Perceived Noise Assessment of Offset Three-Stream Nozzles for Low Noise Supersonic Aircraft

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We assess the potential of three-stream nozzle concepts to reduce the takeoff perceived noise level from future supersonic aircraft. The study encompasses the effects of nonaxisymmetric exhaust configurations as well as the effect of an enlarged plug. Asymmetry in the plume was created via eccentric tertiary and secondary ducts, in combination with a wedge-shaped deflector in the tertiary duct; and by reshaping the primary plug from circular to elliptical cross-section. The eccentricities were directed to increase the thickness of the lower-speed tertiary and secondary flows underneath the fast primary stream, thereby reducing noise in the general downward direction. The plug ellipticity was designed to flatten the primary stream along the major axis of the ellipse, thereby improving its coverage by the lower-speed streams with the goal of improving sideline noise reduction. The enlarged plug design was motivated by sonic-boom signature considerations. Acoustic measurements using helium-air mixture jets from small-scale, rapid-prototyped nozzles generated sound pressure level spectra at a number of polar and azimuthal angles for each configuration. These were converted to estimates of flyover perceived noise level and effective perceived noise level (EPNL) assuming a typical takeoff profile. The effect of the enlarged plug is to reduce the takeoff (downward) and sideline EPNLs, each by about 1.7 dB. Configurations with eccentricity in the tertiary flow only, all other components being axisymmetric, reduced the downward EPNL by as much as 5.1 dB but did not reduce the sideline EPNL. Adding eccentricity to the secondary ducts results in sideline noise reduction of about 2 EPNdB while providing downward reduction of around 5.6 EPNdB. The effect of the elliptical plug is to add another 1.0 dB to the sideline reduction. The best configuration involves the combination of eccentricity in the secondary and tertiary ducts with ellipticity of the primary plug; it yields noise reductions of 5.8 EPNdB and 2.9 EPNdB in downward and sideline directions, respectively. Including the effect of the enlarged plug, a cumulative (takeoff plus sideline) noise reduction of 12 EPNdB is estimated.

I. Introduction

Airport noise compliance remains a challenge for the development of future supersonic commercial aircraft. The turbofan engines powering these aircraft must have smaller cross section than their subsonic counterparts to enable efficient flight at supersonic speed and minimization of sonic boom signature. The resulting lower bypass ratio means higher exhaust velocity and thus significantly increased jet noise on takeoff. Without means of attenuation, it is unlikely that future noise regulations will be met.

Noise reduction concepts for high-speed jets have taken many forms and have generated a large body of literature. A comprehensive review can be found in a paper by Morris and McLaughlin.¹ Here we focus on approaches pertaining to multi-stream jets, specifically the method of offset-stream nozzles and associated reduction in radiation efficiency.^{2,3} The focus is on jets with three streams as they relate to the development of advanced variable-cycle engines for supersonic propulsion. We build on past efforts at UC Irvine^{4–6} as well as research at NASA Glenn Research Center^{7–9} to study the acoustics of such jets.

The ultimate goal is to translate the acoustics measured in the laboratory into an estimate of the reduction in flyover perceived noise level. The approach is similar to that recently employed by Huff *et al.*,¹⁰ although a wider coverage of azimuthal angles here may provide a more realistic assessment of sideline noise.

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II. Experimental Details

A. Generic Nozzle Design

The objective of the nozzle design process was to generate test articles that enabled rapid and accurate testing of a variety of nozzles having characteristics compatible with the exhaust of three-stream, variable-cycle engines envisioned for future supersonic aircraft. The nozzles needed to fit the capacity of the UCI Jet Aeroacoustics Facility, a triple-stream jet facility that delivers helium-air mixtures to the primary, secondary, and tertiary ducts of the nozzle. Helium-air mixtures simulate accurately the acoustics and fluid mechanics of hot jets.¹¹ The sub-millimeter tolerance requirements for the nozzle exit motivated a design where all the nozzle components are built in one piece, using high-definition stereolithography which allows nozzle lips as thin as 0.2 mm. The material used was Accura 60 plastic (3D Systems) with tensile strength in the range of 58-68 MPa. The design comprises a fixed base on which replaceable nozzle attachments are mounted. Figure 1 depicts the main design features of a representative nozzle. Measurement of the total pressure of each stream involves thin channels, of 0.75-mm diameter, introduced into support struts in each of the ducts. The channels begin at the outer surface of the attachment, follow an L-shaped path through the struts, and terminate into upstream-facing ports in their respective ducts. The diameter at the exit of the tertiary duct, D_t , ranged from 31.5 mm to 42 mm. Figure 2 shows a perspective view of the base and nozzle attachment.



Figure 1. Generic design for the three-stream nozzles.



Figure 2. Perspective view of base and nozzle attachment.

