AIAA Journal
Vol. 43, No. 7, July 2005

Experiments and Analyses of Distributed Exhaust Nozzles

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Experimental and analytical aeroacoustic properties of several distributed exhaust nozzle (DEN) designs are presented. Significant differences between the designs are observed and correlated to computational fluid dynamics flowfield predictions. Up to 20 dB of noise reduction on a spectral basis and 10 dB on an overall sound pressure level basis are demonstrated from the DEN designs compared to a round reference nozzle. The most successful DEN designs acoustically show a predicted thrust loss of approximately 10% compared to the reference nozzle. Characteristics of the individual minijet nozzles that comprise the DEN such as jet–jet shielding and coalescence are shown to play a major role in the noise signature.

Introduction

JET noise continues to be a dominant aircraft noise source that limits operations of current aircraft and hinders the design of future aircraft. Although techniques aimed at changing the engine cycle or those implementing mixing enhancement devices are incrementally improving the community noise situation, dramatic improvement will require revolutionary changes to conventional engine/airframe systems. One such concept with potential for significant noise reduction is the distributed exhaust nozzle (DEN).

Noise suppression from the DEN concept results from a favorable shift in the spectral shape of the radiated jet noise. The smaller jets that comprise the distributed exhaust nozzle radiate noise at higher frequencies than larger single- or dual-flow exhaust nozzles. Atmospheric attenuation increases nearly exponentially with increasing frequency, and spectral noise components contribute less and less to the effective perceived noise level (EPNL) noise metric as the frequency increases above 4 kHz. In fact, noise at frequencies higher than 10 kHz is not even included in the calculation of EPNL. In addition to shifting the noise signature toward more favorable high frequencies, the small jets mix with the ambient air and reduce the speed and temperature of the jet plume to lower levels that then reduce the radiated low frequency noise.

Traditionally, distributed exhaust nozzle concepts have been studied from the perspective of replacing conventional engine exhaust nozzles with another configuration composed of many small tubes, chutes, or spokes.[1] However, this inevitably leads to high levels of base drag caused by the aft-facing area required to distribute the exhaust as well as other internal losses such as friction. NASA is conducting research aimed at studying the distributed-exhaust concept from an integrated exhaust/airframe system perspective where the propulsion system is integrated into the airframe and small exhaust nozzles are distributed over large portions of the wing surface area. Such an advanced configuration is more likely able to mitigate many of the inherent thrust performance penalties associated with a DEN installation. An integrated distributed exhaust propulsion system also has further potential for noise reduction because additional noise suppression will be realized through shielding of engine noise away from the community by the airframe design.

In 2000, NASA teamed with Northrop Grumman Corp. (NGC) to design and test a horizontal slot nozzle[2] concept in the Low Speed Aeroacoustic Wind Tunnel (LSAWT), shown in Fig. 1. Although the LSAWT DEN configuration provided only minimal noise suppression, the agreement between computational fluid dynamics (CFD) predictions and thrust and flowfield measurements was sufficient to justify continued application of NGC's CFD design approach in pursuit of more aggressive noise reduction. CFD has subsequently been used to design three new DEN nozzles for testing in the Langley Research Center Small Anechoic Jet Facility (SAJF).

To investigate more aggressive acoustic designs, a simpler approach was chosen for the subject test by fabricating the DEN models using a stereolithography process. Although this restricts the flow temperature to less than 150°F, it provides a means of inexpensively screening designs. In addition, one of the designs was a smaller version of the horizontal slot design.[2] Even though the horizontal slot design does not provide significant noise reduction, testing the smaller stereolithography model provided a link back to the larger scale, hot-flow model test. Although the SAJF horizontal slot data are not reported here, the acoustic characteristics including spectral content and relative levels compared to the round reference nozzle were similar to those found in the larger LSAWT design. This gives confidence that the trends and observations of the two new DEN designs can also be expected as the model size increases and hot flow is used.

Nozzle Descriptions

For this work, two new SAJF DEN designs were analyzed, tested, and compared to a round reference nozzle with similar mass flow. The DEN designs were refined using CFD in an attempt to optimize aeroperformance and mixing characteristics that affect noise radiation. As expected, compromises were required between these two generally opposing requirements. The first DEN design is shown in Fig. 2 and will be referred to as the DROPS design because the exit holes are shaped like teardrops. Figure 3 shows the second DEN design and will be referred to as the slanted pseudoslot (SPS) design. It is similar to the design of the slotted nozzle, also designed by Northrop Grumman, described in Gaeta et al.[3] and Ahuja et al.,[4] except that for the current design the exit passages are not continuous slots but rather an array of rectangular nozzles that give the appearance of slots. In addition, the spanwise spacing of the rows for the current SPS design is further apart than that tested by Gaeta et al.[3] and Ahuja et al.[4] For the current design, the spacing is 5.5 times the slot width and for the Gaeta et al.[3] and Ahuja et al.[4] design the spacing is 3.5 times the slot width. The round reference nozzle was constructed of stainless steel, whereas the two DEN designs

Received 15 May 2002; presented as Paper 2002-2555 at the AIAA/CEAS Aeroacoustics Conference, Breckenridge, CO, 17–19 June 2002; accepted for publication 18 August 2004.

