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Jet Noise Reduction Potential From Emerging Variable Cycle Technologies

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Abstract

Acoustic and flow-field experiments were conducted on exhaust concepts for the next generation supersonic, commercial aircraft. The concepts were developed by Lockheed Martin (LM), Rolls-Royce Liberty Works (RRLW), and General Electric Global Research (GEGR) as part of an N+2 (next generation forward) aircraft system study initiated by the Supersonics Project in NASA's Fundamental Aeronautics Program. The experiments were conducted in the Aero-Acoustic Propulsion Laboratory at the NASA Glenn Research Center. The exhaust concepts utilized ejectors, inverted velocity profiles, and fluidic shields. One of the ejector concepts was found to produce stagnant flow within the ejector and the other ejector concept produced discrete-frequency tones that degraded the acoustic performance of the model. The concept incorporating an inverted velocity profile and fluid shield produced overall-sound-pressure-level reductions of 6 dB relative to a single stream nozzle at the peak jet noise angle for some nozzle pressure ratios. Flow separations in the nozzle degraded the acoustic performance of the inverted velocity profile model at low nozzle pressure ratios.

I. Introduction

The Supersonic Project of the NASA Fundamental Aeronautics Program is developing technologies for future, supersonic, commercial aircraft. The Project has established a set of sonic boom, airport noise, and emission goals for an N+2 aircraft (next generation forward) that could enter service between 2018 and 2020. The N+2 aircraft are expected to achieve cruise speeds between Mach 1.6 and 1.8, have payloads between 35 and 70 passengers, and achieve airport noise levels 10 to 20 EPNdB (cumulative) below FAA Stage 3 requirements. N+2 systems studies conducted by Lockheed Martin (LM), Rolls-Royce Liberty Works (RRLW), and General Electric Global Research (GEGR) indicated that a successful airplane design could be achieved if certain technologies performed as well as projected. The projected technologies to be validated used three-stream engine architectures and corresponding exhaust nozzles that could simultaneously achieve the low noise operation around airports and the high specific thrust required for supersonic cruise. To prove whether the proposed engine cycle and exhaust-nozzle concepts could meet the noise goal, model-scale versions of the nozzles were designed by RRLW and GEGR and tested at the NASA Glenn Research Center. The results of the N+2 exhaust-concept experiments are reported here.

The exhaust concepts proposed by RRLW incorporated ejectors (cylindrically shaped shrouds that surround the jet plume and often extend downstream of the nozzle exit for several nozzle diameters). Research on ejectors for jet-noise suppression began in the mid 1950s with investigations focusing on noise reduction potential for ejectors used with single-stream jets. Some of the first experiments identified the need of combining mixing nozzles with ejectors as ejectors were found to provide little or no suppression when combined with standard round nozzles (Refs. 1 to 3). Since these early investigations, most, if not all, ejector-exhaust designs incorporate mixing nozzles. These early investigations also identified the potential for production of discrete tones by ejectors. Initial parametric studies that would ultimately provide critical design information included engine and flight tests that focused on the importance of ejector diameter, length, and axial location (Refs. 4 and 5). The engine tests showed that up to 8 dB reduction could be achieved when ejectors were used with mixing nozzles and, in most cases, the ejectors provided additional noise suppression over that achieved by the mixing nozzles alone as long as the ejector had sufficient length (typically greater than two nozzle diameters). Results from early flight tests indicated that the mixer-ejector provided little or no in-flight perceived noise benefit although flight studies conducted later (Refs. 6 and 7) showed that perceived noise level reductions could be achieved with a combination of mixer and acoustically-lined ejector. These early studies focused on using the mixer-ejector to reduce jet noise through the reduction of jet velocity. It was realized that complete mixing of the primary jet with entrained ejector flow needed to occur before the exit of the ejector to adequately reduce the jet velocity and the ejector also needed to provide sufficient length to shield any high frequency noise introduced by the enhanced mixing process. A better physical understanding of the mixer-ejector flow was developed somewhat later when the ideal, maximum, ejector-pumping performance (mass flow entrainment) was shown (through an idealized application of the mass, momentum, and energy equations to the ejector control volume) to be related to the ejector area and occurred when the flows are fully mixed at the ejector exit (Refs. 8 to 10). Ejector pumping was shown to increase with increasing ejector area although, in real flows, an optimum area exists and increased area beyond this point produces diminished ejector pumping due to losses in the secondary duct which are not captured in the idealized ejector analysis. The idealized analysis does not address the mixing process within the ejector that is a function of ejector length and is the result of turbulent mixing between the primary jet and ejector flow. When the turbulent shear layer formed by the primary jet and ejector flow extends to the ejector-shroud wall, a strong streamwise flow is established across the entire ejector cross section and significant suction is created at the ejector inlet. Enhanced mixing (and therefore shorter ejectors) can be achieved through mixers that streamwise vortices may allow for shortened ejector lengths. While the single-stream studies provide critical guidance for ejectors designed for future engine architectures, the flow structure of multi-stream jets incorporating mixing nozzles is far more complicated than the single stream counterpart. Mixers in multi-stream jets are typically used to mix the high-speed core flow with the fan flow and may not provide adequate mixing between the mixed core and fan streams with the entrained ejector flow to achieve adequate pumping of the ejector. The implementation of an ejector in the RRLW model provides the opportunity to evaluate ejectors in a multi-stream application.

The GEGR concept combined two noise-reduction concepts that had been explored previously: inverted velocity profiles (IVP) and fluid shields (FS). The inverted velocity profile concept takes the cold flow typically produced by the fan stage of the engine and redirects it along the centerline of the exhaust plume while diverting the hot stream to an annulus around the cold stream. Several reports (Refs. 11 to 15) from the early 1980's documented these impacts. This was considered beneficial for noise for several reasons. In previous incarnations of this concept the bypass ratio was relatively low and the cold bypass stream had a Mach number greater than 1, thus containing shocks from the underexpanded nozzle. Sheathing this shock-containing stream in the hot flow changed the broadband shock-associated noise produced. Additionally, by spreading the high speed flow over a thin annulus it mixed out sooner than when it was confined to the center of the jet, providing a lower mixed jet velocity at the peak jet mixing noise source region downstream. This effect was accentuated as the bypass ratio was increased. The price paid for enhanced mixing is increased noise from the initial shear that now has a higher velocity gradient. The fluid shield concept aims to reduce the high frequency penalty of the IVP by decreasing the higher velocity gradient over the first portion of the jet plume.

The results of the acoustic and flow-field studies for the RRLW and GEGR models are presented. The facilities, hardware, and measurements are described in the following section. Far-field acoustics were used to investigate the acoustic performance of the models and Particle Image Velocimetry measurements were used to investigate the flow fields. Results of the experiments are presented in Section III and a discussion of the concept development process is contained in Section IV.

II. Experimental Approach

The experiments were conducted in the Aero-Acoustic Propulsion Laboratory (AAPL) at the NASA Glenn Research Center shown in Figure 1. The AAPL is a 65 ft radius geodesic dome treated with acoustic wedges. The AAPL contains the Nozzle Acoustic Test Rig (NATR), which produces a 53 in. diameter simulated forward-flight stream reaching Mach numbers of 0.35. The High Flow Jet Exit Rig (HFJER), a dual-stream jet engine simulator capable of replicating most commercial turbo-fan engine temperatures and pressures (see Ref. 16), is centered in the simulated flight stream of the NATR. A third-stream capable of achieving mass-flow rates between 0.5 to 6 lbm/sec has been added to the HFJER. The third-stream flow temperatures are equal to that of the bypass stream as the former stream branches off the latter stream after the bypass heater.