B. Cycle Point

The nozzles were tested at a set point (AA530) representative of a supersonic turbofan engine at takeoff power. Table 1 summarizes the exhaust conditions for each stream. The nozzle pressure ratio (NPR) is the ratio of the jet stagnation pressure to ambient pressure, the nozzle temperature ratio (NTR) is the ratio of jet stagnation temperature to ambient temperature, and the bypass ratio (BPR) is the ratio of either secondary or tertiary stream mass flow rate to the primary stream mass flow rate. Subscripts p, s and tindicate the primary, secondary and tertiary streams, respectively. The total BPR was 3.6. The Reynolds number of the primary jet was 3.5×10^5 . The velocity and Mach number of stream were matched exactly using helium-air mixture jets.

| - | | | | | | | | | | | | | | |
|---|-------|---------|---------|-------|------------------|------------------|------------------|-----------------|-----------------|------------------|------------------|------------------|-----------|-----------|
| | | Primary | | | Secondary | | | | Tertiary | | | | | |
| | Cycle | NPR_p | NTR_p | U_p | BPR _s | NPR _s | NTR _s | $U_{\rm s}/U_p$ | $A_{\rm s}/A_p$ | BPR _t | NPR _t | NTR _t | U_t/U_p | A_t/A_p |
| | | - | _ | (m/s) | | | | - | _ | | | | _ | _ |
| A | AA530 | 2.02 | 3.38 | 590 | 2.33 | 2.02 | 1.34 | 0.63 | 1.44 | 1.31 | 1.53 | 1.24 | 0.48 | 1.06 |

C. Specific Nozzle Designs

1. General Design Process

A large number of coaxial and asymmetric nozzles were designed, evaluated using Reynolds Averaged Navier Stokes (RANS) computations, and built in the research program.⁵ The design process reflects an evolution based on experience, guidance from the RANS plume statistics, and input from NASA. Axisymmetric (coaxial) nozzles are designated with the prefix AXI, while eccentric (offset-stream) nozzles use the prefix ECC. With a few exceptions, the nozzle designs underwent an initial evaluation using RANS before proceeding to the building step. The RANS results helped determine the aerodynamic performance and provided guidance as to the noise reduction potential.³ With regards to aerodynamic performance, designs with specific thrust loss greater than 0.5% were dropped from consideration, with strong favor for designs where the specific thrust loss did not exceed 0.25%. The RANS results were also scrutinized for any signs of flow separation and the appropriate fixes were applied. This report focuses on nozzles developed towards the end of research the program, where a certain level of maturity in the design process was achieved.

2. Axisymmetric Designs

The axisymmetric nozzle designs formed the points of departure for the eccentric arrangements. Their evolution has been covered in a previous report,⁶ so here we will focus on two designs of interest: AXI03U and AXI04U. Their radial coordinates are presented in Fig. 3. Nozzle AXI03U is a short-cowl variant of the NASA baseline nozzle featured in Ref. 8. The purpose of the short cowl was to bring the secondary and tertiary exits closer to the primary exit, therefore enhancing the potential for the secondary and tertiary streams to provide noise suppression from the primary stream. A concern about this design is the substantial increase of the boat-tail angle relative to the original NASA design. Because this could have negative impacts on the sonic boom signature, it was decided to modify the nozzle design pertaining to cycle AA530 to achieve roughly the same boat-tail angle as the original NASA nozzle. This was accomplished by enlarging the plug while preserving the exit areas of all three ducts, resulting in design AXI04U.



Figure 3. Radial coordinates of axisymmetric nozzles. (a) AXI03U; (b) AXI04U.

3. Offset-Stream Methods

Asymmetric jets were created by non-uniform distributions of the tertiary and secondary annulus widths, combined with insertion of a wedge-shaped deflector in the tertiary duct. Denoting the width of the tertiary annulus W_t , and noting that $D_{p,\text{eff}}$ provides a scale for the lateral extent of the strongest noise sources, the ratio $W_t/D_{p,\text{eff}}$ is used to describe the relative size of the tertiary stream. Similarly, for the secondary stream the ratio $W_s/D_{p,\text{eff}}$ is used, where W_s is the width of the secondary annulus. In plotting the azimuthal distributions of these two normalized widths, the azimuthal angle ϕ is defined relative to the downward vertical direction.

The key geometric parameters of the wedge-shaped deflector are depicted in Fig. 4. L denotes the "height" of the wedge and δ is the deflection angle, or wedge half-angle. In addition to the parameters shown in Fig. 4, it is also useful to consider the azimuthal "blockage" created by the deflector, denoted ϕ_{BLOCK} . In the design of the offset tertiary stream, the nozzle lip on the thin side of the annulus was recessed to avoid formation of a very narrow long duct and the associated viscous losses.



Figure 4. Geometric parameters of wedge-type deflector. Convention for azimuthal angle is also shown.

4. Elliptical Plug

The experimental matrix included three nozzles with elliptical plugs, the major axis of the ellipse being on the vertical plane. The change in plug cross-section was aimed to induce inward collapse of the primary flow, thus facilitating its coverage by the secondary/tertiary streams in the sideline azimuthal direction where noise suppression is challenging. The plug length and cross-sectional area distribution were preserved. Figure 5 describes the reshaping of the plug and presents the radial-azimuthal relations for the ellipse. Figure 6 describes the axial transitions, where parabolic and cubic splines are used to depart from and then blend back into the radial distribution of the original plug. Finally, Fig. 7 shows a CAD model of the modified plugs and lists the relevant design parameters. The exit geometry of the primary duct was not affected by the reshaping of the plug. Although non-circular plugs have been explored in single-stream jets,¹² this is the first known application to multi-stream jets.



Figure 5. Reshaping of the plug cross section.



In the relations that follow s = -dr/dx

 x_1 to x_2 : parabolic segment to zero slope x_3 to x_4 : cubic spline to original radius

$$a = a_{2} + \frac{1}{2} s_{1} \frac{(x - x_{2})^{2}}{x_{2} - x_{1}} \qquad a = r_{4} + (a_{2} - r_{4}) f(\eta)$$

$$\eta = \frac{x - x_{3}}{x_{4} - x_{3}}$$

$$f(\eta) = 1 - (3 - \sigma) \eta^{2} - (\sigma - 2) \eta^{3}$$

$$\sigma = \frac{x_{4} - x_{3}}{a_{2} - r_{4}} s_{4}$$

Figure 6. Axial transitions involved in the reshaping of the plug.