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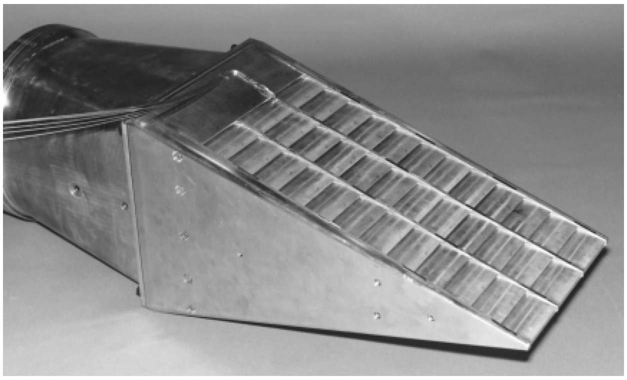

Fig. 1 Horizontal slot DEN design tested in the NASA LSAWT in 2000.

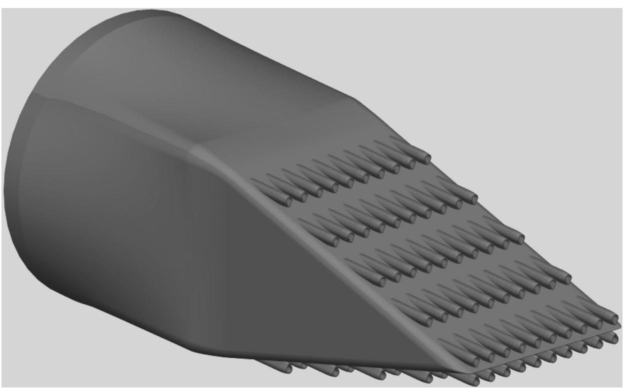

Fig. 2 DROPS DEN design tested in NASA SAJF in 2002.

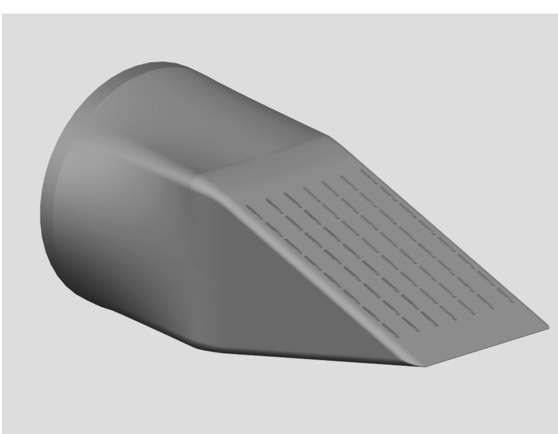

Fig. 3 SPS DEN design tested in NASA SAJF in 2002.

were constructed by a stereolithography technique. Figure 4 shows a sketch describing the coordinate system used for this work.

The round reference nozzle had a 2-in. (5.08-cm) diameter, for a total exit area of 3.14 in.^{2} (20.3 cm^2). Several CFD iterations were performed to size the distributed exhaust nozzles such that they had approximately the same mass flow as the round nozzle. This resulted in the SPS design having an exit area of 3.32 in.^{2} (21.4 cm^2) and the DROPS design having an exit area of 3.25 in.^{2} (22.0 cm^2). The individual mininozzles for the SPS design each had an area of approximately 0.030 in.^{2} (0.194 cm^2), and a single mininozzle for the DROPS design had an area of approximately 0.032 in.^{2} (0.207 cm^2).

Experimental Approach

The nozzles were tested in NASA Langley's SAJF. An eight-element microphone array on an approximate 7-ft sideline was used to measure radiated noise. Because of the size of the chamber and of the nozzles, acoustic measurements were only made in the aft quadrant from polar angles of $\theta = 90$ to 155 deg. Narrowband data

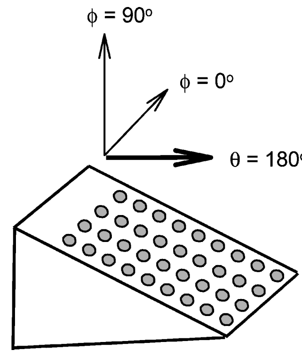

Fig. 4 Sketch of nozzle coordinate system and azimuthal orientation planes.