Acoustic measurements were made with the far-field array shown in Figure 1. The array contains 24 microphones located on a 45 ft constant radius arc covering polar angles between 45° and 160°, where angles greater than 90° are in the downstream direction relative to the third-stream nozzle exit. All data are corrected for atmospheric absorption (Ref. 17) and wind tunnel shear layer effects (Ref. 18) and are presented on a one-foot lossless (no atmospheric absorption) arc. Data are acquired using 1/4 in. Bruel and Kjaer microphones (without protection grids) pointed directly at the nozzle exit. Microphone sensitivity and frequency response have been applied to all measurements. Narrowband data were acquired in 12 Hz bands and results are presented as power-spectral density (PSD) unless otherwise stated.

Two types of particle image velocimetry (PIV) measurements were performed: (1) two-component streamwise experiments and (2) cross-stream stereo PIV experiments. For all PIV studies, Redlake ES11000 cameras with 2.6K x 4K CCD arrays were used to record images. For the streamwise experiments, two cameras, each with a 380 by 325 mm field of view, were used in a side-by-side configuration with a 28 mm overlap between camera images. The laser light sheet (created with a 400 mJ per pulse, 532 nm, dual-head Nd-YAG laser) illuminated the jet centerline. In the cross-stream experiments, the laser light sheet illuminated cross-stream planes in the jet. The field of view for the reconstructed velocity field was 400 by 360 mm. For all PIV experiments, the core and fan streams were seeded with a pH stabilized dispersion of aluminum oxide (0.7 μm particles) in ethanol. The third stream was seeded with dry alumina particles using a fluidized bed seeder. The free jet was seeded with a Rosco Delta 3000 foggers that generates 0.5 to 4.5 μm particles.

For the stereo PIV experiments, the 2-D vector maps from the left and right cameras were generated using a multi-pass processing approach. The processing strategy used an initial pass with 64 by 64 pixel subregions on 32 pixel centers followed by 6 passes (using simulated annealing) at 32 by 32 pixel subregions on 16 pixel centers, followed by two final passes using subregion distortion processing. Symmetric Phase Only Filtering was used on the cross-stream data sets to reduce the effect of flare light from the model.

All PIV surveys used 400 image pairs per axial station, yielding 400 velocity vector maps at each axial station. The velocity vector maps were then ensemble averaged to compute the first and second order statistics. Hard velocity cutoff limits and Chauvenet's criteria were used to remove outliers.

The RRLW models are shown in Figure 2. The model in Figure 2(a), the Highly Variable Cycle (HVC) exhaust model, was used in experiments preceding the N+2 system studies and served as the basis for the redesigned model (see Fig. 2(b)) used in the N+2 studies. The HVC model had a core lobed-mixer nozzle, an elliptic fan nozzle, and an actuated ejector. Sidewalls were used to attach the ejector doors to the outer shell of the fan nozzle. The N+2 HVC model shown in Figure 2(b) used the HVC core lobed mixer, a circular fan nozzle, a third-stream nozzle that pumped an ejector, and ejector flaps that diverted flow from the fan and third streams to the core stream. The contours of the ejector and sidewalls of the N+2 HVC model were significantly different from those used in the HVC model. The three-stream nozzle system in Figure 2(c) was the baseline-nozzle system for the N+2 HVC investigations.

The cycle points used in the HVC experiments are shown in Table 1. The nozzle pressure ratio, NPR, is the ratio of the stagnation pressure of the jet to the ambient pressure. The nozzle temperature ratio, NTR, is the ratio of the stagnation temperature of the jet to the ambient temperature. Subscripts c and f indicate core and fan stream conditions, respectively. As shown in the Table, all data were acquired at subsonic exhaust speeds on the core and fan streams and heated conditions on the core stream. The data were acquired at free jet Mach numbers (M_{fj}) equal to 0 (static conditions) and 0.3.

The cycle points used in the N+2 HVC experiments were similar to those shown in Table 1 with the third stream operated at nozzle pressure ratios slightly lower than those of the fan stream. For all experiments, the exhaust speeds of the core, fan, and tertiary stream were subsonic.

A cross-sectional view of the GEGR model is shown in Figure 3. The core stream of the HFJER was internally routed within the model to the annular "Hot Flow" stream shown in Figure 3. The fan stream was routed to the inner flow stream along the plug. The fluid shield was on the measurement side of the jet was supplied from the HFJER tertiary stream. A conventional aspect of the nozzle was the changing of the divergent part of the nozzle. Plans for the full-scale engine had variable A9/A8 to optimize cruise performance. However, in the first design iteration two nozzle contours were designed, both of which were highly overexpanded at low-altitude operating points. Based on preliminary RANS CFD, it was felt that the acoustic effect of the overexpanded flow would be minimal. This was determined to be a mistake in validation tests. An additional difference from previous work was the mixing of streams to produce the "hot" outer stream. The effective bypass ratio of cold flow to hot flow was therefore less than 1, pushing the concept outside the range of previous experiments. Additionally, the nozzle features a significant plug, required to minimize the effect of the nozzle boat tail angle. The reference (baseline) configuration was a single-stream nozzle with the same fully-mixed flow conditions as those of the IVP configuration.

III. Results

A. RRLW HVC and N+2 HVC Model

Acoustic results for the HVC model (see Fig. 2(a)) operated at representative takeoff conditions and M_{fj} = 0.0 are shown in Figure 4. The angles indicated in the legend are the ejector door angles relative to the closed position (no ejector opening) at 0°. As the ejector door angle increases, the ejector inlet area increases. Observation angles greater than 90° are in the downstream direction relative to the ejector-door trailing edge. The baseline data were acquired for an equivalent-area-nozzle system with a round fan nozzle and no ejector doors. Tones are present in the acoustic data acquired at the 5° door position for all observation angles. The baseline nozzle produced the lowest acoustic levels for observation angles less than, or equal to, 90°. In the peak jet noise direction (see Fig. 4(b)), acoustic levels for the 10° and 20° ejector door configurations are lower than those of the baseline-nozzle system for frequencies below 800 Hz.

Acoustic results obtained for the same jet conditions as those in Figure 4 and M_{fj} = 0.3 are shown in Figure 5. The tones observed in the spectra acquired at M_{fj} = 0.0 are not present in the spectra at M_{fj} = 0.3. No acoustic benefit was achieved with the ejector relative to the baseline-nozzle system except at very low frequencies (below 400 Hz) in the peak jet noise direction.

The results from cross-stream stereo PIV experiments obtained at the same conditions as those for Figure 4 are shown in Figure 6. The orientation of the model is shown in the upper left corner of the Figure. The location of the ejector-door trailing edges are indicated with solid black lines in the contour plot in the top row of Figure 6(a). The solid black arrows on the mean velocity contours indicate the velocity vector direction in that region of the flow. The mean velocity plots show that the corners of the ejector sidewalls distort the flow and create vorticity (not shown in the Figure) that elongate the jet plume in the direction of the sidewalls. Additionally, the fluid within the ejector appears to be stagnant. The vorticity in the core region of the flow generated by the core-lobed mixer is distorted by the elliptic fan nozzle and ejector. The distortion of the core flow inhibits the mixing of the core-lobed nozzle. The turbulent kinetic energy contours show that the elongation of the flow in the direction of the sidewalls increases TKE in the region of the shear layer directly downstream of the ejector doors. The inadequate acoustic performance of the HVC model is likely associated with the lack of ejector flow and the increases in TKE levels associated with the impact of the ejector sidewalls on the evolving jet plume.

