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Noise of Dual-Stream Beveled Nozzles at Supercritical Pressure Ratios

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The nozzles of a dual-stream turbofan engine are operated invariably at supercritical pressure ratios at cruise, thereby producing shocks in the jet plume. Consequently, broadband shock-associated noise is generated in addition to turbulent mixing noise. The jet exhaust noise impinges on the fuselage and is then transmitted into the interior of the aircraft cabin. In a companion paper, the beveled nozzle has been shown to provide a community noise benefit during takeoff. (Viswanathan, K., "Elegant Concept for Reduction of Jet Noise from Turbofan Engines," *Journal of Aircraft*, Vol. 43, No. 3, 2006, pp. 616–626.) Here, the aeroacoustic characteristics of two beveled nozzles, with bevel angles of 24 deg (bevel24) and 45 deg (bevel45), operated at supercritical pressure ratios, are presented under static conditions as well as in the presence of a Mach 0.32 flight stream. The intended application is for the control of aft-cabin noise. The velocity of the primary jet plays a strong role in the reduction of noise at the aft polar angles, with a substantial benefit at higher jet velocities. The magnitude of reduction in overall levels for bevel45 at the aft angles ranges from ∼5 to ∼12 dB under static conditions, depending on the Mach number of the secondary stream. In the presence of a flight stream, the jet conditions, as well as the bevel angle, control the flight effects at different azimuthal angles. It is demonstrated that at typical cruise power settings, the current concept with bevel24 yields a reduction of ∼4 dB in overall levels; the reduction occurs over a wide range of lower frequencies without any increase at the higher frequencies. Given this reduction in impingement levels on the rear fuselage, this design could yield a cabin noise benefit in addition to the benefit for community noise at takeoff conditions.

I. Introduction

THE nozzles of a dual-stream turbofan engine are operated invariably at supercritical pressure ratios at cruise, thereby producing shocks in the jet plume. Consequently, broadband shock-associated noise is generated in addition to the turbulent mixing noise component. The jet exhaust noise impinges on the fuselage and is transmitted into the interior of the aircraft cabin. Figure 1 shows an aircraft with the jet plume and notional acoustic waves radiated in the direction of the fuselage; the region of peak cabin noise is also highlighted. To reduce the interior noise, especially in the aft cabin where the noise levels tend to peak, it is desirable to reduce the jet exhaust noise at the source rather than add more acoustic treatment to the fuselage sidewall. Thus, control of cabin noise requires a good understanding of the exterior source field, especially the jet exhaust noise. This paper addresses the jet exhaust noise at cruise conditions, which is a problem of importance to the aircraft manufacturers.

The rich spectral content and the directional characteristics of shock-associated noise make it a fascinating area of research. Numerous experimental studies with measurements of near- and far-field spectra, surveys of shock-containing plumes, and flow visualization utilizing various optical techniques, carried out at several research facilities, clarified the many features of this noise component and formed the basis for our understanding of shock noise. However, most investigations of shock-associated noise have been limited to single-stream nozzles, and there has been only limited information on the characteristics of the broadband shock-associated noise from dual-stream nozzles of realistic geometries. Viswanathan[1] noted that the lack of experimental data has hampered our efforts at gaining a better understanding of the noise generation processes and presented the results of a systematic parametric study on the noise of dual-stream jets both at subcritical and supercritical nozzle pressure ratios.

Some of the salient results of the aforementioned study of a convention dual-stream exhaust system, with round core and fan nozzles, are summarized before the modifications to the spectra due to the beveled nozzle are presented. As shown in Ref. 1, there are tremendous differences in the radiated noise depending on the establishment of shocks in the primary, secondary, or both streams. Figure 2 shows spectral comparisons at three test conditions as follows: The nozzle pressure ratio (NPR) in the secondary stream (NPRs) is held constant at a subcritical value of 1.8, $M_s = 0.96$, and the NPR in the primary stream (NPRp) is increased progressively from 1.8, $M_p = 0.96$, to 2.4, $M_p = 1.2$, to 3.0, $M_p = 1.36$. M_p and M_s denote the Mach numbers of the primary and secondary streams, and M_d is the corresponding design Mach number. When the primary stream is supersonic, with the secondary stream at a subsonic or low supersonic Mach number, the shock-associated noise from the primary jet controls the radiated noise to all angles. This trend is clearly evident, especially at the polar angle of 90 deg in Fig. 2. All polar angles are measured from the jet inlet axis. The characteristics of the shock-associated noise are similar to those from a single jet, and the importance of the secondary shear layer is presumably diminished greatly.

When the secondary stream is supersonic and the primary stream is either subsonic or at a low supersonic Mach number, the radiated sound pattern is significantly different. Figure 3 shows spectral comparisons at three test conditions as follows: the NPRp is held constant at a subcritical value of 1.8, $M_p = 0.96$, and the NPRs is increased progressively from 1.8, $M_s = 0.96$, to 2.4, $M_s = 1.2$, to 3.0, $M_s = 1.36$. First, the shock-associated noise from the secondary stream becomes apparent in the forward angles and at 90 deg. However, of greater significance is the radiation of shock-associated noise to large aft angles, which becomes more pronounced with increasing Mach number in the secondary stream. The typical NPR at cruise conditions for commercial high-bypass-ratio (BPR) turbofan engines are in the ranges from ∼2.1 to ∼2.5 for NPRp and from ∼2.4 to ∼2.8 for NPRs, with NPRs being greater than NPRp at all cycle conditions. At these supercritical pressure ratios, increased levels

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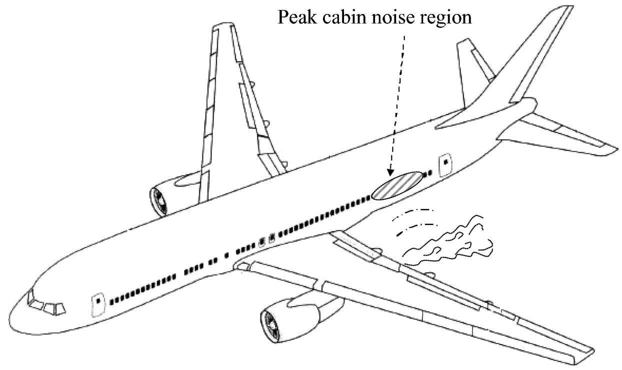

Fig. 1 Airplane with region of peak cabin noise highlighted.

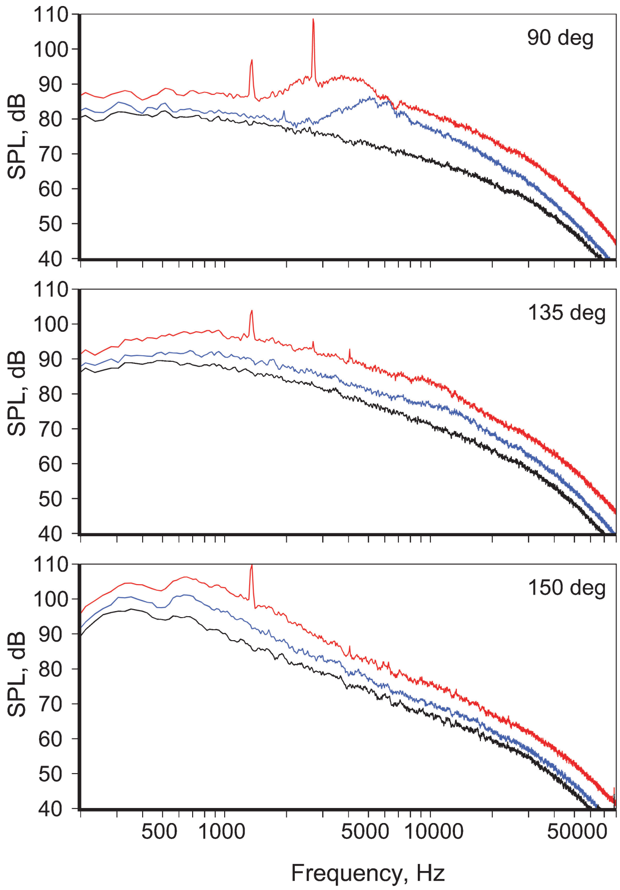

Fig. 2 Spectral variation due to change in primary stream with fixed secondary jet conditions: NPRs = 1.8, $T_s/T_a = 1.0$; black, NPRp = 1.8, $T_p/T_a = 2.37$; blue, NPRp = 2.4, $T_p/T_a = 2.7$; red, NPRp = 3.0, $T_p/T_a =$ 3.04.