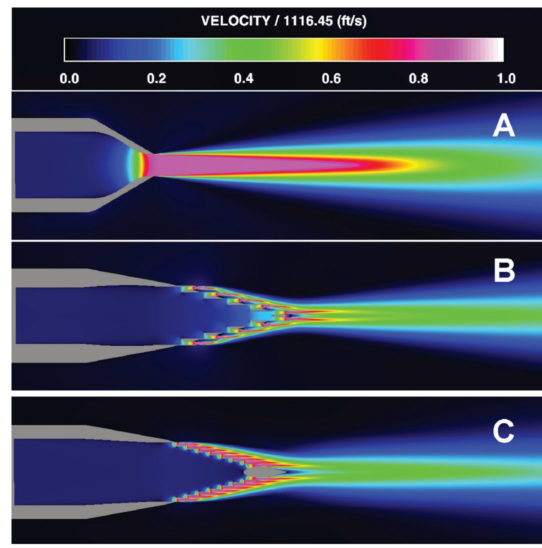

Fig. 5 Centerplane velocity magnitude contours for a) round reference nozzle, b) DROPS, and c) SPS.

up to 100 kHz were acquired with $\frac{1}{4}$-in. B&K 4139 microphones and postprocessed to standard $\frac{1}{3}$-octave bands. The data were then extrapolated to a 12-ft arc centered at the nozzle exit and corrected to standard day reference conditions using the Shields and Bass atmospheric attenuation model.[5]

A range of nozzle-pressure-ratio (NPR) conditions were measured starting from NPR = 1.45 and ending with NPR = 2.20. For all pressure conditions, the flow total temperature was held at 120°F. The flow temperature was limited to relatively cool conditions by the plastic stereolithography models. This paper focuses on the NPR = 1.72 condition because most of the CFD was run for this case and it also corresponds to the fully mixed takeoff pressure ratio for the cycle conditions tested previously for the horizontal slot DEN design.[2] Although other azimuthal planes were measured, only the $\phi = 0$ and 90 deg planes are reported in this paper as the intermediate angles did not provide significant additional insight.

CFD Analysis

CFD simulations were run on the reference nozzle and both DEN designs using Northrop Grumman's generalized compressible Navier–Stokes code.[6] Full quadrant solutions were obtained for the reference nozzle and the SPS design. The DROPS design was analyzed using three-dimensional strip analysis with periodic boundary conditions due to time constraints. The CFD was performed at nozzle pressure ratios of 1.45, 1.72, and 2.20. However, the most detailed analysis was performed at NPR = 1.72. The total temperature for all CFD runs was 120°F.

Figure 5 shows predicted velocity contours through the hole spanwise centers for the reference nozzle and the DEN designs. The DEN designs show a dramatic increase in mixing that results in a plume with significantly lower flow velocity than the round reference nozzle. This is in contrast to the horizontal slot DEN design[2] that showed very little reduction in plume velocity compared to

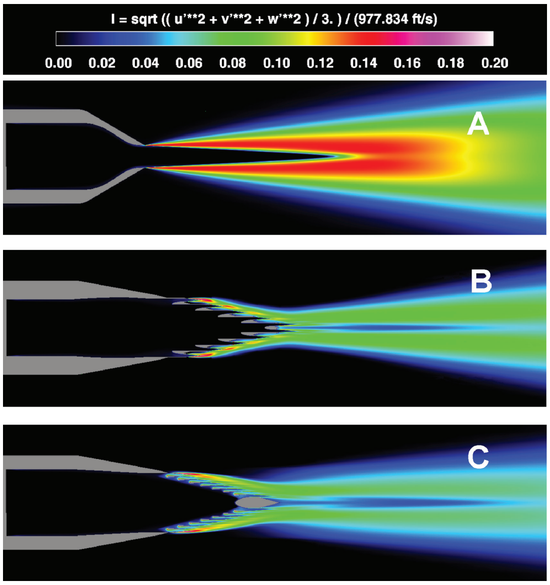

Fig. 6 Centerplane turbulence intensity contours for a) round reference nozzle, b) DROPS, and c) SPS.

the reference nozzle. Figure 6 shows predicted turbulence intensity contours for the same cross sections. Again, there is a significant reduction in turbulence intensity for the DEN designs compared to the reference nozzle.

The CFD predictions show that for both of these DEN designs the individual mini-exhaust jets maintain their identity for a significant distance before they begin to coalesce into a larger jet plume. This is a critical factor in order for acoustic suppression to be realized from any distributed exhaust design. CFD predictions and experimental measurements of the horizontal slot DEN design[1] showed that without enough separation of the minijets, they will coalesce into a large plume with a noise signature more characteristic of the single large jet rather than many small jets. The CFD flowfield solutions for the current DEN designs show much greater potential for noise reduction based on jet-to-jet mixing and overall plume characteristics. The acoustic measurements presented in the next section confirm this assessment.