Figure 7. CAD model of elliptical plug and associated design parameters.

5. Review of Nozzles

We summarize the main features of the nozzles covered in this report. The summary is accompanied by Figs. 8 through 14 that provide key geometric parameters, the cycles involved, the reference nozzle, and where applicable the mass flow rate loss and the specific thrust loss predicted by RANS (in cases lacking RANS computations, the notation N/A is used). Even though in the reshaping of the ducts the geometric areas were preserved, the mass flow rate loss is thought to be caused by subtle effects like the deflection of streams when the wedge is included. In an actual engine design, this can easily be accounted for by resizing the duct. Thus, the loss in specific thrust is the most relevant measure of aerodynamic performance.

- AXI03U: Short-cowl, nominal-plug design.
- AXI04U: Short-cowl, enlarged-plug design.
- ECC09U: Shaped tertiary annulus combined with wedge deflector in tertiary duct.
- ECC12U: Shaped tertiary and secondary annuli, in combination with wedge deflector in tertiary duct.
- ECC17U: AXI04U with elliptical plug; ellipse major axis on the vertical plane.
- ECC18U: ECC09U with elliptical plug; ellipse major axis on the vertical plane.
- ECC19U: ECC12U with elliptical plug; ellipse major axis on the vertical plane.

Figure 15 shows photographs of the coaxial and selected eccentric nozzles.



Figure 8. Specifications for nozzle AXI03U.



Figure 9. Specifications for nozzle AXI04U.



Figure 10. Specifications for nozzle ECC09U.



Figure 11. Specifications for nozzle ECC12U.



Figure 12. Specifications for nozzle ECC17U.



Figure 13. Specifications for nozzle ECC18U.



Figure 14. Specifications for nozzle ECC19U.



Figure 15. Photographs of the exits of selected nozzles. (a) AXI03U; (b) AXI04U; (c) ECC12U; and (d) ECC19U.

III. Aeroacoustic Testing

A. Setup and Instrumentation

Noise measurements were conducted inside an anechoic chamber equipped with twenty four 1/8-in. condenser microphones (Bruel & Kjaer, Model 4138, TEDS) with frequency response up to 120 kHz. Figure 16 shows the layout and a photo of the facility. Nominally, twelve microphones were mounted on a downward arm (azimuth angle $\phi = 0^{\circ}$) and twelve were mounted on a sideline arm ($\phi = 60^{\circ}$). However, a number of microphones malfunctioned over the course of the project, prompting the installation of 15 microphones on the sideline arm and a small number (~ 5) microphones on the downward arm, the latter used just for reference. In this case, different azimuthal angles were surveyed by rotating the nozzle. Regardless of the deployment, the polar angle θ ranged approximately from 20° to 120° relative to the downstream jet axis, and the distance to the nozzle exit \mathcal{R}_{exp} ranged from 0.92 m to 1.23 m. The microphones were connected, in groups of four, to six conditioning amplifiers (Bruel & Kjaer, Model 2690-A-0S4). The 24 outputs of the amplifiers were sampled simultaneously, at 250 kHz per channel, by three 8-channel multi-function data acquisition boards (National Instruments PCI-6143) installed in a Dell Precision T7400 computer with a Xeon quad-core processor. National Instruments LabView software is used to acquire the signals. The temperature and humidity inside the anechoic chamber are recorded to enable computation of the atmospheric absorption. The microphones are regularly calibrated using a pistonphone; however, the best check of the microphone (and overall system) accuracy is the repetition protocol discussed in Section III.C.



Figure 16. Setup for far-field aeroacoustics measurements.

B. Signal Processing

The microphone signals were conditioned with a high-pass filter set at 300 Hz. Narrowband spectra were computed using a 4096-point Fast Fourier Transform, yielding a frequency resolution of 61 Hz. The spectra were corrected for microphone actuator response, microphone free field response and atmospheric absorption, thus resulting in lossless spectra. The correction for atmospheric absorption utilized the relations in Bass $et al.^{13}$ For the typical testing conditions of this experiment, and for the farthest microphone location, the absorption correction was 4.5 dB at 120 kHz.

C. Experiment Conduct and Repeatability

For each nozzle configuration within a given test campaign, at least two acoustic runs were performed matching the target velocity and Mach number (Table 1). In addition, the background noise was recorded and the background spectra were subtracted from the signal spectra prior to the conversion to lossless spectra discussed in Section III.B. The final SPL spectrum for each nozzle configuration (within a given campaign) represents the weighted average of the individual spectra. The weight tries to account for minor deviations from the target values of the intended cycle point and is loosely based on Lighthill's acoustic analogy. It uses the computed mass flow rate \dot{m} of the entire nozzle and the fully-mixed exit velocity $U_{\rm mix}$, defined as

$$U_{\rm mix} = \frac{\dot{m}_p U_p + \dot{m}_s U_s + \dot{m}_t U_t}{\dot{m}} \tag{1}$$

The weight has the form

$$w = \frac{\dot{m}_{\text{target}}}{\dot{m}} \left(\frac{U_{\text{mix,target}}}{U_{\text{mix}}}\right)^8 \tag{2}$$

where the subscript "target" indicates the target value. The first fraction on the right hand side relates to an effective size of the jet, against which the sound intensity scales linearly. The second fraction comes from the well known U^8 power law for the intensity. Assuming that N runs were performed for a given nozzle configuration, the weighted average of the individual spectra SPL_n was obtained from

$$SPL = 10 \log_{10} \left[\frac{1}{N} \sum_{n=1}^{N} w_n \ 10^{0.1} \ SPL_n \right]$$
(3)

The individual weights w_n did not exceed the range $0.9 < w_n < 1.1$ and for most experiments fell in the range $0.95 < w_n < 1.05$, corresponding to individual estimated errors of ± 0.2 dB.