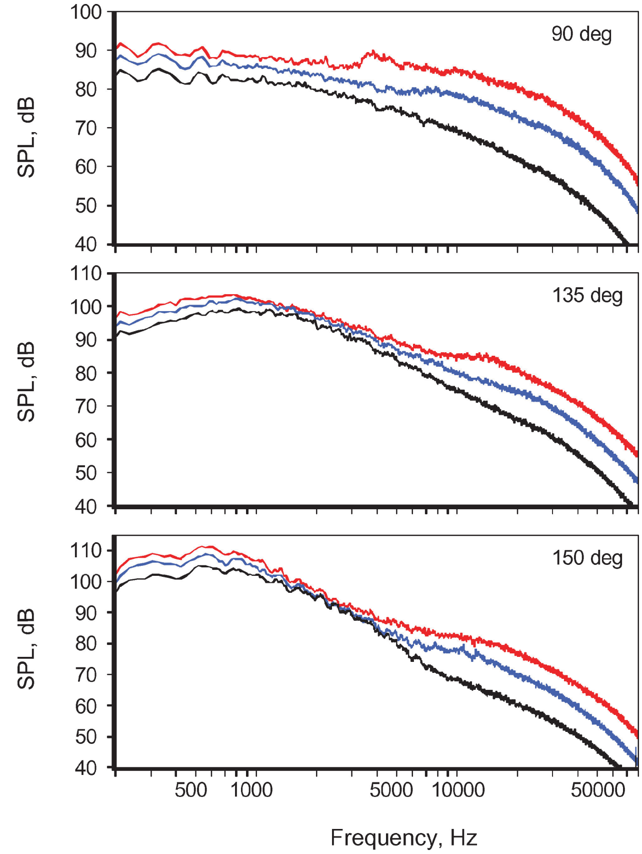

Fig. 3 Spectral variation due to change in secondary stream with fixed primary jet conditions: NPRp = 1.8, $T_p/T_a = 2.37$, and $T_s/T_a = 1.0$; black, NPRs = 1.8; blue, NPRs = 2.4; and red, NPRs = 3.0.

of aft-cabin noise have been observed in flight tests. Conclusive evidence was presented in Ref. 1 that indicates that strong radiation to aft angles occurs only when the secondary stream is supersonic, regardless of the Mach number of the primary stream. In this regard, the characteristics of the shock-associated noise from the secondary stream are very different from those of a single jet or a dual-stream jet with the shocks in the primary jet. The overall sound pressure level (OASPL) of the shock-associated noise at the lower polar angles, that is, at angles less than 90 deg relative to the inlet axis, is, in general, proportional to the strength of the shocks and scales with $(M_p^2 - M_d^2)^2$ when $M_p > 1$ or $(M_s^2 - M_d^2)^2$ when $M_s > 1$. At higher polar angles, there is a progressive increase in OASPL whether the primary or secondary Mach number is increased. See Ref. 1 for more details.

Viswanathan[2] proposed the beveled nozzle as a viable concept for jet noise reduction for single jets and demonstrated large reductions in overall levels of ~5 dB in the sector of peak polar noise radiation below the longer lip of the beveled nozzle. In a companion paper, Viswanathan[3] adapted the beveled nozzle for high-BPR turbofan engines with dual-stream nozzle systems. Only the primary nozzle is beveled, and the fan nozzle (or the nacelle) is unmodified. Experimental measurements indicated that a reduction in the effective perceived noise level (EPNL) of ~4 EPNdB is achieved at typical takeoff (sideline plus cutback) conditions. The results in Ref. 3 pertain to community noise, and are confined to subcritical NPR. In this paper, experimental results from the modified dual-stream nozzle system are presented at supercritical NPR. The intended application, as noted earlier, is for the control of aft-cabin noise. As such, attention is focused primarily on spectra radiated to aft angles.

II. Concept Description and Test Details

A brief overview of the experimental program is provided here. Detailed descriptions of the nozzle geometry, test matrix, anechoic facility, instrumentation system, etc. are provided in Refs. 1–3. For the sake of completeness, a photograph of the nozzle and a sketch of the coordinate system with the definitions of the polar angle, bevel angle, and azimuthal angle are reproduced in Figs. 4a and 4b. Two beveled primary nozzles with bevel angles of 45 deg (bevel45) and 24 deg (bevel24) have been tested. Acoustics results and comparisons with a conventional nozzle system with round nozzles for the primary and fan streams are provided in the following section. It is important to pay attention to the noise radiated near an azimuthal angle of 90 deg (as per the measurement convention adopted here) and at aft polar angles because this radiation sector is pertinent for aft-cabin noise. The thrust performance of the beveled nozzles at both subcritical and supercritical pressure ratios is presented in Ref. 3, and, hence, is not included in this paper.

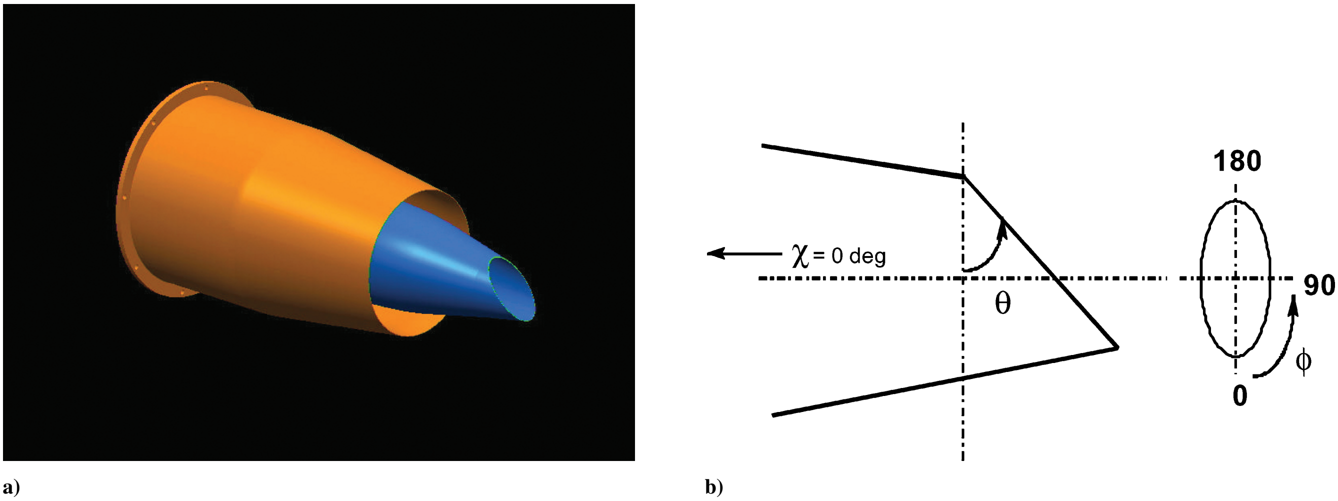

Fig. 4 Concept for noise reduction from dual-stream nozzles with primary nozzle beveled a) design drawing and b) convention for measurements of polar angle χ, bevel angle θ, and azimuthal angle ϕ.

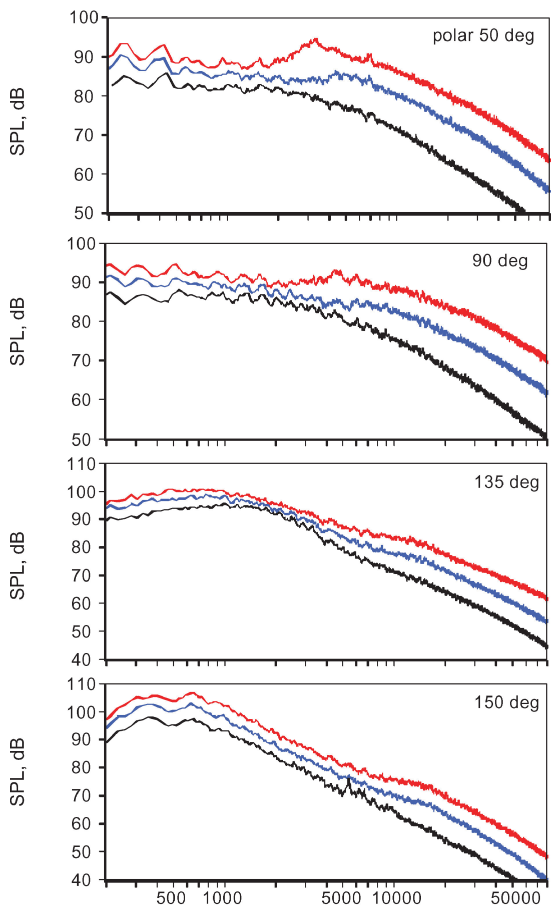

Fig. 5 Spectral variation due to change in secondary stream with fixed primary jet conditions: azimuthal angle = 0 deg and bevel45; NPRp = 1.96, $T_p/T_a = 2.46$, and $T_s/T_a = 1.0$; black, NPRs = 1.8; blue, NPRs = 2.4; and red, NPRs = 3.0.