The results of PIV experiments at the same jet conditions as those indicated in Figure 6 with $M_{fj} = 0.2$ are shown in Figure 7. The trends in the data at $M_{fj} = 0.2$ are similar to those observed at $M_{fj} = 0.0$. The introduction of the simulated forward flight stream did not induce flow in the ejector and the flow distortions associated with the ejector sidewalls and elliptical fan nozzle were similar to those observed at $M_{fj} = 0.0$.

Acoustic results for the N+2 HVC model operated at core and fan stream conditions similar to those in Figure 5 are shown in Figure 8. Multiple discrete tones were produced by the model at all observation angles. Measurements at other operating conditions and for other ejector and ejector flap angles produced results similar to those shown in Figure 8. Cavities between the ejector sidewalls and ejector doors as well as the ejector-flap hinges were covered and the measurements were repeated. These model modifications had little impact on the production of tones. Closing the ejector flap reduced or eliminated the tones but resulted in elevated broadband noise most likely due to flow separation in the core stream resulting from the divergence angle of the ejector flap. Subsequent experiments were conducted with the ejector flap deflected (resulting in a convergent ejector flap contour), the ejector flap opening covered, and the surface contour upstream of the ejector-flap entrance smoothed. The spectra in Figure 9, obtained after the ejector-flap modifications, show that the modifications eliminated the discrete tones indicating that the tones were the result of unsteady flow separations upstream of the ejector flap and within the ejector flap opening. It was not possible to eliminate discrete tones for all operating conditions and ejector flap angles.

Results from the N+2 HVC stereo PIV experiments are shown in Figure 10. The mean streamwise velocity contours indicate that ejector flow has been established for the N+2 HVC model. However, the modified ejector sidewalls did not eliminate the impact of the sidewalls on the downstream evolution of the flow which resulted in higher than expected TKE levels in the shear layer downstream of the region where the ejector doors connected to the ejector sidewalls. Additionally, the core-lobed mixer appeared to have little impact on the jet mixing.

B. GEGR Model

Acoustic results for the GEGR model are shown in Figure 11 and compared with those obtained reference nozzle (“REF”) for representative temperature cycles (“low”, “mid”, “hi”). For a constant temperature, the ideal thrust was increased by increasing NPR. The results show that the radiated noise levels associated with the inverted velocity profile drop dramatically above a given NPR (ideal thrust) and can be lower than the corresponding reference nozzle for the highest NPR investigated. However, for lower thrust points, the inverted velocity profile jet produced noise levels higher than those of the reference nozzle. PIV results indicated that increased noise levels (compared to the reference nozzle) at low NPR were probably generated by flow separation near the nozzle trailing edge. Figure 12 shows an instantaneous velocity vector map from the PIV testing superimposed on the nozzle. At the lip between the thin inner cold flow and larger hot outer there is a large low velocity region, the result of separation in the hot stream in the divergent portion of the nozzle. When statistics are computed from the velocity maps (see Fig. 13), the mean velocity shows a near-zero mean velocity in this region of the flow. There is also a significant amount of turbulence generated here, with peak levels greater than that found at the peak-mixing region downstream. Although such separations and turbulence were found for a wide range of flow conditions, all of which were overexpanded for the divergent nozzle, there were significant differences in the details of the separation. Notably, initial RANS CFD solutions used to design the model flow lines did not pick up the strong flow separations resulting from the overexpanded flow. However, Large Eddy Simulations (LES) conducted after the test (see Fig. 3) clearly predicted the separation.

Acoustic results obtained at high enough nozzle-pressure ratios to suppress separation at the divergent nozzle exit (higher than those used in Fig. 3) are shown in Figures 14 and 15. The overall sound pressure levels (OASPL) for the IVP nozzle were 2 dB below those of the reference nozzle at polar angles broadside to the jet and 6dB below those of the reference nozzle at the peak radiation angle (see Fig. 14).

The sound spectra in Figure 15 show a 3 to 5 dB reduction in peak levels and a slight high-frequency increase for the IVP nozzle relative to the reference nozzle.

The fluid shield flow produced a further reduction of ~1 dB, but did not provide more reduction at the high frequencies where the IVP increased acoustic levels relative to levels produced by the reference nozzle. Most of this reduction was attributed to the reduction in fully mixed jet velocity, all cases being evaluated on a constant thrust basis.

IV. Discussion and Conclusions

The flow lines for both HVC models were based on results from RANS solutions. Due to the screening nature of the effort, many of the three-dimensional characteristics of the model (such as the lobed mixer geometry and ejector-sidewall contours) were omitted from the computation. The screening RANS solutions did not capture the flow separations and unwanted vorticity associated with realistic components in the design. While high fidelity RANS calculations performed on the HVC model following testing adequately captured the stagnant flow in the ejector and the general impact of the ejector sidewalls on the evolving jet plume, the computation and gridding time were significant and computational solutions of this type would be difficult to implement in an evolving design. Additionally, time-accurate solutions may be required to capture the unsteady separations associated with N+2 HVC model.

The test results for the GEGR model showed the potential for noise reduction from IVP and FS concepts. However, the test results also indicated the need for accurate computational flow solutions early in the design process. The RANS solutions did not capture the nozzle flow separations that resulted in poor acoustic performance at low NPR. Additionally, LES solutions were not available until after the model was designed and tested possibly due to the required computation time.

One major result of the studies presented here is the need for reliable and efficient computational tools for future low-noise exhaust concepts that involve complex geometries. Critical flow separations were not captured in screening RANS calculations and these flow separations resulted in reduced acoustic performance of both exhaust concepts. As flow streams are added to the engine, the complexity of the flow lines increases which increases the possibility of flow separation. In addition to reliable and efficient computations, there is a need to incorporate all relevant flow surfaces in the computational domain.

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TABLE 1.—SETPOINTS FOR HVC EXPERIMENTS

NPR_c	NPR_f	NTR_c $TT_c/Tamb$	NTR_f $TT_f/Tamb$	M_{fj}
1.6000	1.6000	2.9000	1.2900	0.00
1.8000	1.8000	2.9000	1.2900	0.00
1.6000	1.8000	2.6900	1.2900	0.00
1.6000	1.8000	3.0500	1.2000	0.00
1.6000	1.8000	2.9000	1.1000	0.00
1.6000	1.6000	2.9000	1.2900	0.30
1.8000	1.8000	2.9000	1.2900	0.30
1.6000	1.8000	2.6900	1.2900	0.30
1.6000	1.8000	3.0500	1.2000	0.30
1.6000	1.8000	2.9000	1.1000	0.30

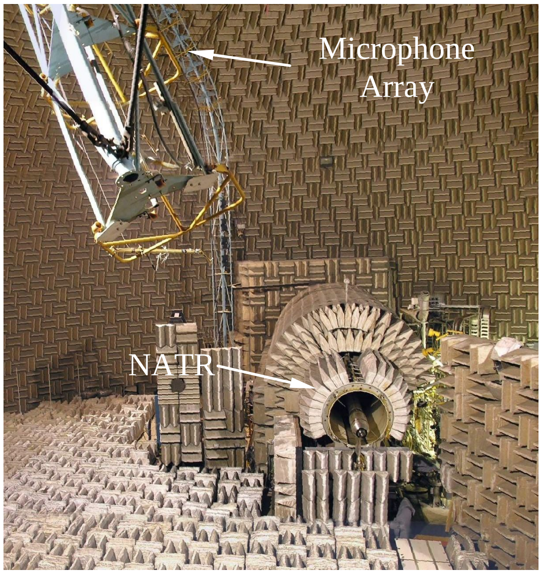


Figure 1.—A photograph of the Aero-Acoustic Propulsion Laboratory (AAPL) showing the Nozzle Acoustic Test Rig (NATR).