The repeatability of the far-field acoustic tests is examined by plotting the spectra of the same jet recorded in distinct campaigns. Figure 17 plots the spectra of jet AXI04U, at three polar angles, recorded at four dates spaced apart by at least two months. The spectra were smoothed, using a Savitzky-Golay filter, to facilitate the comparisons. In addition, because there were minor variations in the microphone polar angles from one campaign to the next (the result of small changes in the axial position of the nozzle), the spectra were interpolated to the fixed polar angles stated in the figure. The near perfect overlap of the spectra is evident, indicating good control of the experimental conditions and integrity of the nozzle as it underwent multiple testing. Repeated acoustic surveys for eccentric nozzles were less numerous than those for coaxial (reference) nozzles. Figure 18 shows three repeats for jet ECC12U, spaced at least two weeks apart. Again, the near perfect overlap of the -spectra is evident.



Figure 17. Repeatability of the spectra of jet AXI04U, recorded on the four dates shown.



Figure 18. Repeatability of the spectra of jet ECC12U, recorded on the three dates shown.

IV. Sound Pressure Level Spectra

Far-field, narrowband SPL spectra will be presented for the jets covered in this report. The formatting is exemplified in Fig. 19. The spectra will be plotted for six polar angles θ with respect to the downstream axis. The spectra of the jet in question will be plotted in blue, and those of the reference case will be plotted in red.

A. Effect of Enlarged Plug on Coaxial Jet Noise

The effect of the enlarged plug on the emission of the coaxial jet is first considered. Figure 19 compares the spectra of the coaxial jets from the nozzle with the nominal plug (AXI03U) and the nozzle with the enlarged plug (AXI04U). The enlarged plug configuration is quieter by about 5 dB at high frequencies and for $30^{\circ} < \theta < 70^{\circ}$, most noticeably near $\theta = 45^{\circ}$. The noise reduction afforded by the enlarged plug could be due to source-observer shielding.^{12, 14}



Figure 19. SPL spectra for jets AXI04U and AXI03U.

B. Eccentric Configurations with Round Plug

Considering now the eccentric configuration with round plug, the spectra of jet ECC09U are plotted in Fig. 20, with comparison to the spectra of jet AXI04U. Downward reductions on the order of 15 dB are seen for the low polar angles in the medium to high frequency range. Noise reduction is considerable up to $\phi = 30^{\circ}$, but for $\phi \ge 60^{\circ}$ the sound is either unchanged or slightly elevated. Some sideline benefit is noted at low polar angles.

Nozzle ECC12U features asymmetric tertiary and secondary ducts. The combined asymmetry increases the acoustic benefit over nozzle ECC09U, as shown in Fig. 21. In the downward direction, and for polar angles near the angle of peak emission, reductions of up to 17 decibels are measured in the mid to high frequencies. There is now a distinct benefit in the sideline direction. The strong downward reduction is accompanied by significant noise excess in the upward direction.



Figure 20. SPL spectra for jets ECC09U and AXI04U. Azimutal angles: (a) $\phi = 0^{\circ}$; (b) $\phi = 30^{\circ}$; (c) $\phi = 60^{\circ}$; (d) $\phi = 90^{\circ}$; (e) $\phi = 180^{\circ}$.



Figure 21. SPL spectra for jets ECC12U and AXI04U. Azimutal angles: (a) $\phi = 0^{\circ}$; (b) $\phi = 30^{\circ}$; (c) $\phi = 60^{\circ}$; (d) $\phi = 90^{\circ}$; (e) $\phi = 180^{\circ}$.

C. Effect of Elliptical Plug on Jet from Coaxial Ducts

The effect of the plug with elliptical cross section on the noise emission of jet issuing from coaxial ducts is examined. Nozzle ECC17U resulted from replacing the circular plug of nozzle AXI04U with the elliptical plug depicted in Fig. 7. Recall that the axial distribution of the plug cross-sectional area was preserved. Figure 22 compares the SPL spectra of jets ECC17U and AXI04U. In the azimuthal sector $60^{\circ} \le \phi \le 90^{\circ}$, the elliptical plug provides reductions of as much as 4 dB at mid frequencies. The reductions are concentrated near the polar angle of peak emission. Even though the benefit looks modest compared to the large downward spectral reductions achieved with the eccentric configuration, it is nevertheless relevant to the challenging task of reducing sideline noise.

D. Combination of Elliptical Plug with Eccentric Ducts

Nozzle ECC18U resulted from replacing the circular plug of nozzle ECC09U with the elliptical plug. Figure 23 shows modest improvement in sideline noise reduction relative to ECC09U (Fig. 20). Similarly, nozzle ECC19U has the same lines as nozzle ECC12U but with the elliptical plug. Comparing the spectra of jet ECC19U, Fig. 24, with the spectra of jet ECC12U, Fig. 21, we note that the elliptical plug brings a small but distinct reduction in the sideline noise.