For the design nozzle pressure ratio of 1.72, the discharge coefficient of the SPS nozzle was 0.93, whereas the discharge coefficient of the DROPS nozzle was 0.95. The thrust coefficient of both the SPS and DROPS nozzles was approximately 0.89. The CFD showed a slight improvement in thrust performance (0.91) as the NPR increased to 2.20. Experimental measurements of aeroperformance quantities were not made; however, earlier work demonstrated that the GCNS code is very reliable in computing these types of flows.[2]

Caution should be used when comparing acoustic data from nozzles with different thrust characteristics. An aircraft system requires a specific level of thrust so that a nozzle with lower thrust must either be oversized or operated at a higher pressure ratio to generate the same amount of thrust as one with better propulsive efficiency. Either of these options will increase the noise so it can be misleading to only consider noise suppression without considering the associated performance penalty. Recall that the DEN designs reported here were oversized slightly to produce the same mass flow and, therefore thrust, as the reference nozzle. Oversizing the DEN designs based on the calculated thrust coefficient results in an elevation of the DEN SPL levels by approximately 0.5 dB.

Although the thrust loss of these DEN specimens might be unacceptable for conventional aircraft designs, the distributed exhaust concept lends itself very well toward more revolutionary aircraft designs where the small exhaust holes can be integrated into the wing surface. Such an installation could recover some of the lost performance through upper surface blowing lift enhancement. A full aircraft system mission study is required to adequately assess the acceptable thrust loss compared to the noise suppression provided by the distributed exhaust design.

Acoustic Measurements

Figures 7 and 8 show overall-sound-pressure-level (OASPL) directivity data for the round reference nozzle compared to the DROPS and SPS nozzles at a nozzle pressure ratio of 1.72. Both nozzles provide greatest noise suppression at the aft-most angles where jet noise is typically the loudest. The $\phi = 0$ deg orientation of the DROPS nozzle is nearly 10 dB quieter than the round reference nozzle at the aft-most measurement angles and shows a consistent noise benefit relative to the reference nozzle through the whole measurement range. The SPS nozzle does not achieve suppression until midway into the aft quadrant. For each DEN, there is a loud and a quiet azimuthal orientation with the $\phi = 0$ deg orientation being 2–3 dB quieter than $\phi = 90$ deg. Effects that contribute to the difference between azimuthal planes will be discussed shortly.

Spectra from the two DEN designs compared to the round reference nozzle at NPR = 1.72 are shown in Figs. 9–12. Figures 9 and 10 show the DROPS and SPS for both azimuthal angles close to the peak noise polar angle of $\theta = 150$ deg. Figures 11 and 12 show the DROPS and SPS, respectively, for both azimuthal angles and a polar angle of $\theta = 90$ deg. From these spectra, it is clear that the DEN models are in fact shifting the noise to higher frequencies as designed. Significant noise reduction up to 20 dB is observed for some frequency bands compared to the round reference nozzle, which has a noise peak an order of magnitude lower in frequency than the DEN models. Consistent with the OASPL plots, the DROPS nozzle provides more noise reduction than the SPS nozzle. It is hypothesized based on the CFD calculations shown in Figs. 5 and 6 that the DROPS nozzle provides greater separation between the minijets and provides more overall mixing that results in greater noise reduction.

Note that at an azimuthal orientation of $\phi = 90$ deg, particularly at a polar angle of $\theta = 90$ deg, there is a low frequency local maximum in the DEN spectrum that does not occur in the $\phi = 0$ deg azimuthal orientation. Both DEN designs show a low frequency peak around

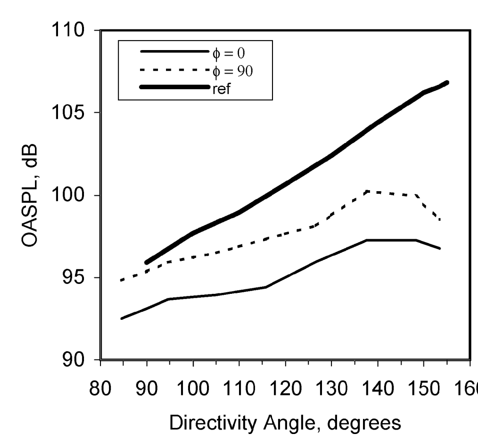

Fig. 7 OASPL for DROPS nozzle and reference nozzle at NPR = 1.72.