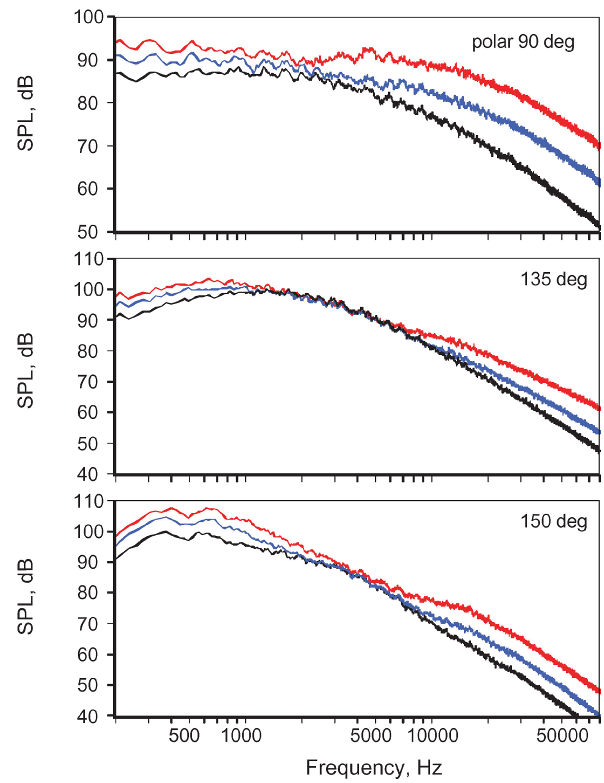

Fig. 6 Spectral variation due to change in secondary stream with fixed primary jet conditions: azimuthal angle = 90 deg and bevel45; NPRp = 1.96, $T_p/T_a = 2.46$, $T_s/T_a = 1.0$; black, NPRs = 1.8; blue, NPRs = 2.4; and red, NPRs = 3.0.

III. Results and Discussion

A. Noise Characteristics at Static Conditions

First, we examine the azimuthal variations in sound pressure level (SPL) due to changes in the cycle conditions for the beveled nozzle with bevel45. The cycle conditions are varied as follows: for a fixed primary with NPRp = 1.96 and $T_p/T_a = 2.46$, NPRs is increased from 1.8 to 2.4 to 3.0. Figure 5 shows the spectra at an azimuthal angle of 0 deg (below the nozzle) and Fig. 6 at an azimuthal angle of 90 deg. A careful examination of Fig. 5 and the entire database reveals that the spectral characteristics in the forward quadrant (lower polar angles) are similar to those observed at a polar angle of 90 deg; hence, typical trends at 90 deg are shown later, and we focus our attention on aft polar angles. In both Figs. 5 and 6, the contribution of the shock-associated noise from the secondary stream is evident at a polar angle of 90 deg. However, there are subtle differences at the aft angles when NPRs is increased. Whereas there is an increase in levels at almost all frequencies at the azimuthal angle of 0 deg, there is no increase at the midfrequencies (3–8 kHz) at an azimuthal angle of 90 deg. The aft-radiating shock component at the higher frequencies (above 8 kHz) is clearly visible at both azimuthal angles. When the velocity of the primary stream is reduced by operating the primary stream unheated at the same NPRp (Figs. 7 and 8), two trends become more pronounced: The aft-radiating shock noise

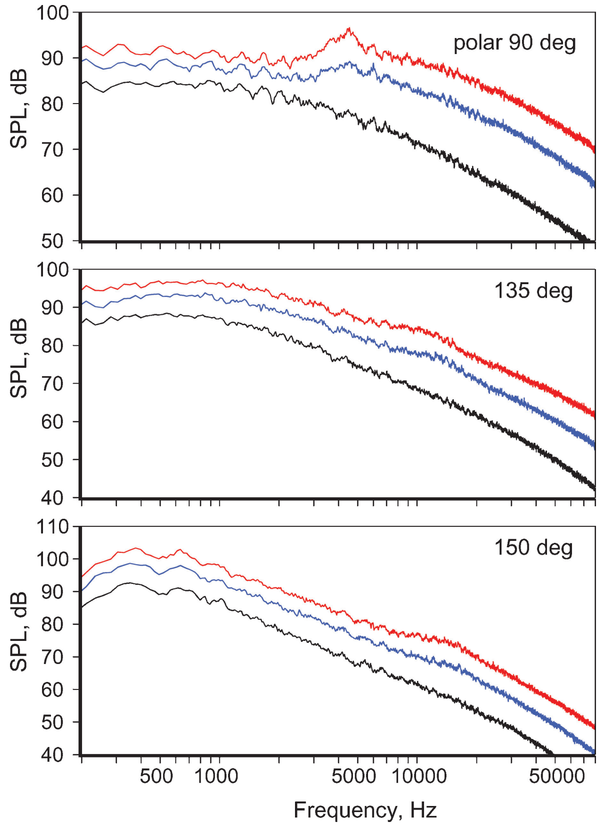

Fig. 7 Spectral variation due to change in secondary stream with fixed primary jet conditions: azimuthal angle = 90 deg and bevel45; NPRp = 1.96, $T_p/T_a = 1.0$, and $T_s/T_a = 1.0$; black, NPRs = 1.8; blue, NPRs = 2.4; and red, NPRs = 3.0.

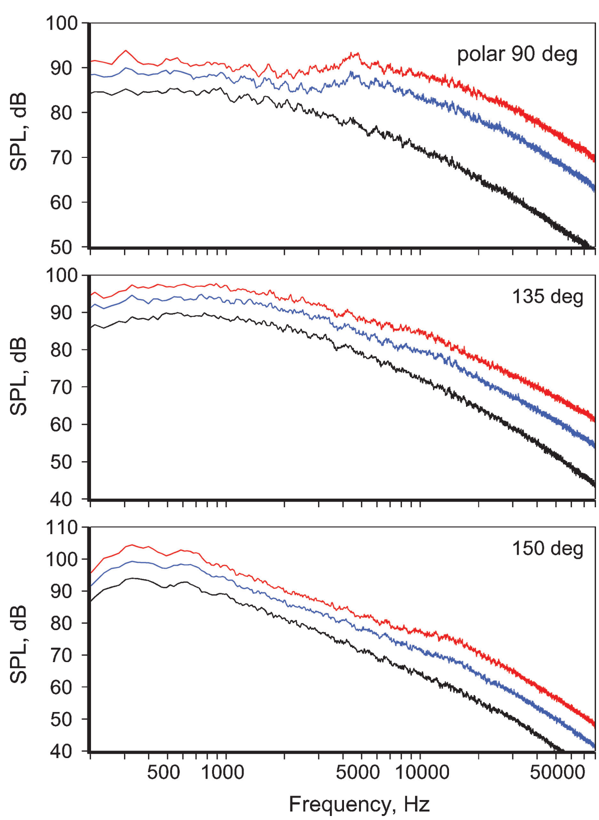

Fig. 8 Spectral variation due to change in secondary stream with fixed primary jet conditions: azimuthal angle = 90 deg and bevel45; NPRp = 1.96, $T_p/T_a = 1.0$, and $T_s/T_a = 1.0$; black, NPRs = 1.8; blue, NPRs = 2.4; and red, NPRs = 3.0.

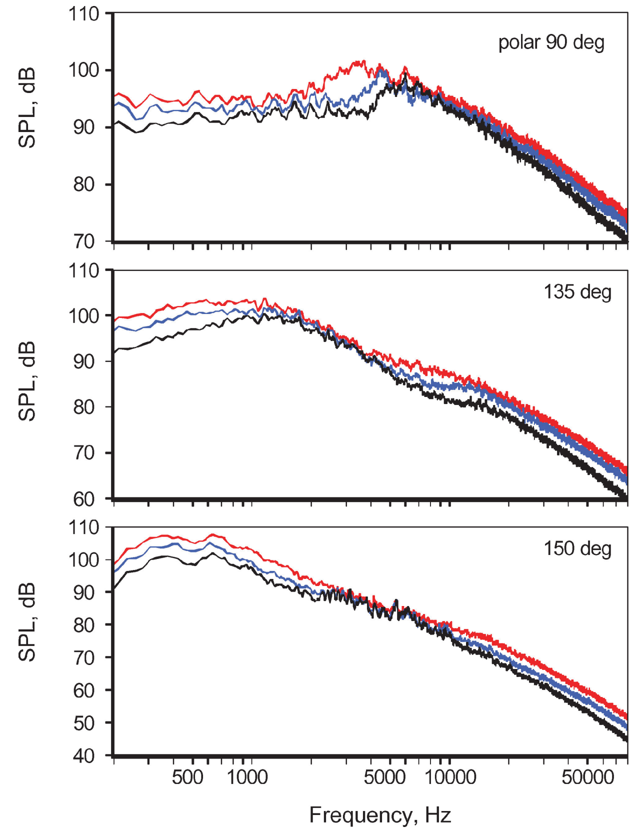

Fig. 9 Spectral variation due to change in secondary stream with fixed primary jet conditions: azimuthal angle = 0 deg and bevel45; NPRp = 3.0, $T_p/T_a = 3.04$, and $T_s/T_a = 1.0$; black, NPRs = 1.8; blue, NPRs = 2.4; and red, NPRs = 3.0.