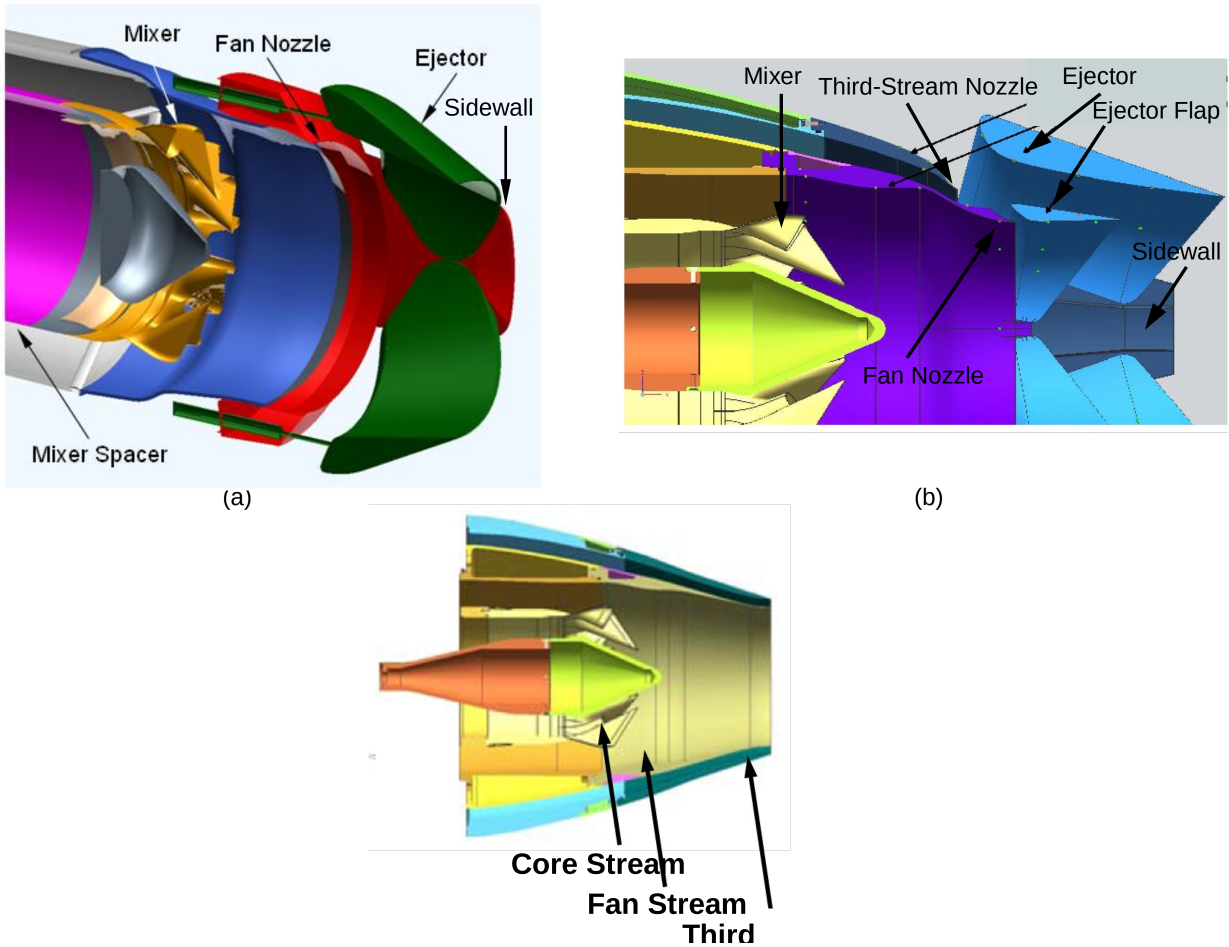


Figure 2.—The models designed by Rolls-Royce Liberty Works for the Supersonics Project in the Fundamental Aeronautics Program. The model in (a) is the Highly Variable Cycle (HVC) system, in (b) the N+2 HVC system, and in (c) the baseline nozzle system for the N+2 HVC system.

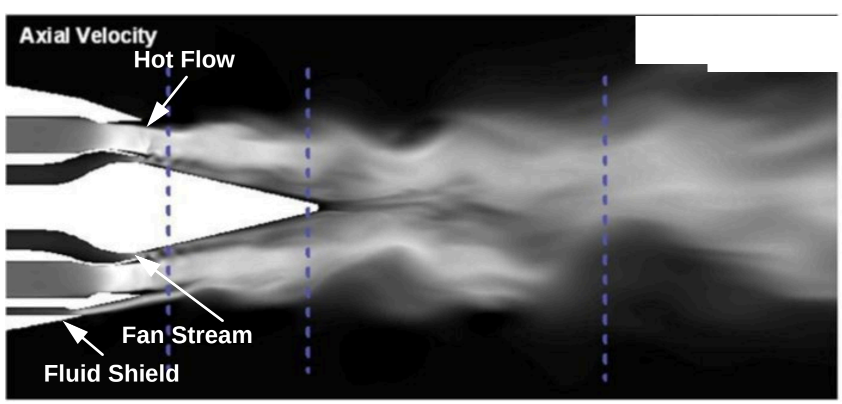
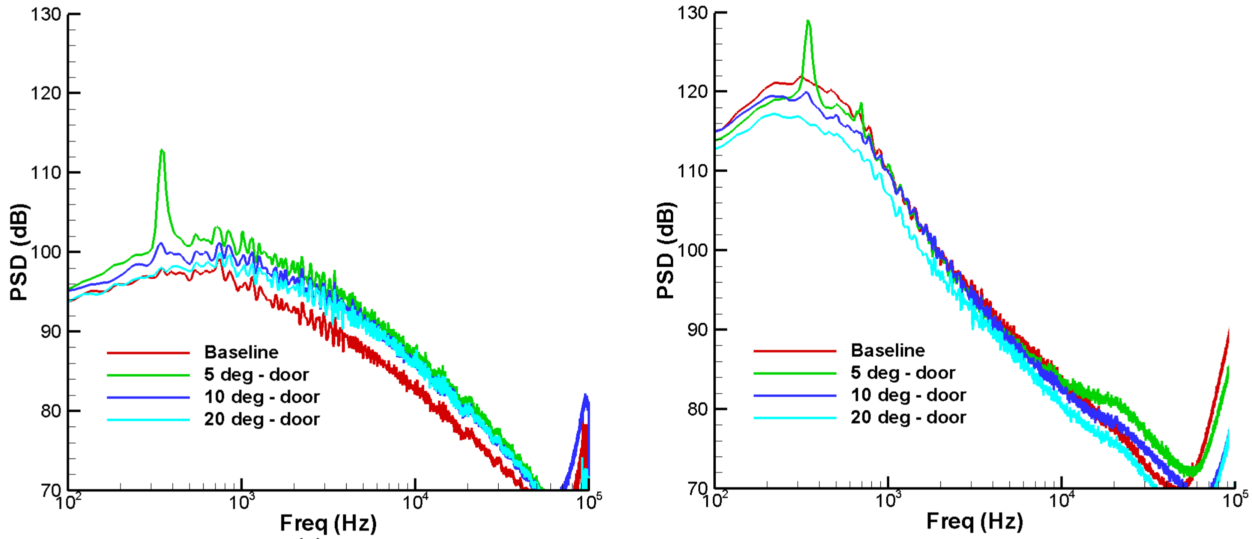
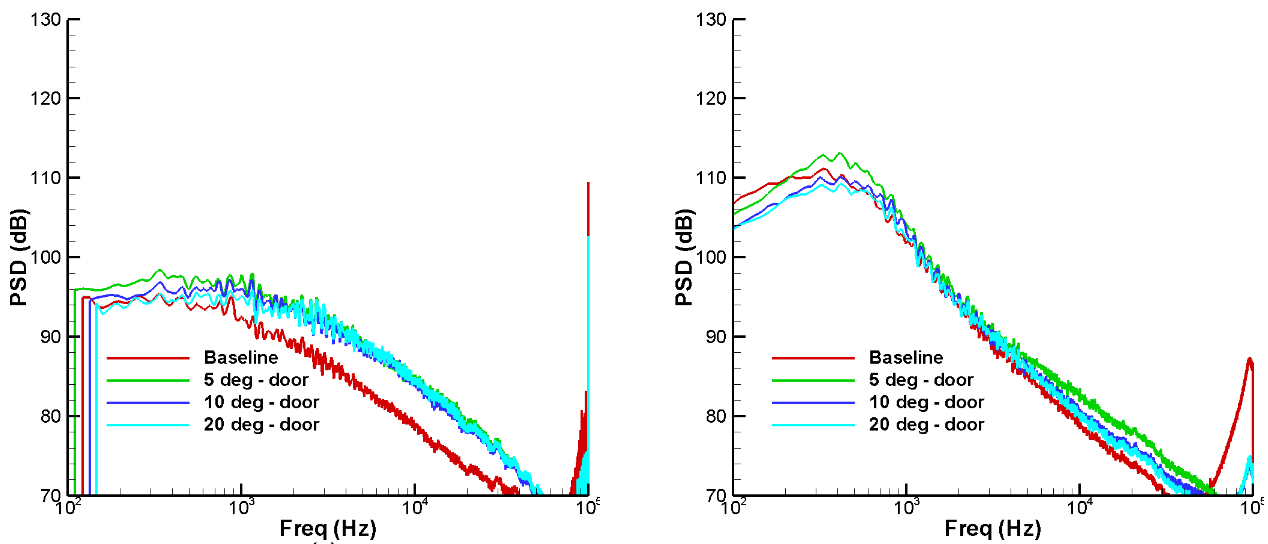


