity angle (or aircraft location at each instant in) as a function of frequency (50-10000 Hz). Acoustic data for the scale model is acquired up to 80,000 Hz. The frequencies are linearly scaled to those that would occur for the full-scale engine. The sound pressure level amplitude is also scaled to the full-scale levels. The absolute scales on the plots are not provided, however these scales are consistent for each set of plots.

Figure 7 shows the range of jet EPNL for static and flight simulation conditions at an azimuthal angle of 90 degrees, corresponding to the measurement location directly under the flight path of the aircraft, for a range of aerothermodynamic conditions generally covering approach to full power take-off. The x-axis metric is the mass average of the fan and core stream exhaust velocities, normalized with the ambient speed of sound. The data is compared on this normalized scale to account for small variations in the conditions set as well as the ambient conditions. The simulated flight data is corrected for passing through the shear layer of the external flow stream using a modified version of the Amiet method [16]. The lightly shaded symbols indicate the cycle points corresponding to the cutback condition, this is the engine power setting (core and fan nozzle pressure ratios and temperatures) corresponding to the cutback or fly-over Annex 16 Chapter 3 certification point (Vmix/Aamb=0.86, Vmix=990 ft/sec). The static data shows a constant modest noise reduction at normalized velocities up to about 0.8, then a steadily increasing noise benefit due to the chevron nozzle at higher levels. The simulated-flight conditions also exhibit the same trend with a slightly larger noise reduction at the same normalized velocity. Acoustic data was not acquired for the lowest normalized velocities for the simulated flight conditions because it is very hard to distinguish this low level of jet noise from the free-jet background noise.

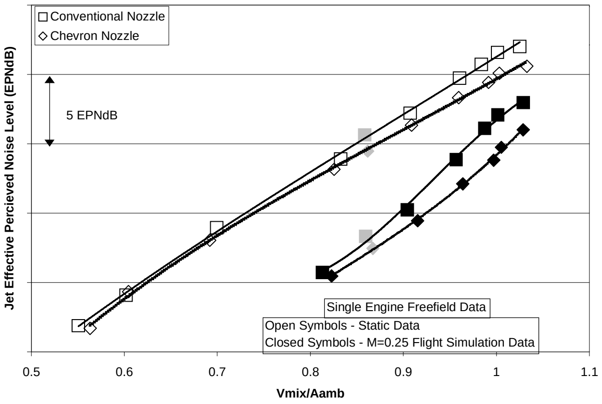

Figure 7 Jet effective perceived noise level as a function of normalized velocity for the cutback measurement location.

Figure 8 shows the same results as Figure 7 for the same aero-thermodynamic cycle conditions, at an azimuthal angle of 34 degrees, corresponding to the sideline configuration, the certification point corresponding to the measurement location offset to the aircraft flight path. The shaded symbols correspond to the sideline engine cycle conditions (Vmix/Aamb=1, Vmix=1150 ft/sec). The noise level at this orientation follows a very similar trend as the fly-over orientation. One interesting difference between the two orientations is that the absolute noise level is higher at the sideline orientation than the fly-over orientation, even for static data. This noise difference is likely due to the pylon - the mixing characteristics of the jet plume may vary in the azimuthal direction due to the effects of the pylon - this has been observed in computational work on chevron nozzles [17].

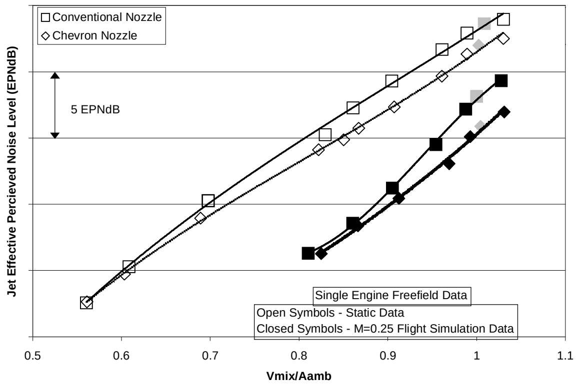

Figure 8 Jet effective perceived noise level as a function of normalized velocity for the sideline measurement location.