(above ~10 kHz) is more readily apparent due to the reduced mixing noise, and there is a monotonic increase in levels at all frequencies at both azimuthal angles.

When shocks are established in the primary stream, with NPRp = 3.0 and $T_p/T_a = 3.04$, and NPRs is varied as before, with values of 1.8, 2.4, and 3.0, there are major differences in the spectral changes with NPRs at the two azimuthal angles as shown in Figs. 9 and 10. At the aft angles, there is an increase in spectral levels at the higher frequencies (> ~9 kHz) as NPRs is progressively increased at an azimuthal angle of 0 deg. However, at an azimuthal angle of 90 deg, there is either no change or a reduction in level when NPRs is increased. Furthermore, the spectral shapes at a polar angle of 135 deg are different, with the characteristic double hump not observed at an azimuthal angle of 90 deg. The spectral shape and characteristics at different azimuthal angles are, thus, affected differently by changes to the cycle conditions for the beveled primary nozzle. In addition, the noise levels at an azimuthal angle of 0 deg are significantly lower when compared with the levels at an azimuthal angle of 90 deg at all cycle conditions. This trend is similar to that observed at subsonic jet Mach numbers in Ref. 3 and can be used advantageously for cabin noise reduction by orienting the beveled nozzle suitably to shield the aft cabin. A rotatable beveled nozzle would, of course, provide the greatest flexibility in reducing community noise at takeoff and aft-cabin noise at cruise. Similar azimuthal trends are observed for bevel24 as well.

We now investigate the noise reduction potential of the beveled nozzles relative to the conventional nozzle. The importance of the primary velocity is established with Figs. 11–13. Figure 11 shows spectral comparisons at an azimuthal angle of 0 deg for the conventional dual-stream nozzle and the modified primary nozzles with bevel24 and bevel45. The operating conditions are NPRp = 1.96, $T_p/T_a = 2.46$, and NPRs = 3.0, with shocks in the secondary stream. At lower radiation angles, there is only a slight variation in the spectral levels, with bevel45 producing elevated levels. At the aft angles,

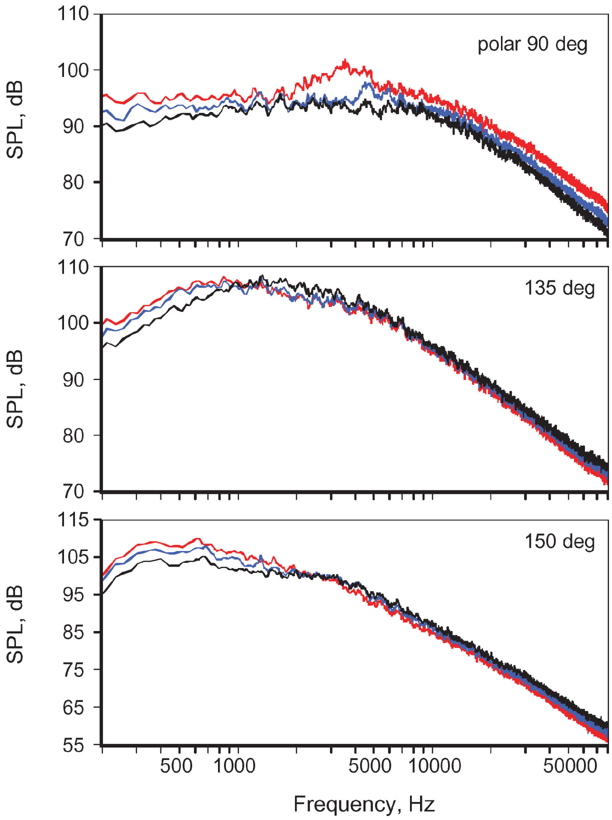

Fig. 10 Spectral variation due to change in secondary stream with fixed primary jet conditions: azimuthal angle = 90 deg and bevel45; NPRp = 3.0, $T_p/T_a = 3.04$, and $T_s/T_a = 1.0$; black, NPRs = 1.8; blue, NPRs = 2.4; and red, NPRs = 3.0.

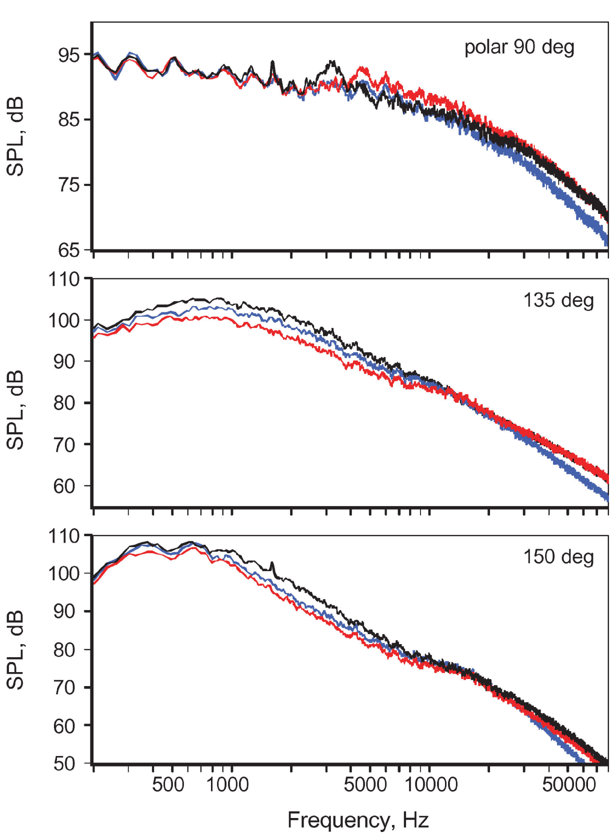

Fig. 11 Performance of beveled nozzles relative to round nozzle: NPRp = 1.96 ($M_p = 1.04$), $T_p/T_a = 2.46$, NPRs = 3.0 ($M_s = 1.36$), and azimuthal angle = 0 deg; black, round; blue, bevel24; and red, bevel45.

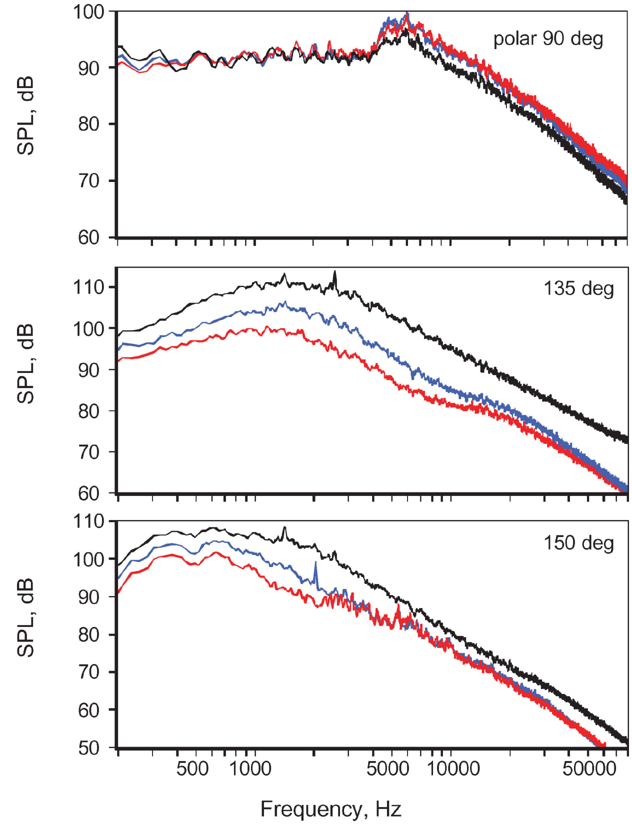

Fig. 12 Performance of beveled nozzles relative to round nozzle: NPRp = 3.0 ($M_p = 1.37$), $T_p/T_a = 3.04$, NPRs = 1.8 ($M_s = 0.96$), and azimuthal angle = 0 deg; black, round; blue, bevel24; and red, bevel45.