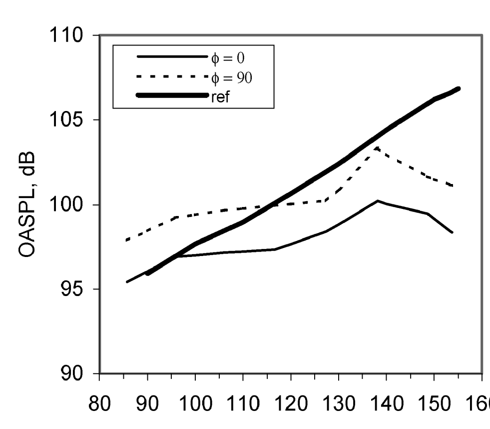

Fig. 8 OASPL for SPS nozzle and reference nozzle at NPR = 1.72.

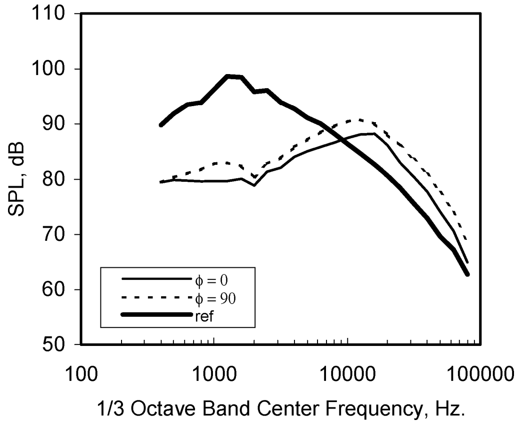

Fig. 9 Spectra for DROPS nozzle and reference nozzle at NPR = 1.72, $\theta = 150$ deg.

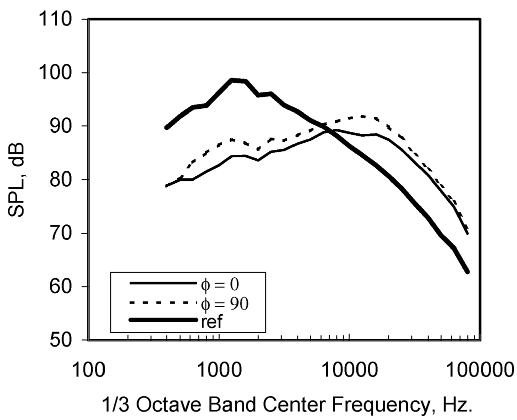

Fig. 10 Spectra for SPS nozzle and reference nozzle at NPR = 1.72, $\theta = 150$ deg.

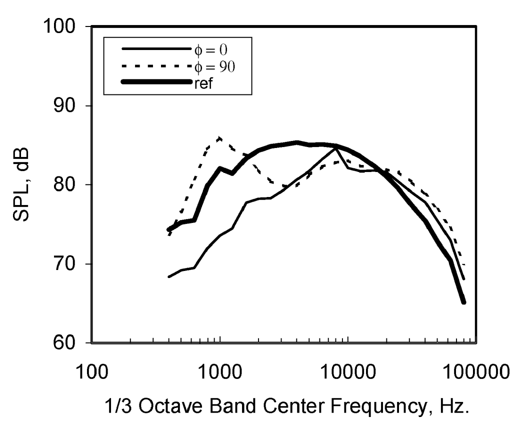

Fig. 11 Spectra for DROPS nozzle and reference nozzle at NPR = 1.72, $\theta = 90$ deg.

1000 Hz. This characteristic spectral "hump" is also observed in the slanted slot DEN reported in Gaeta et al.[3] in the same frequency range found here. Although the exact cause of this hump is not yet known, the similarity of the hump between the SPS, DROPS, and slanted slot design implies that a common design characteristic might be causing the noise. Based on comparing the spectra from the two azimuthal planes in Figs. 9–12, this hump is the primary factor in the 2–3 dB OASPL difference between the two azimuthal planes shown in Figs. 7 and 8, especially toward the sideline polar angles. If the design characteristic causing the noise could be identified and eliminated, the noise augmentation of the DEN toward these sideline angles at $\phi = 90$ deg could be eliminated.

Figures 13 and 14 show plots of the noise difference between the DROPS and SPS nozzles and the reference nozzle at three different pressure ratios for azimuthal angle $\phi = 0$ deg and polar an-

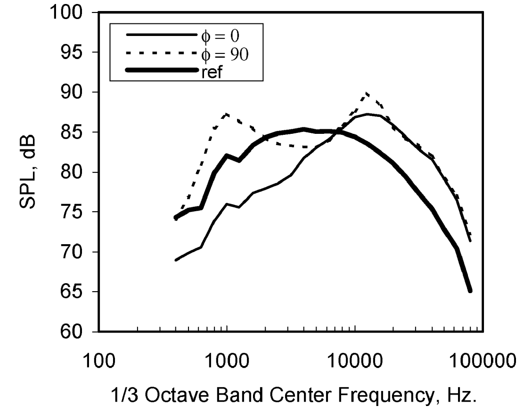

Fig. 12 Spectra for SPS nozzle and reference nozzle at NPR = 1.72, $\theta = 90$ deg.