E. Differential Spectra for Elliptical plug

Given that the elliptical plug was a distinct design change from past concepts of offset-stream nozzles, this section summarizes the effects of the elliptical plug in the form of differential spectra. The following differential spectra are examined: ECC17U relative to AXI04U (effect of elliptical plug on emission of coaxial jet); ECC18U relative to ECC09U (effect of elliptical plug on emission of jet from with eccentric tertiary duct); and ECC19U relative to ECC12U (effect of elliptical plug on emission of jet from with eccentric secondary and tertiary ducts). For clarity of presentation, the differential spectra were smoothed versus frequency using a Savitzky-Golay filter. The results are presented in Figs. 25 through 27. For the jet from coaxial ducts, Fig. 25, the elliptical plug causes a slight elevation of levels in the general downward direction $(0^{\circ} \leq \phi \leq 30^{\circ})$ and in the aft arc, while there is a significant reduction at large polar angles and in the azimuthal sector $0^{\circ} \leq \phi \leq 15^{\circ}$. In the sideline azimuthal sector $60^{\circ} \leq \phi \leq 90^{\circ}$ there are distinct benefits of up to 4 dB in the aft arc and in the broadside direction for $\phi = 60^{\circ}$. The elliptical plug thus has a complex effect on the acoustics, with definite benefits on the sideline emission. Figure 26 shows that the elliptical plug has mixed impacts on the jet from nozzle ECC09U (eccentric tertiary stream), the most notable reduction occurring at $\phi = 60^{\circ}$ and at large polar angles. On the other hand, application of the elliptical plug to nozzle ECC12U, Fig. 27, has benefits practically throughout the polar and azimuthal angle ranges, except for some excess noise at very low polar angle and at $\phi \approx 60^{\circ}$.



Figure 22. SPL spectra for jets ECC17U and AXI04U. Azimutal angles: (a) $\phi = 0^{\circ}$; (b) $\phi = 15^{\circ}$; (c) $\phi = 30^{\circ}$; (d) $\phi = 60^{\circ}$; (e) $\phi = 90^{\circ}$.



Figure 23. SPL spectra for jets ECC18U and AXI04U. Azimutal angles: (a) $\phi = 0^{\circ}$; (b) $\phi = 30^{\circ}$; (c) $\phi = 60^{\circ}$; (d) $\phi = 90^{\circ}$; (e) $\phi = 180^{\circ}$.



Figure 24. SPL spectra for jets ECC19U and AXI04U. Azimutal angles: (a) $\phi = 0^{\circ}$; (b) $\phi = 30^{\circ}$; (c) $\phi = 60^{\circ}$; (d) $\phi = 90^{\circ}$; (e) $\phi = 180^{\circ}$.



Figure 25. Differential SPL spectra for jet ECC17U relative to jet AXI04U. Azimutal angles: (a) $\phi = 0^{\circ}$; (b) $\phi = 15^{\circ}$; (c) $\phi = 30^{\circ}$; (d) $\phi = 60^{\circ}$; (e) $\phi = 90^{\circ}$.



Figure 26. Differential SPL spectra for jet ECC18U relative to jet ECC09U. Azimutal angles: (a) $\phi = 0^{\circ}$; (b) $\phi = 30^{\circ}$; (c) $\phi = 60^{\circ}$; (d) $\phi = 90^{\circ}$; (e) $\phi = 180^{\circ}$.



Figure 27. Differential SPL spectra for jet ECC19U relative to jet ECC12U. Azimutal angles: (a) $\phi = 0^{\circ}$; (b) $\phi = 30^{\circ}$; (c) $\phi = 60^{\circ}$; (d) $\phi = 90^{\circ}$; (e) $\phi = 180^{\circ}$.

V. Perceived Noise Level Assessment

In assessing the acoustic performance of the various jets tested in this program, it is important to define a "figure of merit" that comes as close as possible to the noise certification metrics. Despite the limitations of small scale and lack of forward flight, it is nevertheless important to reduce the acoustic measurements into estimates of Perceived Noise Level (PNL) to obtain a more realistic assessment of the noise reduction potential of the jets. This chapter describes the basic steps in converting the acoustic measurements into PNL estimates, and evaluates the acoustic performance of the jets accordingly.

A. Flight Path and Geometric Relations

1. Flight Path

Referring to Fig. 28, the flightpath is selected to be a piece-wise linear trajectory, at zero altitude until x = 0and sloped at the climb angle γ for x > 0. Thus, the lift-off point is defined to be x = 0. The aircraft travels at constant Mach number M_{∞} and, for x > 0, constant climb angle γ . The engine axis is at a constant "angle of attack" α relative to the local direction of the flight path. The coordinates $(x_a, y_a, 0)$ refer to the actual aircraft position, while (x, y, 0) are the aircraft coordinates at the retarded time. The observer is located at $(x_0, 0, z_0)$ where z_0 will take the values 0 m for the takeoff monitor and 450 m for the sideline monitor. \mathcal{R}_a is the actual aircraft-observed distance and \mathcal{R} is the aircraft-observer position at the retarded time.

For the constant climb conditions assumed here, the retarded-time interval along the flight path is $M_{\infty}\mathcal{R}$. It is then straightforward to derive the following expression for the retarded time delay:

$$\Delta t = \frac{-(M_{\infty,x}(x_a - x_0) + M_{\infty,y}y_a) + \sqrt{(M_{\infty,x}(x_a - x_0) + M_{\infty,y}y_a)^2 + \mathcal{R}_a^2(1 - M_\infty^2)}}{a_\infty(1 - M_\infty^2)} \tag{4}$$

where $M_{\infty,x} = M_{\infty} \cos \gamma$ and $M_{\infty,y} = M_{\infty} \sin \gamma$ are the x- and y- components of the flight Mach number, respectively, and a_{∞} is the ambient speed of sound.



Figure 28. Flight path and geometric construction for the polar angle θ .