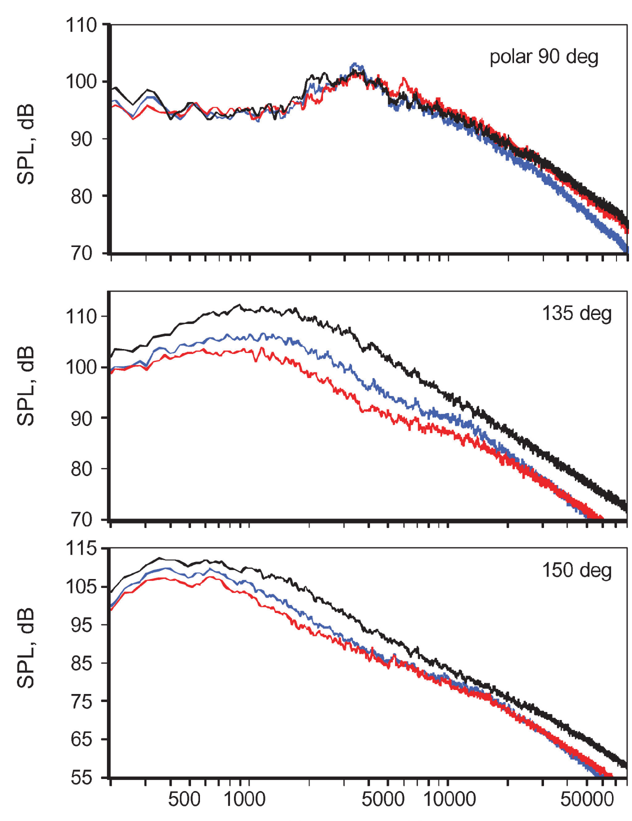

Fig. 13 Performance of beveled nozzles relative to round nozzle: NPRp = 3.0 ($M_p = 1.37$), $T_p/T_a = 3.04$, NPRs = 3.0 ($M_s = 1.36$), and azimuthal angle = 0 deg; black, round; blue, bevel24; and red, bevel45.

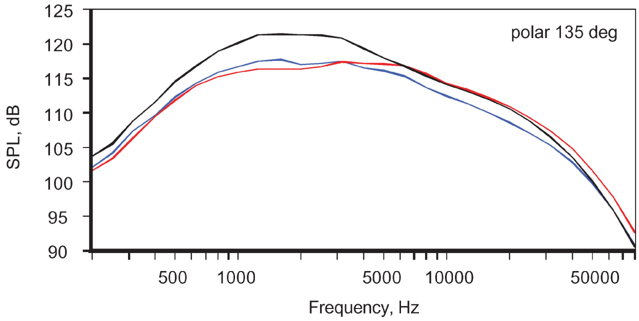

Fig. 14 Performance of beveled nozzles relative to round nozzle: NPRp = 3.0 (M_p = 1.37), T_p/T_a = 3.04, NPRs = 3.0 (M_s = 1.36), and azimuthal angle = 90 deg; black, round; blue, bevel24; and red, bevel45.

the beveled nozzles do yield lower noise levels, ~4 dB over a wide range of lower frequencies (up to 5 kHz).

Next, the velocity of the primary stream is increased and shocks established with NPRp = 3.0 and $T_p/T_a = 3.04$. The secondary stream is subsonic for the results shown in Fig. 12 with NPRs = 1.8. In the forward quadrant, the shock-associated noise to the right of the shock peak is higher for the beveled nozzles. However, as we go aft, the noise levels are lower. In the polar angular range of 125–150 deg, the reduction in OASPL at certain polar angles is as much as 10–12 dB for bevel45 and 5–7 dB for bevel24. These magnitudes of reduction below the longer lip of the beveled nozzle are not unexpected because similar trends have been observed for supersonic single beveled jets in Ref. 2 and because the noise from the primary jet controls the noise radiated to all angles in a dual-stream jet for this operating condition. (See Ref. 1.) When NPRs is increased to 3.0 and shocks are established in both streams while holding the primary conditions constant, similar trends prevail at the aft angles as shown in Fig. 13. However, there is no increase in noise at the lower angles for the beveled nozzles. The magnitudes of noise reduction at the aft angles are also reduced because the turbulent mixing noise generated by the secondary stream contributes more to the total noise when the velocity of the secondary stream is increased. A comparable plot in Fig. 14, at an azimuthal angle of 90 deg and at one polar angle of 135 deg, shows that the noise reduction is not as great as at an azimuthal angle of 0 deg. Again, the azimuthal variations are quite pronounced with much lower levels of noise being radiated below the longer lip of the beveled nozzle.

We examine the variation of the OASPL at two extreme polar angles of 50 and 150 deg with a fixed supersonic Mach number in one of the streams and the Mach number of the other stream varied systematically. In Figs. 15 and 16, the Mach number of the secondary stream M_s is 1.36 and the primary Mach number M_p is varied; comparisons of the OASPL at two azimuthal angles of 0 and 90 deg from bevel45 with the conventional nozzle are shown at 50- and 150-deg polar angles, respectively. Figure 15 indicates that the overall levels from the beveled nozzles are comparable to those of the round nozzle; there are minima when the primary Mach number is around unity, as denoted by the curve fit through the measurements at an azimuthal angle of 0 deg. The maximum difference in OASPL is ~1 dB near the minima with the levels for the round nozzle being lower, but negligible at other values of M_p. At the aft polar angle of 150 deg in Fig. 16, it is obvious that the magnitude of noise reduction is negligible at low values of M_p but increases progressively with increasing M_p. As seen in Figs. 11 and 13, the maximum noise reduction is ~5 dB at the highest Mach number, below the longer lip of the beveled nozzle. Recall that the greatest noise benefit is obtained in the polar angular range from ~130 to ~140 deg and not at higher aft angles.

In Figs. 17 and 18, the primary Mach number remains fixed at 1.36, and the secondary Mach number is varied. At a polar angle of 50 deg (Fig. 17), again there is only a minor difference in the overall levels; the levels for the beveled nozzle are higher at subsonic M_s and lower at supersonic M_s. In Fig. 18, at the aft angle of 150 deg, a reduction of ~9 dB in OASPL is observed below the longer lip of the bevel45 nozzle at the lowest M_s. As noted earlier, it is not clear whether the reduction is in the turbulent mixing noise or shock-associated noise component. This reduction becomes progressively smaller as M_s is increased, due to the increasing contribution from the secondary jet to the total noise. However, even at the highest secondary Mach number, $M_s = 1.36$, there is a ~5 dB noise benefit.

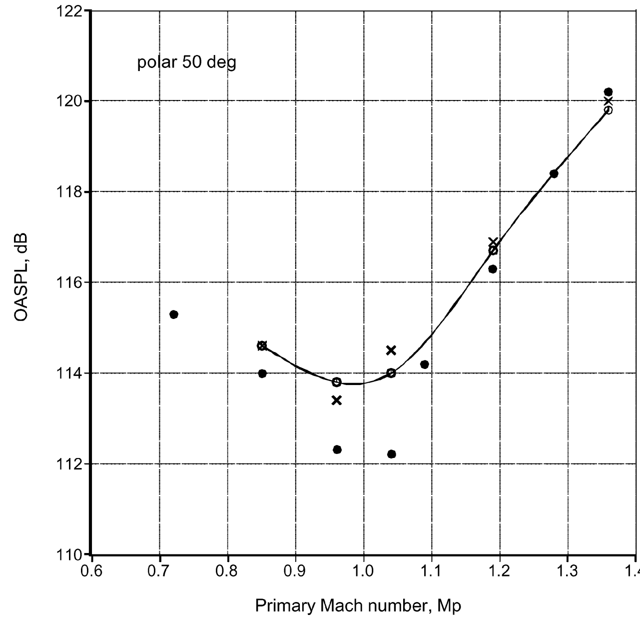

Fig. 15 Variation of OASPL with primary Mach number: M_s = 1.36 and polar angle = 50 deg; •, round; ○, bevel45 and azimuthal angle = 0 deg; ——, curve fit of data denoted by ○; and ×, bevel45 and azimuthal angle = 90 deg.

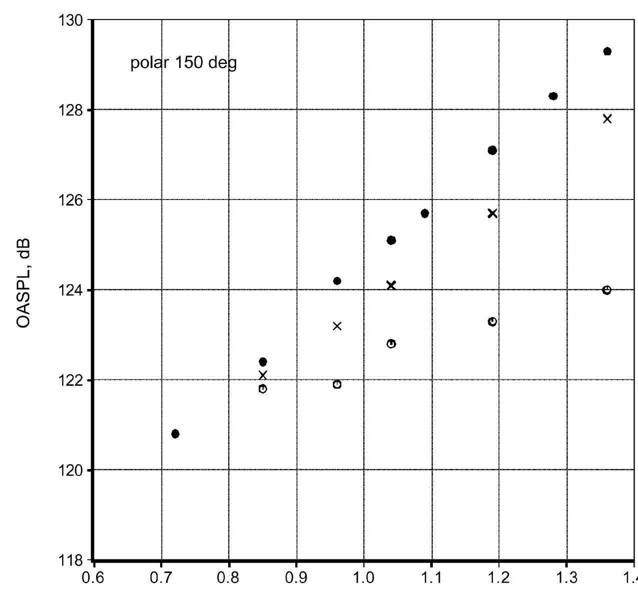

Fig. 16 Variation of OASPL with primary Mach number: M_s = 1.36 and polar angle = 150 deg; •, round; ○, bevel45 and azimuthal angle = 0 deg; and ×, bevel45 and azimuthal angle = 90 deg.