Figure 9 shows the jet PNL directivity for the cutback cycle condition and measurement location for the conventional and chevron nozzle for both static and M=0.25 flight conditions (corresponding to the lightly shaded symbols on Figure 7). The static data shows a very slight benefit for the chevron nozzle over all angles. In this plot the measured data covers directivity angles of 45 to 155 degrees (180 degrees is directly behind the engine), the other angles are simple extrapolations of the data assuming spherical spreading. In the case of the M=0.25 flight simulation data the noise difference characteristics are different. In the mid-range angles (60 – 90 degrees) the conventional and chevron nozzle noise levels are essentially the same. In the aft angles (≥ 100 degrees) the chevron provides increasing noise reduction benefit. However, in the forward angles (≤ 60 degrees) the chevron may be slightly louder than the conventional nozzle. Figure 10 shows the same information for the sideline cycle condition and measurement orientation (corresponding to the lightly shaded symbols on Figure 8). For the sideline cycle condition it is obvious that the chevron nozzle provides more benefit than the lower velocity condition at cutback. For the static conditions, the open symbols, the chevron nozzle shows a fairly constant level of noise reduction over most of the directivity angle range. At the most aft angles (≥ 150 degrees) the conventional and chevron nozzle noise levels are approximately the same. For the M=0.25 flight simulation case, the chevron provides a fairly constant moderate reduction in PNL up to a directivity angle of approximately 110 degrees. Aft of this the chevron provides a reduction of approximately 2.5 to 3 PNdB. Thus the chevron is most effective at the most aft angles, where jet noise really peaks. Another striking feature of Figure 10 is the difference in chevron nozzle effectiveness between static and simulated flight data. The chevron nozzle provides more noise reduction with flight simulation than does the static case. The reason for this is currently unknown.

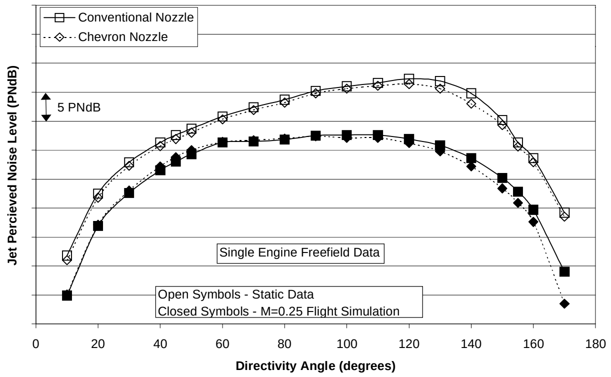

Figure 9 Jet perceived noise level directivity, static and M=0.25 simulated flight conditions, conventional and chevron nozzle, cutback cycle condition (Vmix/Aamb=0.86) and measurement location.

Figure 11 shows the jet (SPL) spectra for the cutback cycle condition and measurement location for three directivity angles, 90, 130, and 150 degrees for the conventional and chevron nozzle configurations. At the 90-degree location, the chevron provides a couple of dB reduction up to approximately 800 Hz. Above 800 Hz, the two configurations virtually lie atop one another. There are some frequencies where the chevron is slightly higher than the conventional nozzle. This slight noise level increase at the higher frequencies is due to the increased small-scale turbulence that is a byproduct of the streamwise vorticity generated by the chevrons. In the design of the chevron nozzle this is an area that requires careful monitoring. The geometric parameters of the chevron nozzle are balanced with the aero-thermodynamic conditions to provide a maximum low frequency noise reduction with a minimum high frequency noise impact.

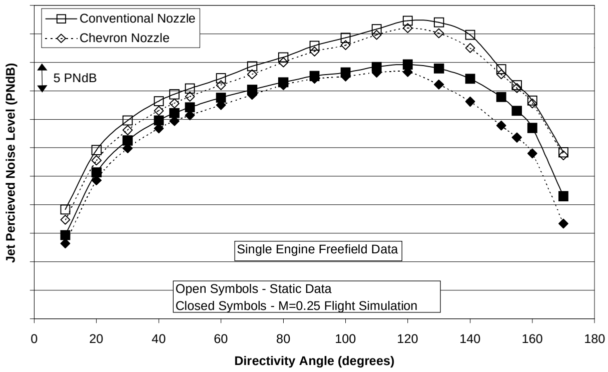

Figure 10 Jet perceived noise level directivity, static and M=0.25 simulated flight conditions, conventional and chevron nozzle, sideline cycle condition (Vmix/Aamb=1) and measurement location.