2. Observer Radius and Polar Angle

Knowing the retarded time delay, and referring to Fig. 28, it is easy to calculate the retarded-time coordinates (x, y, 0) from the actual coordinates $(x_a, y_a, 0)$, and thus to obtain the observer radius

$$\mathcal{R} = \sqrt{(x - x_0)^2 + y^2 + z_0^2} \tag{5}$$

Denoting $x_1 = x - y/\tan(\gamma + \alpha)$ the point where the engine axis intercepts the ground, the triangle $AB\mathcal{R}$ is defined by the points $(x_0, 0, z_0)$, $(x_1, 0, 0)$, and (x, y, 0). The observer polar angle is then obtained from the geometric relations

$$\tan \frac{\theta}{2} = \sqrt{\frac{(p-B)(p-\mathcal{R})}{p(p-A)}}$$

$$A = \sqrt{(x_1 - x_0)^2 + z_0^2}$$

$$B = \frac{y}{\sin(\gamma + \alpha)}$$

$$p = \frac{A + B + \mathcal{R}}{2}$$
(6)

3. Observer Azimuthal Angle

Figure 29 shows the geometric construction involved for determining the observer azimuthal angle ϕ . It is important to realize that the azimuthal angle must be defined in the spherical coordinate system $(\mathcal{R}, \theta, \phi)$ aligned with the engine (jet) axis. This is illustrated in the left part of Fig. 29. To help visualize the geometric relations, a cone of angle θ is drawn around the engine axis. The azimuthal angle must be defined on the plane normal to the cone axis that intercepts the ground at the axial location of the observer. Using the geometric relations shown on the right part of Fig. 29, the observer azimuthal angle is

$$\phi = \arctan\left[\frac{y\cos(\gamma+\alpha) - (x-x_0)\sin(\gamma+\alpha)}{z_0}\right]$$
(7)

When the observer is behind the airplane, the azimuthal angle can exceed 90° for sufficiently large value of the angle $\gamma + \alpha$. In that case, the observer "sees" the upper part of the airplane, which could reduce the benefit of any type of downward noise suppression scheme, whether it is an offset-stream method or barrier shielding. It is thus evident that azimuthal noise mitigation is highly sensitive on the manner in which the airplane is flown.



Figure 29. Geometric construction for the azimuthal angle ϕ . Left: perspective view of cone with angle θ around engine axis. Right: projections on the x - y plane.

4. Elevation Angle and Lateral Distance

The elevation angle β and lateral distance ℓ_{seg} illustrated in Fig. 30 are relevant to the calculation of the lateral attenuation, that is, the attenuation caused by the propagation of sound in the proximity of the ground. Their definitions are based on the standards set forth in the FAA's Integrated Noise Model (INM) Version 7.0,¹⁵ which in turn relies on SAE AIR reports 1751¹⁶ and 5662.¹⁷ Specifically, the definitions of β and ℓ_{seg} refer to the "point of closest approach" (CPA), which is the point along the flight path that minimizes the distance between the flight path and the observer. Using the construction of Fig. 30, it is readily derived that the distance between observer and flight path is minimized at

$$x_{\rm CPA} = \frac{x_0}{1 + \tan^2 \gamma} \tag{8}$$

The related lateral distance is

$$\ell_{\text{seg}} = \sqrt{z_0^2 + x_0^2 \sin^2 \gamma} \tag{9}$$

and the elevation angle is

$$\beta = \arctan\left(\frac{x_{\rm CPA}\tan\gamma}{\ell_{\rm seg}}\right) = \arctan\left(\frac{x_0\,\sin 2\gamma}{2\sqrt{z_0^2 + x_0^2\sin^2\gamma}}\right) \tag{10}$$



Figure 30. Geometric construction for the elevation angle β and lateral distance ℓ_{seg} , relevant to lateral attenuation. CPA denotes the "closest point of approach".

B. Estimation of Perceived Noise Level

Assuming a scale factor S that gives the desired full-scale static thrust, the lossless narrowband SPL spectra measured in the subscale experiments are extrapolated to the frequency $S \times 20$ kHz, i.e., the highest frequency of the audible spectrum. Here the extrapolation used a roll-off of -15 dB/decade. The EPNL results are very insensitive on this slope. Increasing the slope to -10 dB/decade, for instance, impacted the EPNL predictions by less than 0.05 dB and the EPNL differences by less than 0.02 dB. Following the extrapolation, the frequency is divided by the scale factor.

For a given flight path, the following steps are taken to estimate the flyover Perceived Noise Level (PNL) and the Effective Perceived Noise Level.

1. For each time step t of the retarded airplane location (typically in 0.5-s intervals) the lossless, scaled-up spectrum corresponding to $\theta(t)$ and $\phi(t)$ is obtained. This step requires interpolation between spectra and, for polar angles outside the range covered in the experiment, moderate extrapolation. To enhance the accuracy of interpolation or extrapolation the spectra were smoothed using a Savitzky-Golay filter.

2. The spectrum is corrected for distance and atmospheric absorption. The distance correction is

$$-20\log_{10}\left[\frac{1}{S}\frac{\mathcal{R}}{\mathcal{R}_{ref}}\right]$$

where \mathcal{R} is the observer radius and \mathcal{R}_{ref} is the reference radius for the lab measurements. The absorption correction is applied for ambient temperature 29°C and relative humidity 70% (conditions of least absorption) using the relations of Bass et al.¹³

- 3. The spectrum is discretized into 1/3-octave bands and the perceived noise level (PNL) is computed according to Part 36 of the Federal Aviation Regulations.¹⁸
- 4. The PNL is corrected for lateral attenuation according to FAA's INM7.0,¹⁵ using the geometric relations of Section V.A. This impacts only the the sideline estimate.
- 5. The previous step gives the time history of perceived noise level, PNL(t). From it, the maximum level of PNL, PNLM, is determined. The duration of PNL exceeding PNLM-10 dB is calculated and the corresponding "duration correction" is computed according to FAR 36. The effective perceived noise level, EPNL, equals PNLM plus the duration correction. The estimate of EPNL includes the "tone correction", a penalty for excessively protrusive tones in the 1/3-octave spectrum, although the present spectra at cycle AA530 are devoid of such tones.