Similar comparisons for bevel24 at a polar angle of 150 deg are shown in Figs. 19 and 20. Given the minor changes at the lower polar angle of 50 deg even for bevel45, data are presented only for the aft polar angle. With a fixed supersonic secondary Mach number of 1.36, the trends seen in Fig. 19 are similar to those for bevel45 in Fig. 16. However, the magnitudes of noise reductions are lower. When the primary Mach number is fixed at 1.36 and the secondary Mach number increased, we again see trends as for

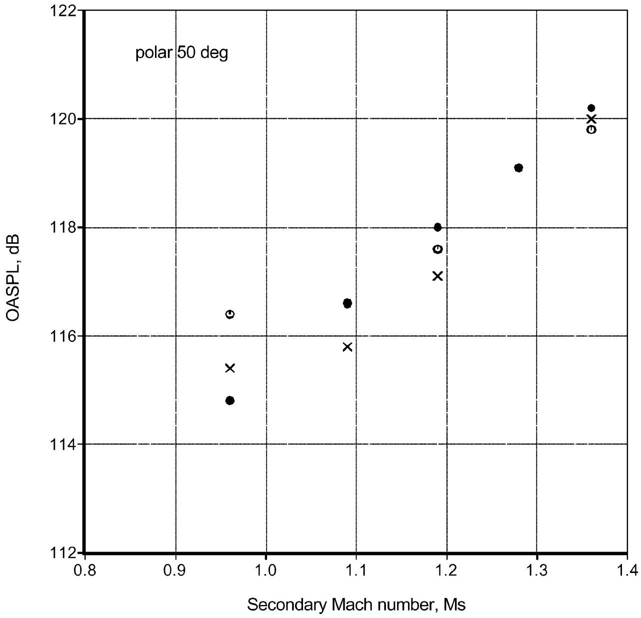

Fig. 17 Variation of OASPL with secondary Mach number: $M_p = 1.36$ and polar angle = 50 deg; •, round; ○, bevel45 and azimuthal angle = 0 deg; and ×, bevel45 and azimuthal angle = 90 deg.

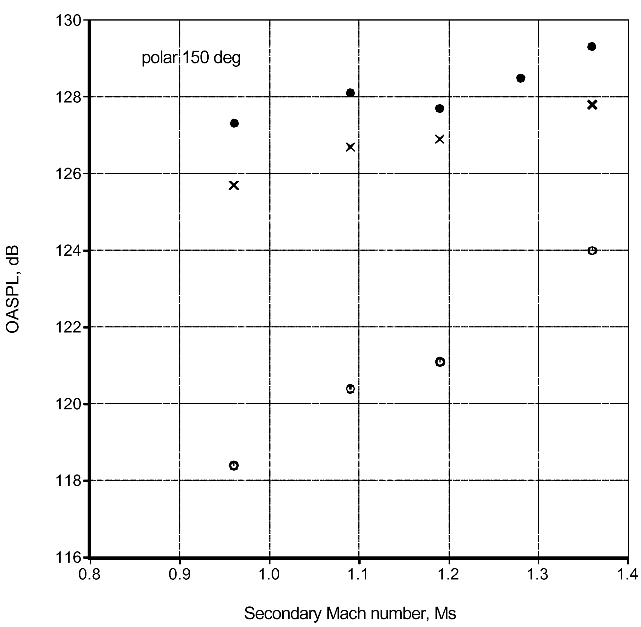

Fig. 18 Variation of OASPL with secondary Mach number: $M_p = 1.36$ and polar angle = 150 deg; •, round; ○, bevel45 and azimuthal angle = 0 deg; and ×, bevel45 and azimuthal angle = 90 deg.

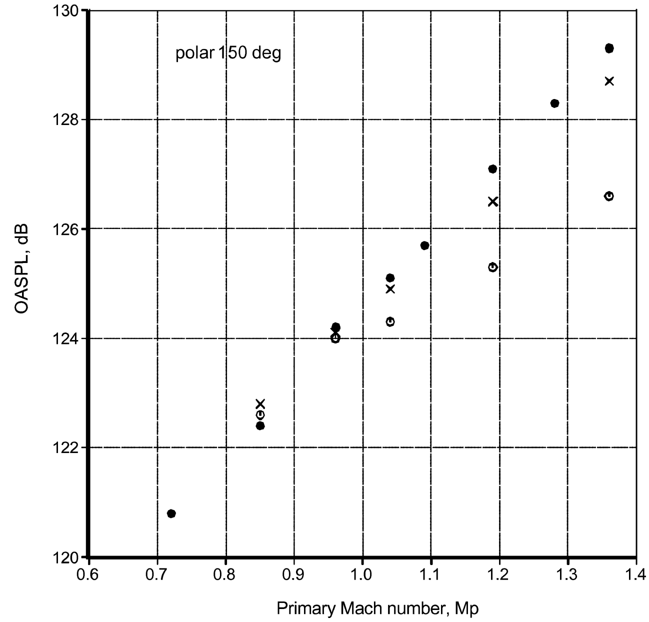

Fig. 19 Variation of OASPL with primary Mach number: $M_p = 1.36$ and polar angle = 150 deg; •, round; ○, bevel24 and azimuthal angle = 0 deg; and ×, bevel24 and azimuthal angle = 90 deg.

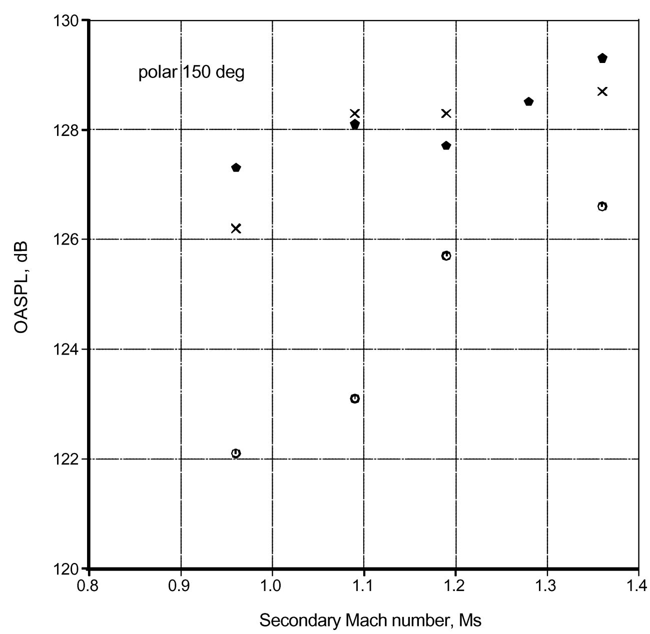

Fig. 20 Variation of OASPL with secondary Mach number: $M_p = 1.36$ and polar angle = 150 deg; •, round; ○, bevel24 and azimuthal angle = 0 deg; and ×, bevel24 and azimuthal angle = 90 deg.

bevel45 in Fig. 18. Clearly, the magnitude of the noise reduction achievable with the bevel24 under static conditions is lower than that for bevel45. This characteristic has been observed for beveled nozzles for single jets and dual-stream jets at subcritical pressure ratios in Refs. 2 and 3.

Figures 11–13 and 15–18 indicate clearly that the velocity of the primary stream is the key parameter in determining the noise reduction achievable with the beveled nozzles. The development of the shocks in the secondary stream could, of course, be modified by the beveled primary. An examination of Figs. 11, 13, and 16 together suggests that even if the secondary shocks are altered it is the primary velocity that controls the noise reduction. Typically, turbulent mixing noise is the major noise component at the aft angles for a single jet, even for shock-containing plumes. It has been verified experimentally[4–6] that both a convergent nozzle and a convergent–divergent nozzle operated at its design Mach number produce virtually identical noise levels at angles close to the jet axis. The mixing noise at these angles is generated by the large-scale turbulence structures in the flow. Therefore, even for dual-stream jets, the noise reduction from the beveled nozzles at the aft angles is attributable to the alteration of the characteristics of the large-scale structures of the inner shear layer. Detailed flowfield measurements and computational fluid dynamics simulations are necessary to gain a better understanding of the flow physics and the noise generation mechanisms. Given the many sources of noise in a dual-stream jet, the three for turbulent mixing noise (inner shear layer, outer shear layer, and the fully mixed jet) and the two shock-cell systems, it is not possible to identify the exact contributions from each source.