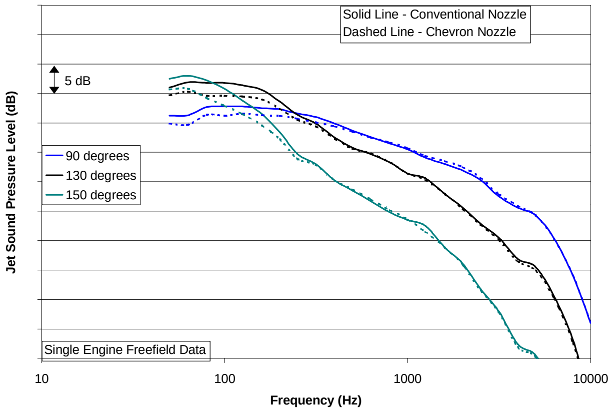

Figure 11 Jet sound pressure level spectra for M=0.25 simulated flight conditions, conventional and chevron nozzle, cutback cycle condition (Vmix/Aamb=0.86) and measurement location, 90, 130, and 150 degree directivity angles.

Some amount of high frequency noise level increase can be acceptable in the jet noise spectra because in the engine there are other noise sources that are dominant in this frequency range. This is the effect that resulted in the slight PNL increase for the forward angles in the simulated flight data at cutback conditions on Figure 9. This is one of the main aspects that makes jet noise reduction so difficult in practice. This seesaw effect can eliminate an overall noise benefit in the EPNL even when there may be some significant noise reductions at some frequencies and angles. The other two angles, 130 and 150 degrees, show similar low frequency noise benefits up to about 500 Hz, and above that generally show the same noise level as the conventional nozzle.

Figure 12 shows the same information at the sideline cycle condition and measurement location. As seen previously in the PNL and EPNL plots at the higher velocities the chevron results in larger noise reductions. At the 90-degree directivity angle the benefit continues to approximately 1000 Hz. At 130 degrees the chevron benefit is larger, on the order of 3 – 4 dB, again up to frequencies around 1000 Hz. Finally, at 150 degrees the chevron is providing SPL reductions up to 5 dB at the lower frequencies and the benefit extends through the complete frequency range, at smaller levels.

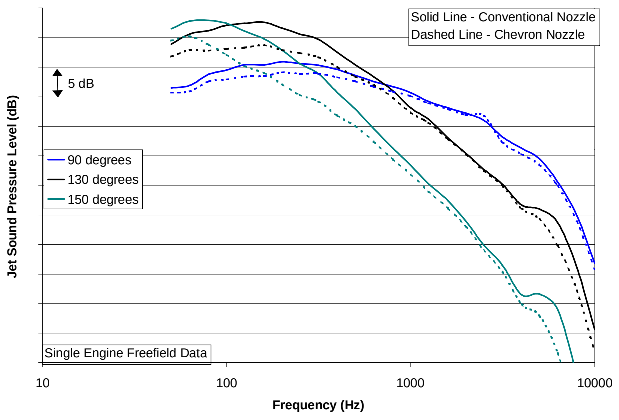

Figure 12 Jet sound pressure level spectra for M=0.25 simulated flight conditions, conventional and chevron nozzle, sideline cycle condition (Vmix/Aamb=1) and measurement location, 90, 130, and 150 degree directivity angles.

Figures 7 and 8 showed jet EPNL reductions on the order of 2 – 3 EPNdB. To relate this to the engine system noise reduction the chevron would produce, these jet noise reductions would need to be evaluated using an engine system flyover noise analysis. The ultimate noise reduction is a function of how dominant the jet noise component is relative to the other engine noise sources at each appropriate aero-thermodynamic condition.

These results have shown that a properly designed chevron for a particular engine cycle and geometry can effectively reduce the jet noise, over most frequencies and angles, and when taken with the other engine noise sources, essentially pay no price for increasing noise at any frequency or angle. This design process has also taken into account other considerations to minimize any other effects to the engine or aircraft. Special consideration is paid to the chevron’s effect on the thrust and flow coefficient.

3 Conclusions

This paper has discussed some of the long-term history of jet noise reduction and specifically a summary of the development of the chevron nozzle for jet noise reduction for high bypass ratio separate flow exhaust systems. Jet noise reduction is a very difficult task due to the constraints imposed by engine and aircraft system requirements. It is extremely difficult to reduce jet noise while not impacting anything else negatively. Chevrons are unique, as a jet noise reduction technology, in that they can have a relatively small impact on weight, performance, and operability.

Jet noise is only one component of the total engine and aircraft system noise signature, but the jet noise reductions demonstrated herein can add up to a significant cumulative system noise reduction, depending on the engine and aircraft under consideration. Continued chevron development for the CFM56-5B, has included scale model tests with the exhaust system mounted under a scale model wing. Static engine testing is scheduled for June of 2003, and flight-testing should occur the fall of 2003.