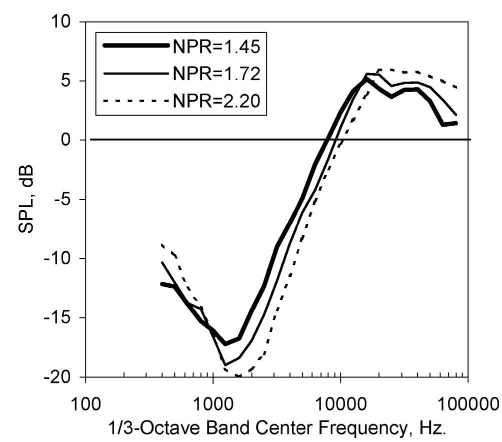

Fig. 13 Difference between DROPS nozzle and reference nozzle at $\phi = 0$ deg, $\theta = 150$ deg.

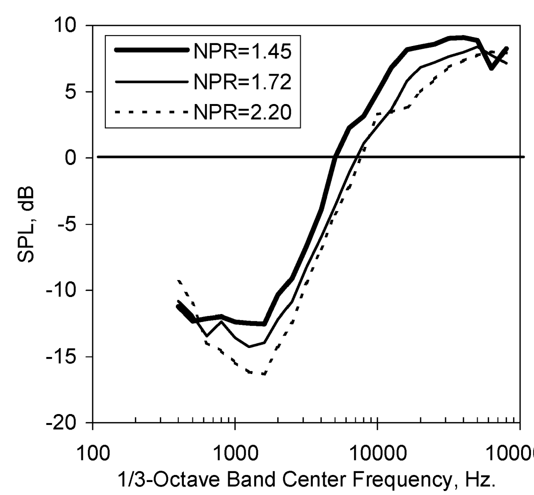

Fig. 14 Difference between SPS nozzle and reference nozzle at $\phi = 0$ deg, $\theta = 150$ deg.

gle of $\theta = 150$ deg. Negative SPL values represent noise reduction, whereas positive values indicate frequency bands louder than the round reference nozzle. Again, it is observed that the DROPS nozzle typically provides more noise reduction than the SPS nozzle. Not only does the DROPS nozzle provide more noise reduction at low frequencies, it generates less noise at high frequencies. Both nozzles provide the greatest noise reduction in the frequency range of 1 to 2 kHz, with increased noise reduction as the NPR increases. At high frequencies where excess noise is generated compared to the round reference nozzle, the two DEN designs show opposite trends. For the DROPS design, more noise is generated as NPR increases. For the SPS design, less excess noise is generated as NPR increases.

All of the acoustic trends observed here are generally consistent with those for the slanted slot DEN reported by Gaeta et al.[3] One notable difference is that the SPS nozzle reported here provides more noise reduction than the first generation slanted slot nozzle, especially at subsonic pressure ratios. The enhanced noise reduction is likely caused by the already mentioned increased spanwise spacing between the slots, which allows better mixing characteristics for the SPS design compared to the slotted design tested by Gaeta et al.[3]

In contrast to the horizontal slot DEN design tested previously,[2] both current designs provide significant noise reduction. As mentioned earlier, it is clear from the CFD that the current designs achieve much better mixing by maintaining the individual minijets for a longer distance before they coalesce into a larger plume. This separation is very important in achieving the low-frequency noise reduction observed here and to shift the peak acoustic frequency to higher values. However, there is an aeroperformance penalty associated with achieving the jet-jet separation and enhanced noise reduction.