Figure 3.—Cross-section of the GE Inverted Velocity Profile nozzle with instantaneous velocity field as predicted by early Large Eddy Simulations (LES). The LES solutions were provided by GE.



(a) (b)

Figure 4.—The acoustic spectra acquired at NPR_c = 1.60, NPR_f = 1.80, NTR_c = 2.69, and M_{fj} = 0.0. The ejector door angles are indicated in the legend. The observation angles are (a) 60° and (b) 160°.



(a) (b)

Figure 5.—The acoustic spectra for the jet conditions in Figure 4 and a simulated forward flight Mach number of 0.3. The ejector door angles are indicated in the legend. The observation angles are (a) 60° and (b) 160°.

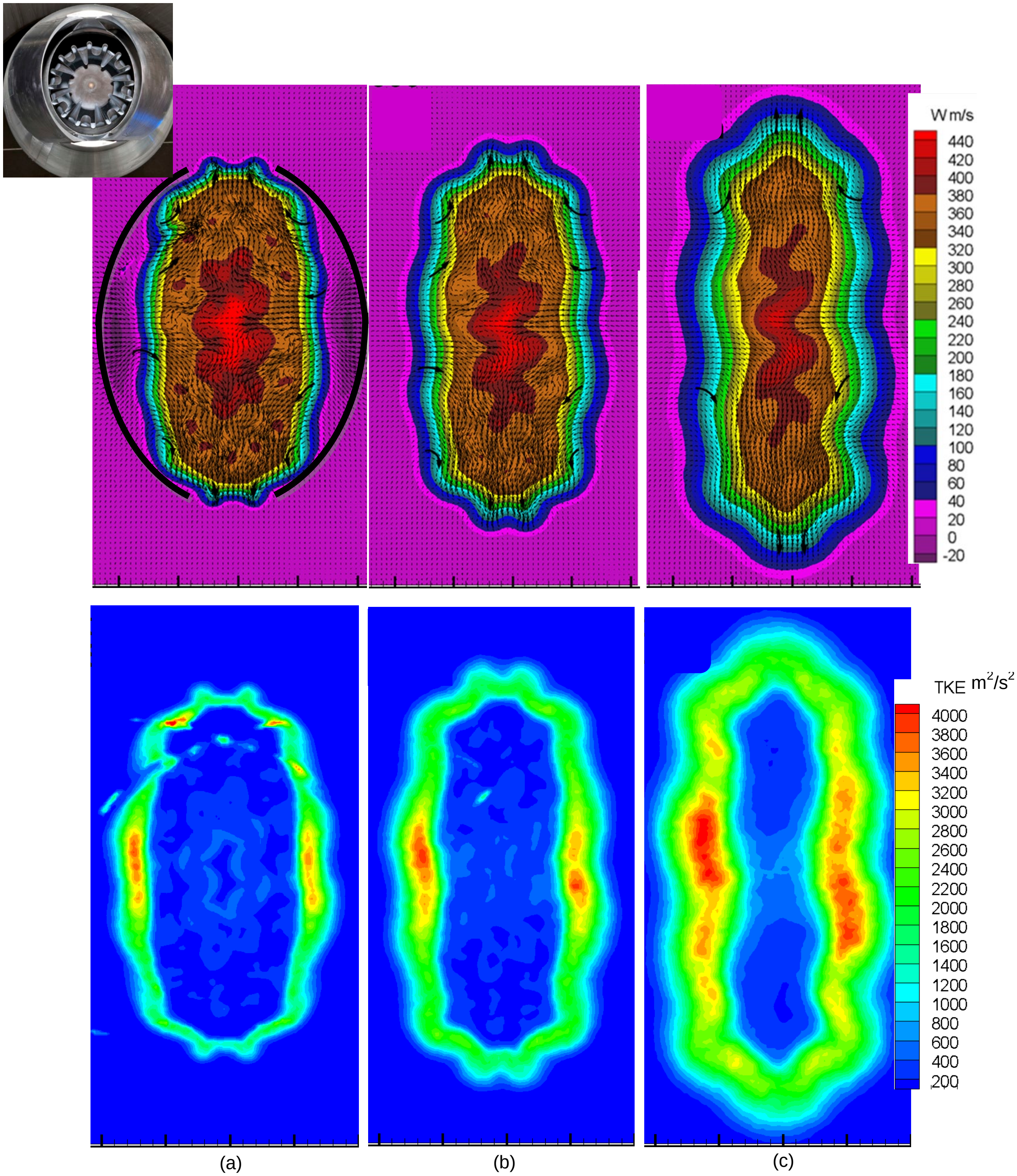


Figure 6.—The results from stereo PIV experiments for cross stream planes located at (a) –0.1D, (b) 0.7D, and (c) 1.8D relative to the trailing edge of the ejector doors. The effective core-nozzle diameter is give by D. The top row contains contour plots of the mean streamwise velocity and cross-stream velocity vectors. The bottom row contains contour plots of the turbulent kinetic energy. The conditions are the same as those indicated in Figure 4.