Even though past studies of PNL in our group have included a Doppler shift,¹⁹ the relations used were based on treatment of the jet noise as a moving source.²⁰ This concept is becoming questionable according to a recent study by Michel & Ahuja.²¹ On the other hand, treating the jet noise source as fixed with the airframe may obliterate the physics of the wavepacket nature of the jet noise source.²² The effect of forward flight on wavepacket emission has been shown to be complex,²³ and this complexity increases for multi-stream jets. Given these open questions, it was deemed preferable to not apply any Doppler shift to the static spectra pending an investigation on the proper way to do this.

C. Flyover Simulations

1. Flight Path

The flight path selected for the present flyover simulations has the shape depicted in Fig. 28. The time history starts 10 s before the lift off point, which is set at $x_a = 0$. The aircraft is traveling at a constant Mach number $M_{\infty} = 0.25$. The climb is performed at angle $\gamma = 5^{\circ}$ and the engine angle of attack is set at $\alpha = 5^{\circ}$. The sideline monitor (SL) is located at $z_0=450$ m and at the axial distance where the aircraft's altitude is 305 m (1000 ft), which is a common reference point. The takeoff monitor (TO) is located at $z_0=0$ m and at the axial distance where the aircraft's altitude is 457.5 m (1500 ft). The flight path parameters are summarized in Table 2.

| Flight Mach number, M_{∞} | 0.25 |
|----------------------------------|----------------------|
| Climb angle, γ | 5.00° |
| Engine angle of attack, α | 5.00° |
| Altitude at take-off monitor (m) | $457.5 \ \mathrm{m}$ |
| Altitude at sideline monitor (m) | $305.0~\mathrm{m}$ |

Table 2 Flight path parameters



Figure 31. Time history of observer polar (θ) and azimuthal (ϕ) angles for the flyover parameters of Table 6.1. Observer is at sideline location. Dashed red lines mark the interval where PNL>PNLM-10 dB for jet ECC19U, the quietest case investigated here.

Figure 31 shows the relationship between observer polar angle and azimuthal angle, with the observer situated at the sideline station as defined above. Of particular interest is the range of azimuthal angles within the time interval relevant to EPNL. In Fig. 31 the time interval is chosen for the quietest jet of this study, and it should be kept in mind that this will change depending on the noise characteristics of the jet. Here the relevant azimuthal range is $55^{\circ} \leq \phi \leq 62^{\circ}$. As illustrated in Fig. 29, this range is sensitive on the pitch angle $\gamma + \alpha$ of the engine axis. A high pitch angle will lead to large azimuthal angles which the offset-stream approach becomes less effective. Thus, the manner in which the airplane is flown, including the use of high-lift devices that reduce α , will have significant impact on the noise signature.

2. PNL Time Histories

Figure 32 compares the axisymmetric jets issuing from the nominal-plug and enlarged-plug nozzles, AXI03U and AXI04U respectively. Here we note that the effect of the enlarged plug translates to EPNL benefits of about 1.7 dB for both the takeoff and sideline monitors.

Figures 33 through 37 plot the PNL time histories of all the asymmetric jets from the enlarged-plug nozzles, with jet AXI04U as the reference. The following general trends are noted:

- All the offset-stream jets offer significant reductions in the takeoff EPNL, the maximum reduction being 5.85 dB for jet ECC19U.
- For the offset-stream jets, sideline EPNL reductions are achieved only for the cases where both the secondary and tertiary ducts have asymmetric shapes. Jets from nozzles with asymmetry only in the tertiary duct did not achieve sideline reduction. This statement is supported by testing of additional nozzles not included in this report.
- The elliptical plug offers a distinct benefit in sideline EPNL reduction. This is clear in the coaxial-duct case ECC17U (Fig. 35). It is also evident that the elliptical plug helps increase the sideline benefit (or reduce the sideline excess noise) of all the offset-stream configurations. Compare, for example, jet ECC12U (Fig. 34) with jet ECC19U (Fig. 37), where the only change is the replacement of the circular plug with the elliptical plug.



Figure 32. Time history of PNL for jet AXI04U compared to AXI03U. (a) Takeoff monitor; (b) sideline monitor.



Figure 33. Time history of PNL for jet ECC09U compared to AXI04U. (a) Takeoff monitor; (b) sideline monitor.



Figure 34. Time history of PNL for jet ECC12U compared to AXI04U. (a) Takeoff monitor; (b) sideline monitor.



Figure 35. Time history of PNL for jet ECC17U compared to AXI04U. (a) Takeoff monitor; (b) sideline monitor.



Figure 36. Time history of PNL for jet ECC18U compared to AXI04U. (a) Takeoff monitor; (b) sideline monitor.



Figure 37. Time history of PNL for jet ECC19U compared to AXI04U. (a) Takeoff monitor; (b) sideline monitor.