Jet–Jet Noise Shielding Study

Characteristic to the DEN technology is a significant reduction in low-frequency noise accompanied by an increase in high-frequency components of noise. For these size nozzles, the crossover point between noise suppression and the high-frequency excess noise generated compared to the round reference ranges between 6 and 10 kHz. The peak frequency for both DEN designs is in the range of 15 kHz. This crossover point is problematic when it comes to projecting the scale model DEN to full size. For conventional nozzles, Strouhal-number scaling using a scale factor related to the nozzle exit area is applied, which shifts model scale frequency in proportion to the geometric scale factor. If a single factor is used to scale the model-scale DEN acoustic spectra, then the high-frequency crossover would cause the DEN models to appear much louder than the round reference nozzle, and these frequencies would dominate the sound field on a perceived-noise-level (PNL) basis. However, the model-scale DEN designs have two length scales. One is associated with the mininozzles, which are close to the actual size they would be at full scale, and the other is associated with the overall nozzle-exit area, which is much smaller than what it would be at full size. Consequently, the lower-frequency energy that is generated by the coalesced jet plume should scale to even lower frequency, but the higher-frequency energy generated by the individual minijets should not shift frequency. In addition, jet-jet acoustic shielding by the arrays of nozzles will be a significant noise reduction effect that can increase with DEN model size. Thus, a full-scale DEN with more rows of mininozzles can provide more suppression on a PNL basis than observed here on an OASPL basis. A method to estimate the full-scale noise from the model-scale DEN spectrum is presented in Kinzie and Schein[7] and supports this idea.

The acoustic shielding effect has been investigated thoroughly in several twin-jet studies,[8–10] but only recently for DEN designs.[2,3,7] The objective here was to obtain nozzle array acoustic shielding data that might aid in scaling at least part of the DEN acoustic spectrum for more extreme (greater flow area) nozzle systems. The DEN models tested here are considered to be small, full-scale sections of a larger nozzle system (i.e., the mininozzles in a full size system will be the same size as tested here, there will just be a lot more of them).

To quantify the shielding effect for the current SPS design, data were acquired from modified configurations by successively blocking (internally) neighboring slots on both the top and bottom array. First slot 7 was blocked and data acquired, then 6 and 7 were blocked, etc., until only slot 1 was flowing. For each of these test points, mass flow was adjusted to maintain the desired value of NPR. In this way, the acoustic effect of adding each individual subsequent slot flow was measured. The nozzle's azimuthal orientation was $\phi = 0$ deg for all shielding runs. Data obtained for NPR = 1.72 are presented here in Figs. 15–17.

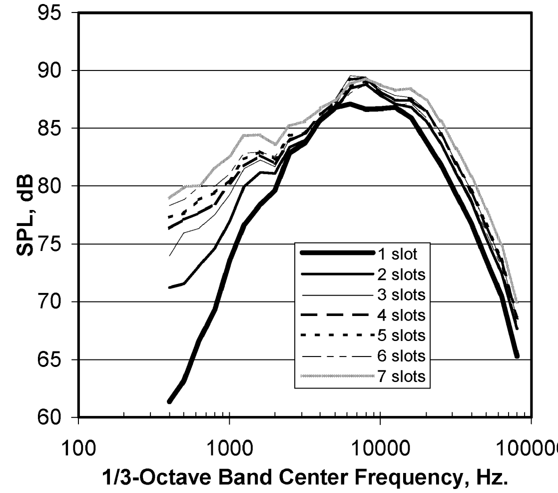

Fig. 15 SPS noise shielding data; NPR = 1.72, $\theta = 150$ deg.

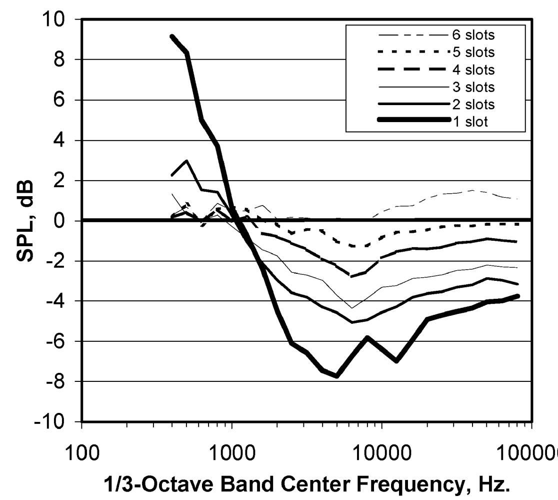

Fig. 16 SPS normalized shielding data; NPR = 1.72, $\theta = 150$ deg.

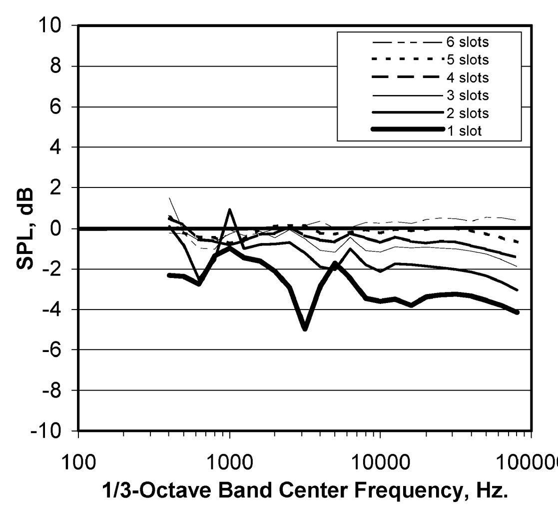

Fig. 17 SPS normalized shielding data; NPR = 1.72, $\theta = 90$ deg.