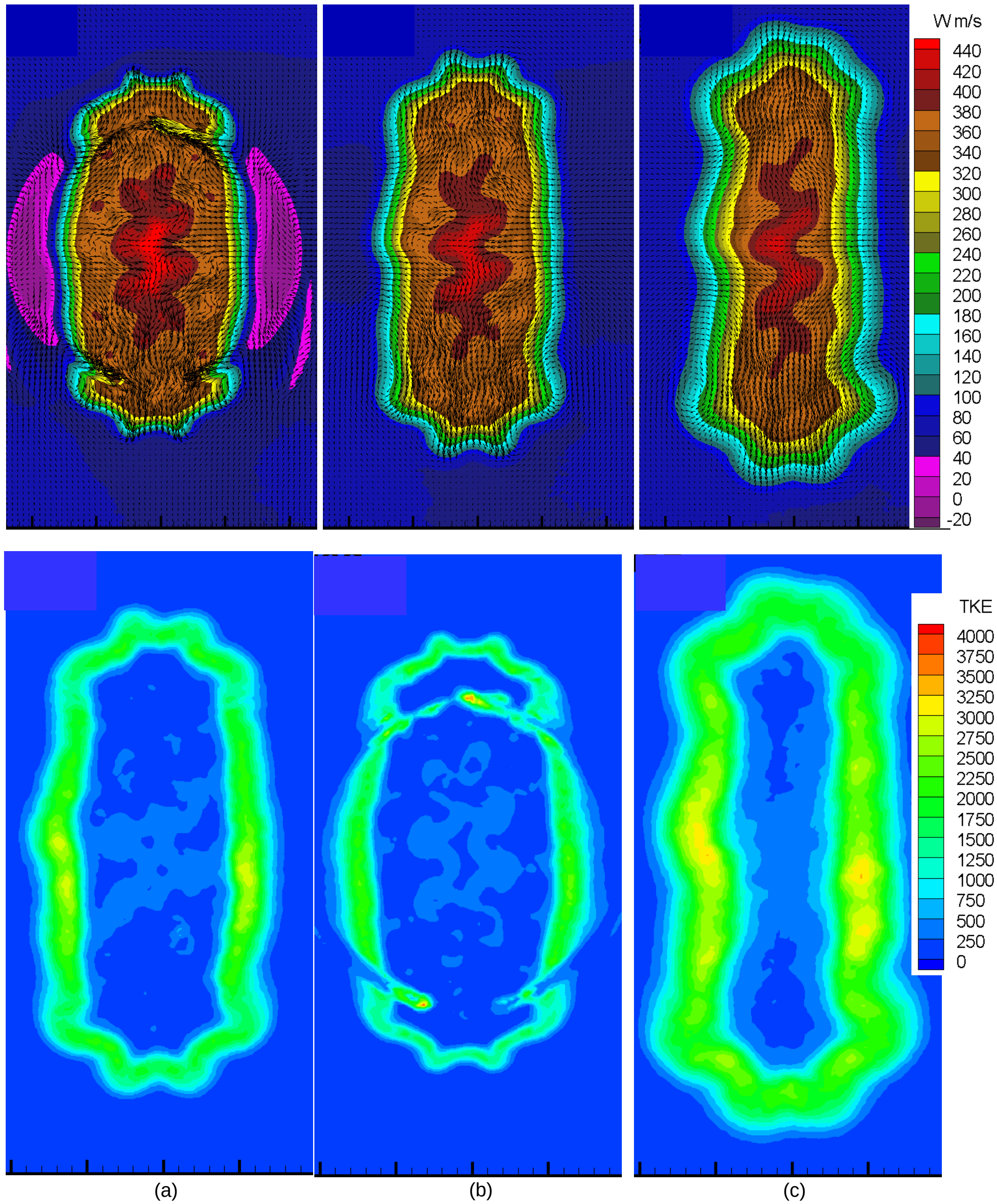
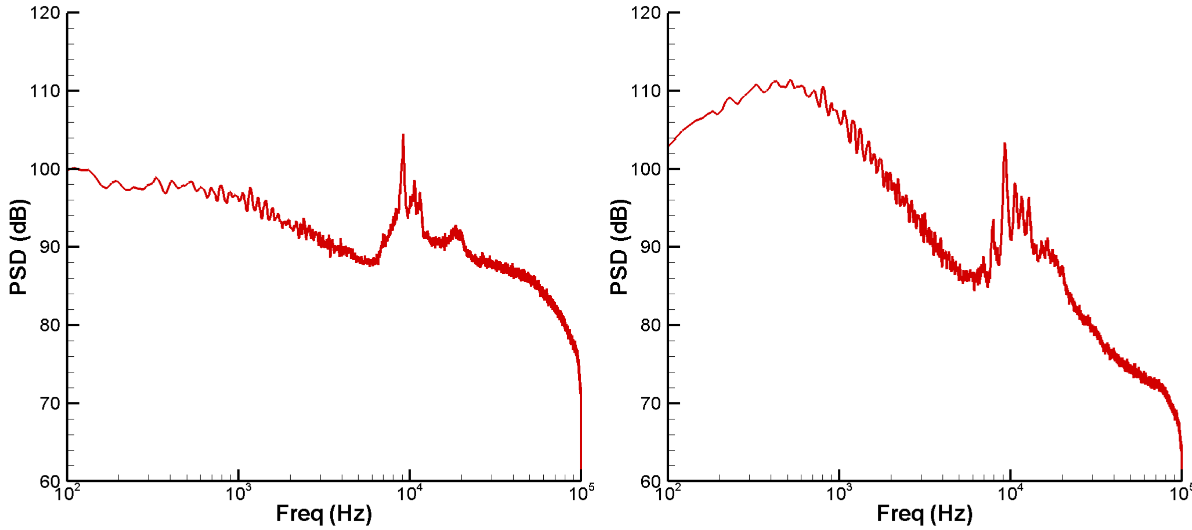
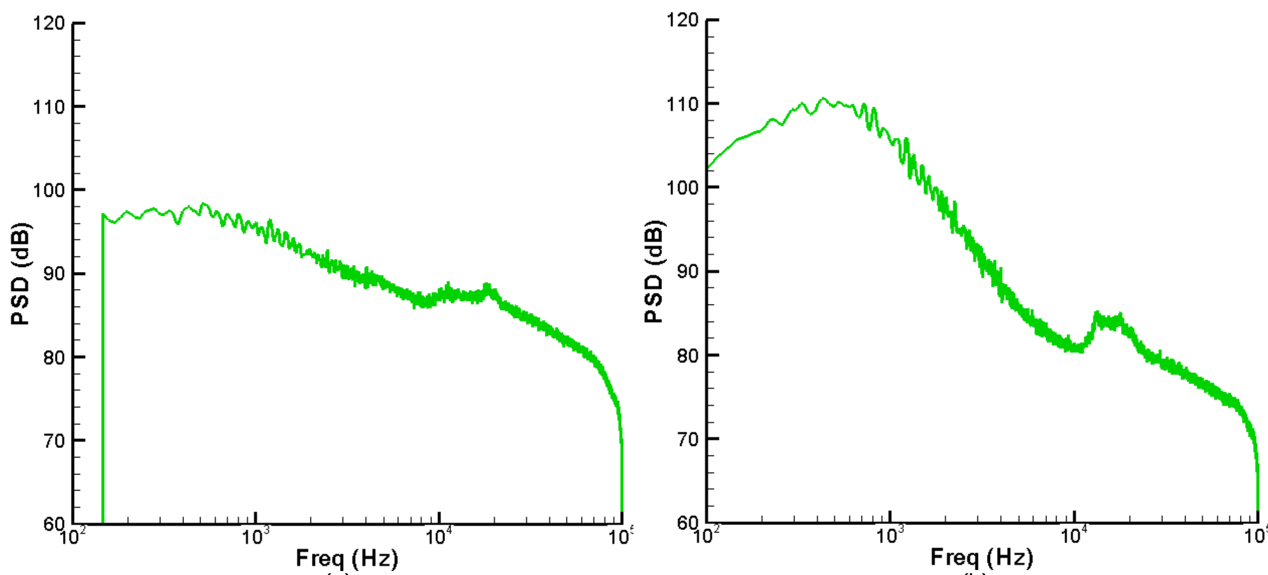