D. EPNL Summary

The EPNL data shown in the previous figures are summarized in Tables 3 and 4. The subscripts TO and SL denote the takeoff and sideline monitors, respectively. Table 3 lists the enlarged-plug configurations and the changes in EPNL (Δ EPNL) are relative to the enlarged-plug reference jet AXI04U. In Table 4, the changes are relative to the nominal-plug reference jet AXI03U. Thus, Δ EPNL in Table 4 combines the effect of the enlarged plug with the effects of the asymmetries. The combined change (TO+SL) can be viewed as an overall figure of merit, although balanced reductions at the takeoff and sideline monitors are also desirable.

Tables 3 and 4 bring out what was previously noted in the discussion of the PNL time histories, namely that jets ECC12U and ECC19U provide the best acoustic results, with ECC19U being the top performer. The combined EPNL benefit for jet ECC19U is 8.75 dB when referenced to the enlarged-plug baseline; and 12.2 dB when referenced to the nominal-plug baseline. It is believed that these numbers are significant

enough to help future supersonic civil aircraft achieve noise signatures similar to those of their subsonic counterparts.

| | - | 0 | | 0 1 0 | |
|--------|--------------------|--------------------|--------------------|--------------------|-----------------------|
| Jet | EPNL _{TO} | EPNL _{SL} | $\Delta EPNL_{TO}$ | $\Delta EPNL_{SL}$ | $\Delta EPNL_{TO+SL}$ |
| AXI04U | 102.74 | 101.49 | - | - | - |
| ECC09U | 97.62 | 102.23 | -5.12 | 0.74 | -4.38 |
| ECC12U | 97.14 | 99.46 | -5.60 | -2.03 | -7.63 |
| ECC17U | 102.89 | 100.18 | 0.15 | -1.31 | -1.16 |
| ECC18U | 97.97 | 101.95 | -4.77 | 0.46 | -4.31 |
| ECC19U | 96.89 | 98.59 | -5.85 | -2.90 | -8.75 |

Table 3 EPNL summary for the enlarged-plug nozzles

Table 4 EPNL summary with differences relative to AXI03U

| | Jet | EPNL _{TO} | EPNL _{SL} | $\Delta EPNL_{TO}$ | $\Delta EPNL_{SL}$ | $\Delta EPNL_{TO+SL}$ |
|---------------|--------|--------------------|--------------------|--------------------|--------------------|-----------------------|
| Nominal plug | AXI03U | 104.51 | 103.18 | - | - | - |
| Enlarged plug | AXI04U | 102.74 | 101.49 | -1.77 | -1.69 | -3.46 |
| | ECC09U | 97.62 | 102.23 | -6.89 | -0.95 | -7.84 |
| | ECC12U | 97.14 | 99.46 | -7.37 | -3.72 | -11.09 |
| | ECC17U | 102.89 | 100.18 | -1.62 | -3.00 | -4.62 |
| | ECC18U | 97.97 | 101.95 | -6.54 | -1.23 | -7.77 |
| | ECC19U | 96.89 | 98.59 | -7.62 | -4.59 | -12.21 |

VI. Conclusions

The investigation reported here assessed the potential of three-stream nozzle concepts to reduce the takeoff perceived noise level from future supersonic aircraft. The study encompassed the effects of non-axisymmetric exhaust configurations as well as the effect of an enlarged plug. Asymmetry in the plume was created via eccentric tertiary and secondary ducts, in combination with a wedge-shaped deflector in the tertiary duct; and by reshaping the primary plug from circular to elliptical cross-section. The eccentricities were directed to increase the thickness of the lower-speed tertiary and secondary flows underneath the fast primary stream, thereby reducing noise in the general downward direction. The plug ellipticity was designed to flatten the primary stream along the major axis of the ellipse, thereby improving its coverage by the lower-speed streams with the goal of improving sideline noise reduction. The enlarged plug design was motivated by sonic-boom signature considerations.

Acoustic measurements using helium-air mixture jets from small-scale, rapid-prototyped nozzles generated sound pressure level spectra at a number of polar and azimuthal angles for each configuration, thereby providing a richer azimuthal coverage than earlier similar studies.¹⁰ The spectra were converted to estimates of flyover perceived noise level and effective perceived noise level (EPNL) assuming a typical takeoff profile. The effect of the enlarged plug is to reduce the takeoff (downward) and sideline EPNLs, each by about 1.7 dB. Configurations with eccentricity in the tertiary flow only, all other components being axisymmetric, reduced the downward EPNL by as much as 5.1 dB but did not reduce the sideline EPNL. Adding eccentricity to the secondary ducts results in sideline noise reduction of about 2 EPNdB while providing downward reduction of around 5.5 EPNdB. The effect of the elliptical plug is to add another 1.0 dB to the sideline reduction. The best configuration involves the combination of eccentricity in the secondary and tertiary ducts with ellipticity of the primary plug; it yields noise reductions of 5.8 EPNdB and 2.9 EPNdB in the downward and sideline directions, respectively. Including the effect of the enlarged plug, a cumulative (takeoff plus sideline) noise reduction of 12 EPNdB is estimated. Although this is a preliminary estimate that needs to be confirmed in large-scale tests, it provides encouragement that the concepts explored here can help achieve the goal of Chapter 14 minus 10 EPNdB.¹⁰

The study indicates that the sideline noise reduction from azimuthally-directional methods, such as those employed here, will be highly sensitive on the manner in which the aircraft is flown. In particular, low pitch angle on takeoff is desirable to exploit as much as possible the benefits of those methods. This may entail the creative design and use of high-lift devices at takeoff. Future efforts should also consider the phenomenon of jet-by-jet shielding,^{24,25} which could improve considerably the sideline noise reduction.

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