The chevron nozzle has proven to be an excellent technology developed jointly between GE Aircraft Engines and NASA as an effective and efficient means to reduce jet noise with minimal impact on engine performance, operability, weight, and cost, for some aircraft systems. This has been an especially important technology development because in some cases it can be a fairly simple and inexpensive retrofit/upgrade for existing engine/aircraft applications.

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References

[1] Lighthill, M.J. On Sound Generated Aerodynamically, I. General Theory. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Volume 211, Issue 1107 (Mar. 20, 1952), 564-587.

[2] Saiyed, N.H., Mikkelsen, K.L., and Bridges, J.E. Acoustics and Thrust of Separate-Flow Exhaust Nozzles with Mixing Devices for High-Bypass-Ratio Engines. 6th AIAA/CEAS Aeroacoustics Conference and Exhibit, June 12-14, 2000, Lahaina, HI.

[3] Janardan, B.A., Hoff, G.E., Barter, J.W., Martens, S., Gliebe, P.R., Mengle, V., and Dalton, W.N. Separate-Flow Exhaust System Noise Reduction Concept Evaluation. NASA CR 2000-210039.

[4] Stone, J.R., Krejsa, E.A., Halliwell, I., and Clark, B.J. Noise Suppression Nozzles for a Supersonic Business Jet. 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 17-19, 2000, Huntsville, AL.

[5] Bradbury, L.J.S. and Khadem, A.H. The Distortion of a Jet by Tabs. Journal of Fluid Mechanics, 1975, Vol. 70, Part 4, pp. 801-813.

[6] Ahuja, K.K. and Brown, W.H. Shear Flow Control by Mechanical Tabs. AIAA 2nd Shear Flow Conference, March 13-16, 1989, Tempe, AZ.

[7] Samimy, M., Zaman, K.B.M.Q., and Reeder, M.F. Effect of Tabs on the Flow and Noise Field of an Axisymmetric Jet. AIAA Journal, Volume 31, Number 4, April 1993, Pages 609-619.

[8] Zaman, K.B.M.Q., Reeder, M.F., and Samimy, M. Control of an Axisymmetric Jet Using Vortex Generators. Physics of Fluids, Volume 6, Number 2, February 1994, Pages 778-793.

[9] Krothapalli, A., McDaniel, J., and Baganoff, D. Effect of Slotting on the Noise of an Axisymmetric Supersonic Jet. AIAA Journal, Volume 28, Number 12, December 1990, Pages 2136-2138.

[10] Longmire, E.K., Eaton, J.K., and Elkins, C.J. Control of Jet Structure by Crown-Shaped Nozzles. AIAA Journal, Volume 30, Number 2, February 1992, Pages 505-512.

[11] Seiner, J.M. and Gilinsky, M.M. Nozzle Thrust Optimization While Reducing Jet Noise. 16th AIAA Aeroacoustics Conference, June 12-15, 1995, Munich, Germany.

[12] Samimy, M., Kim, J.H., and Clancy, P.S. Supersonic Jet Noise Reduction and Mixing Enhancement Through Nozzle Trailing Edge Modifications. 35th Aerospace Sciences Meeting & Exhibit, January 6-10, 1997, Reno, NV.

[13] Saiyed, N.H., Bridges, J.E., and Krejsa, E.A. Core and Fan Streams' Mixing Noise Outside the Nozzle for Subsonic Jet Engines With Internal Mixers. 2nd AIAA Aeroacoustics Conference, State College, Pennsylvania, May 6-8, 1996.

[14] Krejsa, E.A. and Saiyed, N.H. Characteristics of Residual Mixing Noise From Internal Fan/Core Mixers. 35th Aerospace Sciences Meeting & Exhibit, January 6-10, 1997, Reno, NV.

[15] Salikuddin, M., Martens, S., Janardan, B.A., Shin, H., and Majjigi, R.K. Expreimental Study for Multi-Lobed Mixer for High Bypass Exhaust Systems for Subsonic Jet Noise Reduction. AIAA-99-1988, 1999.

[16] Amiet, R.K. Correction of Open Jet Wind Tunnel Measurements for Shear Layer Refraction. AIAA 2nd Aero-Acoustics Conference, March 24-26, 1975, Hampton, VA.

[17] Thomas, R.H., Kinzie, K.W., and Pao, S.P. Computational Analysis of a Pylon-Chevron Core Nozzle Interaction. 7th AIAA/CEAS Aeroacoustics Conference, May 28-30, 2001, Maastricht, The Netherlands.