We may draw another salient conclusion from Figs. 11–13 and 15–18. In the spectral plots at lower angles shown in Figs. 11–13 as well as the OASPL plots at 50 deg shown in Figs. 15 and 17, there is only a small variation between the round and beveled nozzles. At the radiation angle of 50 deg, shock-associated noise should be dominant, especially when one stream contains strong shocks and the other one is at a subsonic Mach number. Given the small changes to the radiated noise even for these cases, it appears that the generation and radiation mechanisms of shock-associated noise are not altered substantially by the beveled nozzle. Note that the maximum Mach number is restricted to ~1.36 in the preceding cases because this value represents the higher limit of the jet Mach numbers at cruise for all commercial turbofan engines. A reduction of ~5 dB in OASPL was observed at lower polar angles at an azimuthal angle of 0 deg for a single jet at very high jet velocity, $M = 1.56$, and $T_p/T_a = 3.2$, in Ref. 2. However, at practical cycle conditions of turbofan engines in service, it would be fair to conclude that changes to the noise radiation due to modifications of the shock structure by the beveled primary nozzles are small. Viswanathan[1] examined the variation of the OASPL of shock-associated noise with the parameter β^4, $\beta = \sqrt{(M_p^2 - 1)}$ or $\sqrt{(M_s^2 - 1)}$, for the conventional dual-stream nozzle. Because the noise characteristics at the lower polar angles are similar for the beveled nozzle, the same trends hold and, hence, are not presented here.

In summary, the main ingredient in the achievement of noise reduction, both for single and dual-stream jets, is the redirection of the noise beamed to the aft angles by the inner shear layer. This recurring theme has been highlighted in all the three papers on beveled nozzles, with the velocity of the primary (or single) jet identified as the key parameter for noise reduction. The secondary effect, that of modifications to the shock structure in the fan stream and possible changes to the noise radiation from this source (Fig. 11), apparently plays a less important role. In general, the effects of bevel24 are less pronounced than those of bevel45 at static conditions. The observed trends are similar, and, hence, data have not been presented for bevel24.

B. Effect of Forward Flight

The effects of forward flight on the shock-associated noise from conventional (round) dual-stream nozzles were examined systematically and reported in Ref. 1. The pertinent issues of the effects due to sound convection by the tunnel flow and refraction by the tunnel shear layer, and methods to deal with these phenomena, were also discussed in Ref. 1. As noted therein, there are two angles, one in the forward quadrant and one in the aft quadrant, where these two effects cancel each other. From the geometry of the wind tunnel and jet rig, these two angles were calculated to be 60 and 130 deg for tunnel Mach numbers in the range of 0.2–0.32. In addition, the measured data at 145 deg for the wind-on case corresponds to the microphone at 150 deg for the static case. Proprietary methods and software allow for the evaluation of flight effect at any desired polar angle. However, in this paper, measured data without any interpolation are presented at these three polar angles.

The main conclusions of the effect of forward flight (for freestream Mach numbers of 0.32) on the shock-associated noise from conventional dual-stream nozzles are first summarized. The effects for a dual-stream jet with the primary jet being supersonic are similar to those of a single supersonic jet in that there is a reduction in spectral levels in the forward quadrant, with an increase in level at angles close to the jet exhaust axis in the aft quadrant. (See Figs. 19 and 20 in Ref. 1.) When the secondary stream is supersonic, there is substantial amplification of the shock peak, especially at the aft angles, with no change in levels at the lower polar angles. (See Fig. 21 in Ref. 1.) In general, the frequency of the screech tone decreases with increasing freestream Mach number regardless of the presence of the shock in either the primary or secondary stream. Furthermore, the spectral peak becomes narrower, and several higher-order peaks become prominent with increasing flight speed. The modifications to these trends for the beveled nozzles, if any, are examined hereafter.

First, we examine the flight effect with shocks in the secondary stream, $M_s = 1.36$, with a transonic primary Mach number of 1.04. Figures 21 and 22 show the effect of forward flight at two azimuthal angles of 0 and 90 deg, respectively, for a freestream Mach number

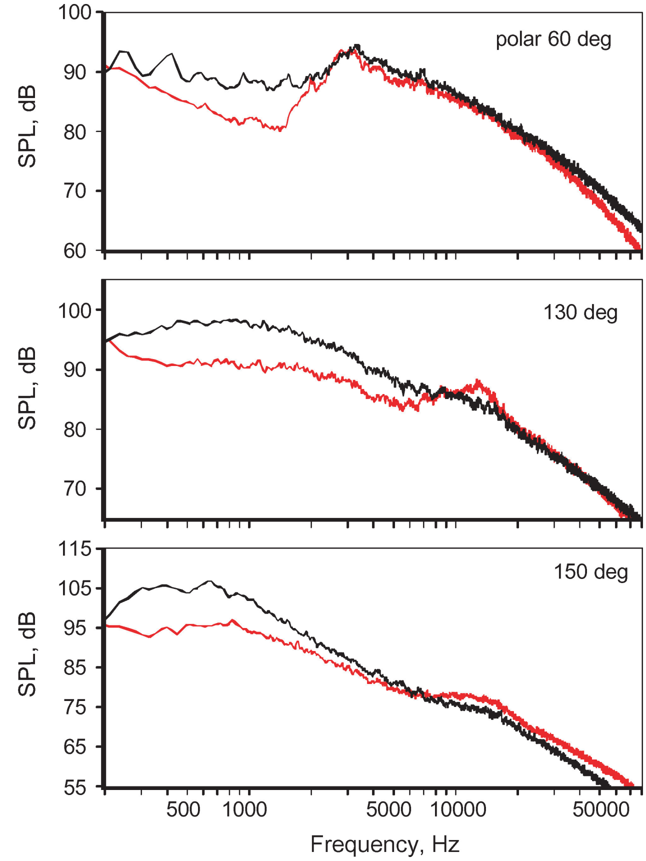

Fig. 21 Flight effect for bevel45: NPRp = 1.96, T_p/T_a = 2.46, NPRs = 3.0, and azimuthal angle = 0 deg; black, M_t = 0.0; and red, M_t = 0.32.

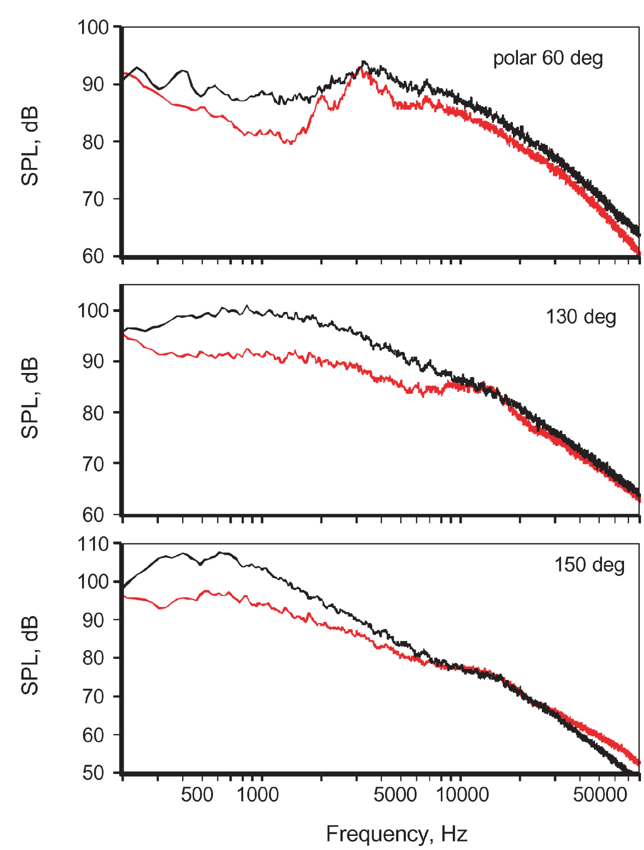

Fig. 22 Flight effect for bevel45: NPRp = 1.96, T_p/T_a = 2.46, NPRs = 3.0, and azimuthal angle = 90 deg; black, M_t = 0.0; and red, M_t = 0.32.

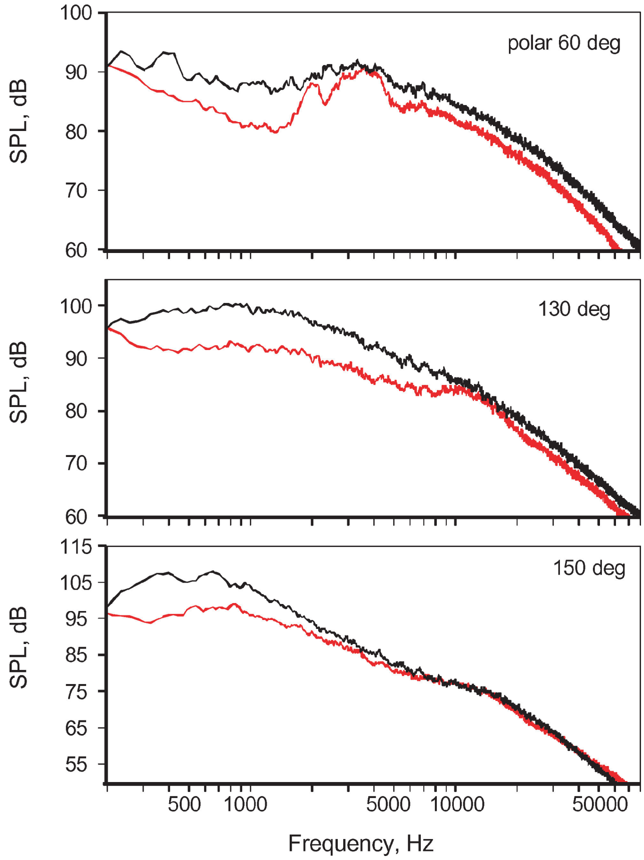

Fig. 23 Flight effect for bevel24: NPRp = 1.96, T_p/T_a = 2.46, NPRs = 3.0, and azimuthal angle = 0 deg; black, M_t = 0.0; and red, M_t = 0.32.