Measured $\frac{1}{3}$-octave band spectra for the $\theta = 150$ deg directivity angle are shown in Fig. 15. For all bands above about 2000 Hz, the spread between spectra is less than 4 dB. Data for the two-slot through six-slot cases are nearly indistinguishable. This demonstrates that once two of the slots are flowing, additional slot flow does not appreciably increase the noise in the high frequency range. The slight increase when the seventh slot is open could be caused by model edge entrainment effects. The larger spread in the low-frequency data is an indication of downstream coalescence of the

Table 1 Expected SPL reduction compared to seven-slot case if specified number of slots are flowing; 10 log(*N*/7)

No. of slots	Delta, dB
6	−0.67
5	−1.46
4	−2.43
3	−3.68
2	−5.44
1	−8.45

individual exhaust plumes generating excess noise. However, this appears to occur primarily in moving from one to two slots.

Using linear acoustic theory, the change in SPL obtained by operating fewer than seven slots can be estimated. The noise reduction relative to the seven-slot case expected from N flowing slots, independent of mixing and shielding effects, is given by $10\log(N/7)$. This quantity is calculated for each test case in Table 1. As an example, if only one slot is flowing, Table 1 shows that the resulting SPL would be approximately 8.45 dB lower than if all seven slots were flowing with no interaction effects between the slots.

To more easily evaluate the effects of jet shielding and plume coalescence on the measured spectra, data for each test point were normalized as follows. The appropriate value from Table 1 was added to each spectrum shown in Fig. 15 to correct SPL levels for the number of flowing slots. Next, the spectral levels measured for all seven slots flowing were subtracted from each of these spectra. Therefore, for a system of completely independent jets, these normalizations would result in 0-dB spectra at all frequencies. The spectra generated in this way are shown in Fig. 16. For a given data point, net negative SPL values represent frequencies for which shielding of jet noise by neighboring slots occurs. Net positive SPL values indicate frequencies for which merging of minijets results in excess mixing noise. Data presented in Fig. 16 show that for $\theta = 150$ deg there is a large acoustic shielding effect for mid to high frequencies, whereas at low frequencies downstream coalescence of the miniplumes generates extra low-frequency noise. As just noted, most of this excess noise appears to occur in going from the one- to two-slot geometry.

Normalized data for the $\mathrm{NPR} = 1.72$, $\theta = 90$ deg measurements are shown in Fig. 17. High-frequency shielding benefits, although reduced somewhat from the $\theta = 150$ deg case, are 2 to 4 dB and still significant. There is, however, no indication of a low-frequency penalty caused by jet coalescence at this sideline radiation angle. It is likely that reflection and refraction through the individual jet layers within the plume is the source of the large amount of shielding observed in the aft angles. This kind of effect would be smaller at the sideline angles compared to the aft angles, which is what is observed here. Additionally, for hot jet flow where the density gradient between jet columns is more significant than found here, the beneficial effects could increase.

Spectral data analyzed in this way will provide guidance on nozzle geometry improvements resulting in even greater noise reduction for future DEN designs. Variable slot spacing, for instance, can provide a means of realizing the benefits of jet-jet acoustic shielding while eliminating some of the excess low frequency noise caused by jet coalescence.

Summary

The data presented here from the distributed exhaust nozzle (DEN) designs show promise for this technology. Noise reductions up to 20 dB on a spectral basis and 10 dB on an overall basis were demonstrated. Although the thrust performance penalty is still relatively high at approximately 11%, it is approaching levels that could be tolerable in future revolutionary design aircraft systems that integrate the propulsion system into the airframe. It is clear that specific details of a particular DEN design can greatly influence the aeroacoustic properties. Phenomena such as jet–jet mixing, shielding, and coalescence all play a significant role in the resulting noise reduction. Testing and analyses such as those presented here will be required to make distributed exhaust technology viable for an aircraft system.

Acknowledgments

Northrop Grumman performed this work under Contract NAS1-02046 funded by the Propulsion Airframe Aeroacoustics subtask of NASA's Quiet Aircraft Technology Program. The authors thank Sang Lee and Meaza Teshome of the NASA Langley Jet Noise Laboratory for their invaluable assistance collecting and processing the acoustic data. The authors also thank Northrop Grumman's Ed Hobart and Gary Carr for their assistance with construction of the stereolithography DEN models and Brian Hallam for timely stress analysis. In addition, Krish Ahuja and Rick Gaeta of Georgia Tech provided helpful insight while comparing the slanted slot DEN results to those reported here.

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