Figure 7.—The results from stereo PIV experiments for cross stream planes located at (a) –0.1D, (b) 0.7D, and (c) 1.8D relative to the trailing edge of the ejector doors. The top row contains contour plots of the mean streamwise velocity and cross-stream velocity vectors. The bottom row contains contour plots of the turbulent kinetic energy. The jet conditions are the same as those indicated in Figure 7 and M_{fj} = 0.2.



(a) (b)

Figure 8.—The acoustic radiation for the N+2 HVC model operated at core and fan stream conditions similar to those in Figure 5 and M_{fj} = 0.3. The ejector flap angle is 10° and the ejector angle is 9.5°. The observation angles are (a) 90° and (b) 150°.



(a) (b)

Figure 9.—The acoustic radiation for the N+2 HVC model with a covered ejector flap operated at the conditions in Figure 9. The ejector flap angle is 10^{o} and the ejector angle is 9.5°. The observation angles are (a) 90° and (b) 150°.

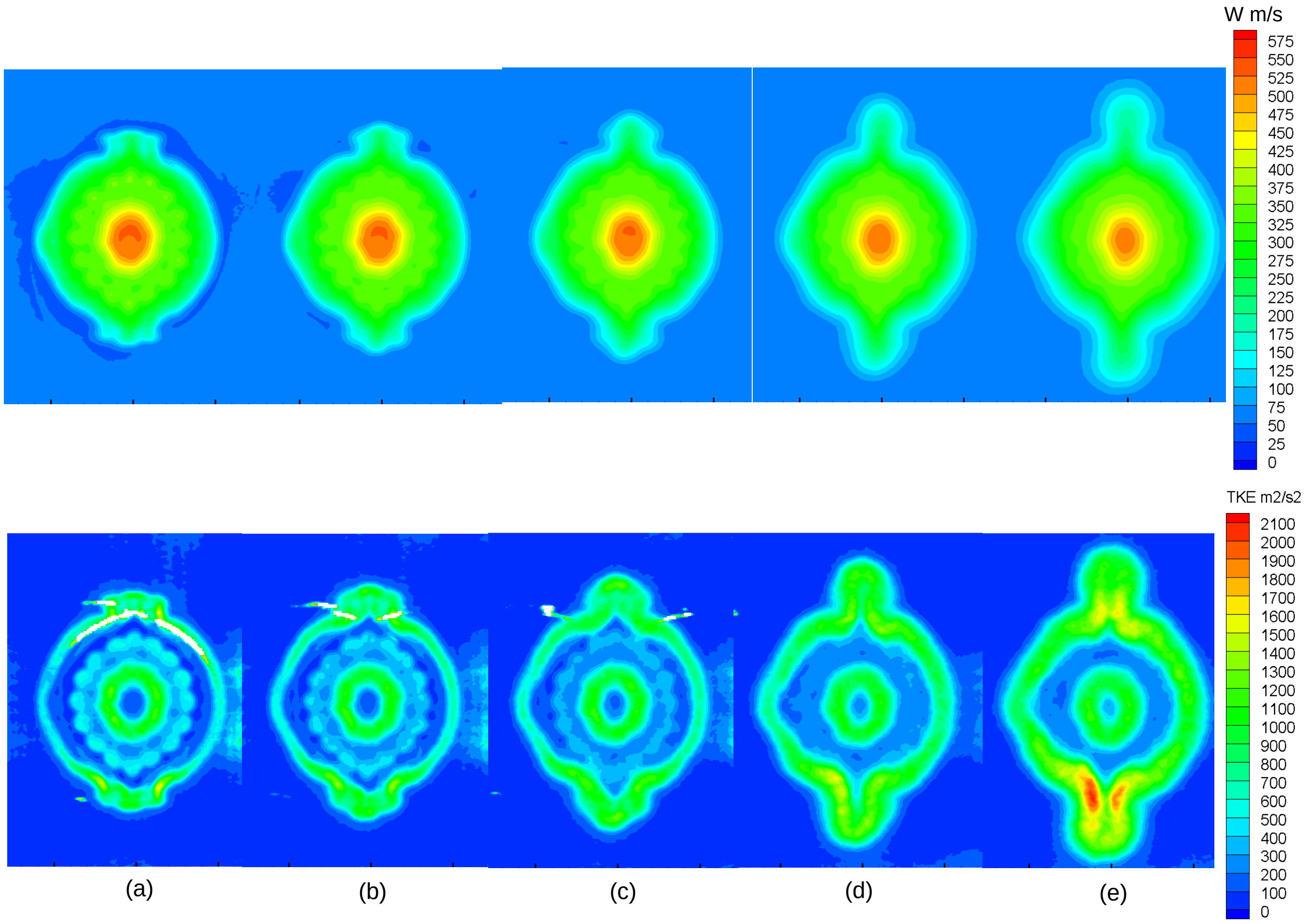


Figure 10.—Streamwise mean velocity contours (top row) and turbulent kinetic energy (bottom row) obtained from stereo PIV experiments at cross-stream planes located at (a) 0.1D, (b) 0.4D, (c) 0.8D, (d) 1.6D, and (e) 2.4D relative to the trailing edge of the ejector doors. The jet conditions are the same as those in Figure 4 and M_{fj} = 0.2.

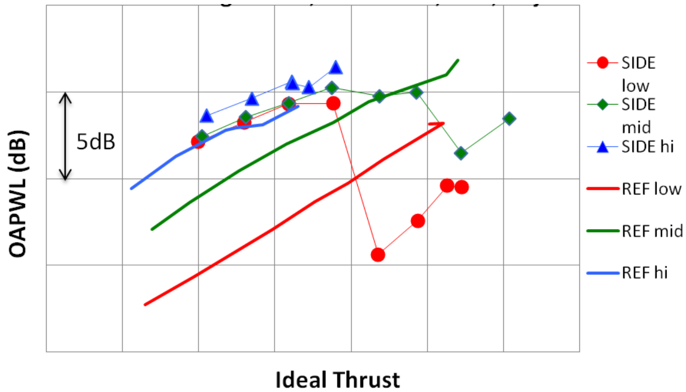


Figure 11.—Acoustic results obtained with the GEGR model showing the overall sound power levels versus ideal thrust for representative low, mid, and high temperature cycles with a simulated forward flight Mach number equal to 0.3. Also shown are acoustic results for reference (REF).

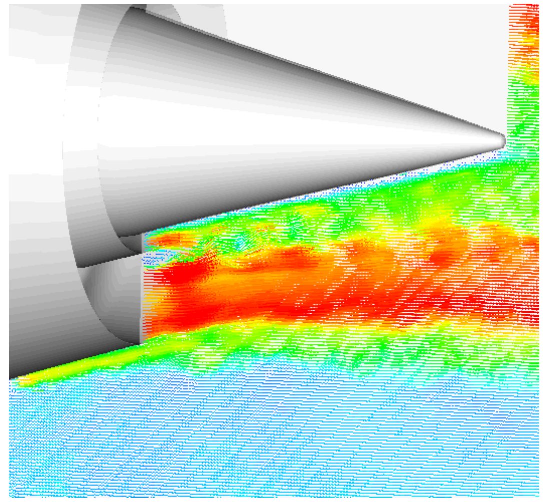


Figure 12.—Instantaneous velocities obtained from the PIV experiments showing separation on the nozzle lip between inner and outer streams.

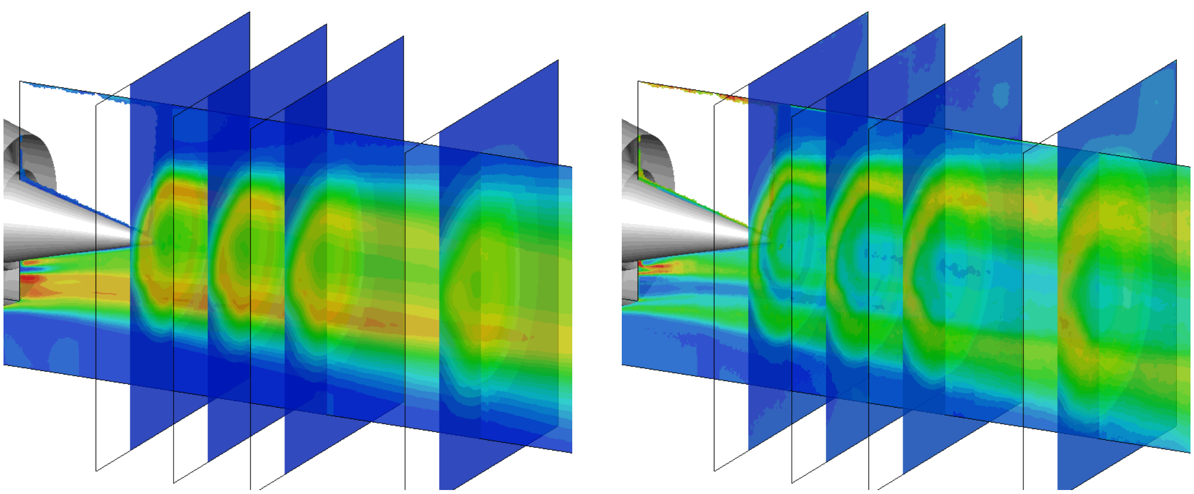


Figure 13.—PIV acquired on the Inverted Velocity Profile nozzle with the fluid shield flow on the bottom half of the nozzle. Mean velocity is shown on the left and the rms velocity on the right. Note the low mean velocity and high rms turbulent velocity at the separated nozzle lip and the asymmetry introduced by the fluid shield.

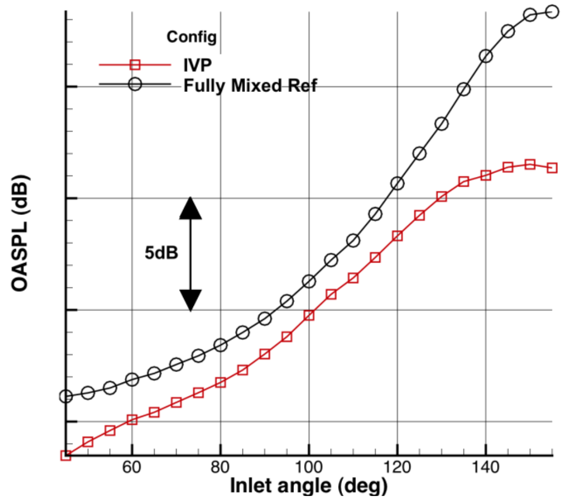


Figure 14.—The overall sound pressure level directivity for the IVP and reference nozzle.

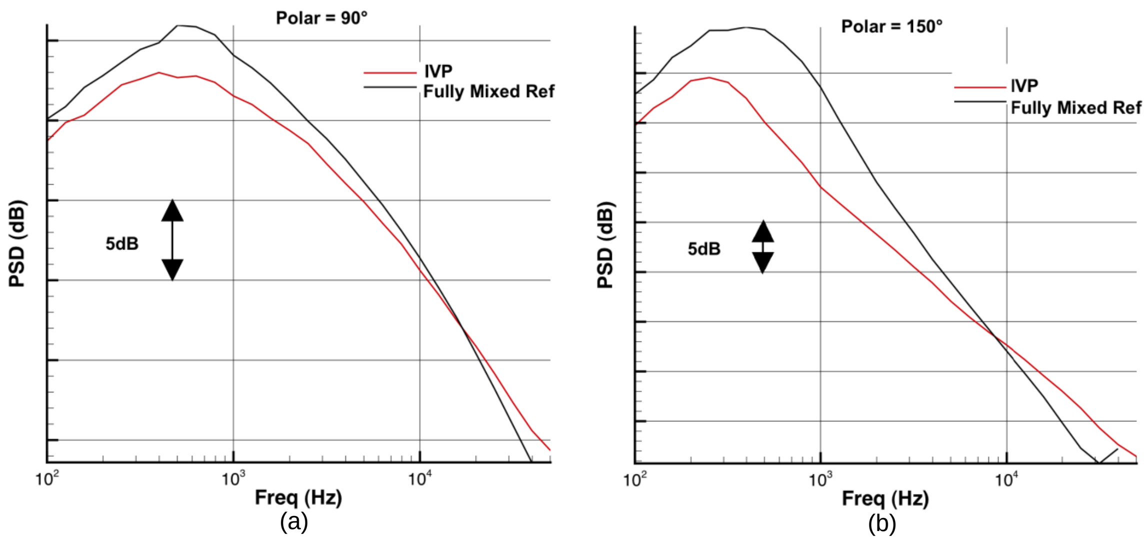


Figure 15.—The acoustic spectra for the IVP and reference nozzle acquired at observation angles equal to (a) 90° and (b) 150°.

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14. ABSTRACT
Acoustic and flow-field experiments were conducted on exhaust concepts for the next generation supersonic, commercial aircraft. The concepts were developed by Lockheed Martin (LM), Rolls-Royce Liberty Works (RRLW), and General Electric Global Research (GEGR) as part of an N+2 (next generation forward) aircraft system study initiated by the Supersonics Project in NASA's Fundamental Aeronautics Program. The experiments were conducted in the Aero-Acoustic Propulsion Laboratory at the NASA Glenn Research Center. The exhaust concepts utilized ejectors, inverted velocity profiles, and fluidic shields. One of the ejector concepts was found to produce stagnant flow within the ejector and the other ejector concept produced discrete-frequency tones that degraded the acoustic performance of the model. The concept incorporating an inverted velocity profile and fluid shield produced overall-sound-pressure-level reductions of 6 dB relative to a single stream nozzle at the peak jet noise angle for some nozzle pressure ratios. Flow separations in the nozzle degraded the acoustic performance of the inverted velocity profile model at low nozzle pressure ratios.

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