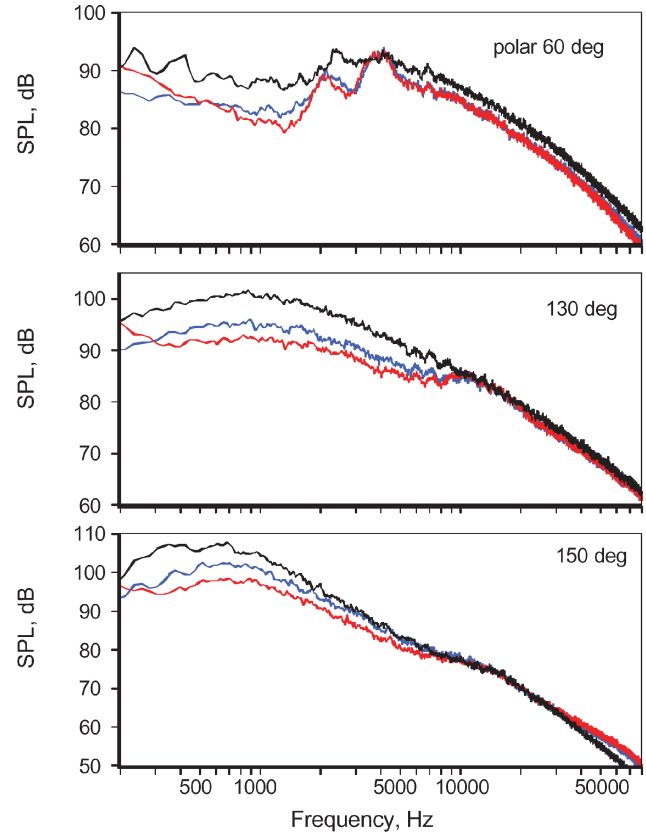

Fig. 24 Flight effect for bevel24: NPRp = 1.96, T_p/T_a = 2.46, NPRs = 3.0, and azimuthal angle = 90 deg; black, M_t = 0.0; blue, M_t = 0.20; and red, M_t = 0.32.

M_t of 0.32. The reduction in the levels of turbulent mixing noise at the lower frequencies (below 5 kHz) is quite pronounced at all polar angles at both the azimuthal angles. However, there is a clear difference in the aft-radiating shock component from the shocks in the secondary stream. Whereas the shock peak, 4–12 kHz, is amplified at the azimuthal angle of 0 deg, there is no significant change at 90 deg. For the flight effect for a conventional dual-stream nozzle at these cycle conditions, see Fig. 21 in Ref. 1. Comparable plots for bevel24 are shown in Figs. 23 and 24, respectively. There is a monotonic decrease in the mixing noise levels with increasing freestream Mach number in Fig. 24. There is no change in the aft-radiating shock component due to the flight stream at both azimuthal angles.

There are some surprising azimuthal effects due to a flight stream at the aft angles, when shocks are present in the primary stream, $M_p = 1.36$, with a subsonic secondary stream, $M_s = 0.96$. The spectral variations at the lower angles are unremarkable and, hence, are not shown. At an azimuthal angle of 0 deg for bevel24 in Fig. 25, there is amplification of the shock peak at a polar angle of 130 deg and a substantial increase of noise over a very wide range of higher frequencies at a polar angle of 150 deg. However, at an azimuthal angle of 90 deg and a polar angle of 130 deg (Fig. 26), there is broadband reduction in levels at all frequencies. At a polar angle of 150 deg, the noise level increases, but by a smaller amount compared with the azimuthal angle of 0 deg. For the flight effect for a conventional dual-stream nozzle at these cycle conditions, see Fig. 20 in Ref. 1. When strong shocks are established in both the streams (not shown) with $M_p = 1.36$, $T_p/T_a = 3.04$, and $M_s = 1.36$, similar azimuthal variations are observed. The preceding results indicate that both the bevel angle and cycle conditions influence the flight effects, with the observed effects being different at different azimuthal angles. All of the spectral results, both under static and flight conditions, attest to the complex interactions among the sources and modifications to the noise field due to azimuthal effects.

Finally, we assess the acoustic performance of the beveled nozzles (with flight effects) relative to the conventional round nozzle.

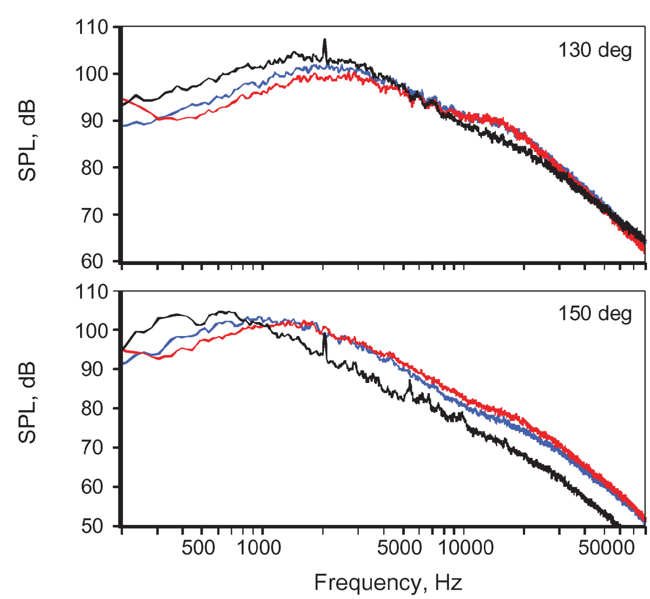

Fig. 25 Flight effect for bevel24: NPRp = 3.0, T_p/T_a = 3.04, NPRs = 1.8, and azimuthal angle = 0 deg; black, M_t = 0.0; blue, M_t = 0.20; and red, M_t = 0.32.

When assessing the impact of the beveled nozzles for cabin noise applications, recall that there is no relative motion between the noise source and the fuselage for an aircraft in flight. However, as shown by Norum and Brown[7] for a single jet, there is alteration of the shock-cell structure due to a coflowing stream. We anticipate that there would be modifications to the shock-cell structure and the large-scale structures in the shear layers for a dual-stream nozzle as well. Furthermore, the maximum Mach number for the freejet at

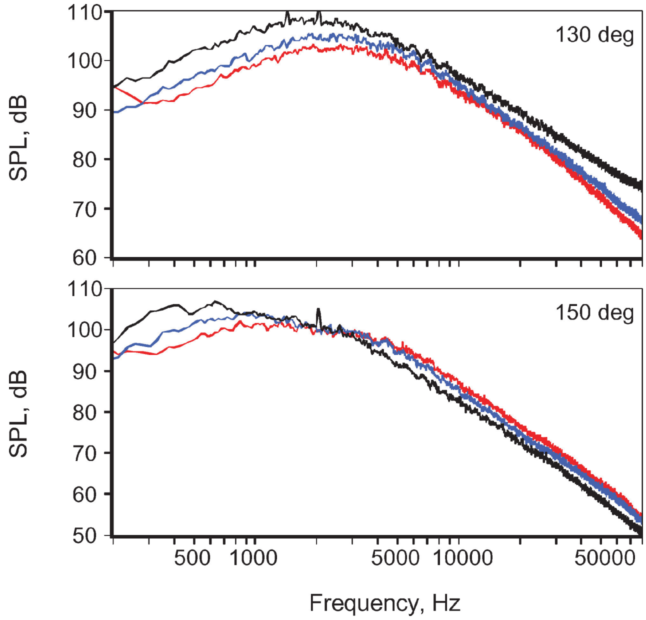

Fig. 26 Flight effect for bevel24: NPRp = 3.0, $T_p/T_a = 3.04$, NPRs = 1.8, and azimuthal angle = 90 deg; black, $M_t = 0.0$; blue, $M_t = 0.20$; and red, $M_t = 0.32$.

the low speed aeroacoustic facility (LSAF) is 0.32, which is substantially lower than a typical cruise Mach number of ~0.8. Newer facilities that would allow higher tunnel Mach numbers and appropriate measurement techniques are currently being considered; the results here are restricted to lower tunnel Mach numbers. In a recent study, Norum et al.[8] report the results of a controlled flight test that quantified the flight effect on both mixing noise and shock-associated noise at higher flight Mach numbers from a single jet; such tests are expensive and have not been carried out for high-BPR turbofan engines with dual-stream exhaust nozzles.

For the sake of convenience, spectral comparisons are presented in one-third octave bands. The small wiggles in the narrowband spectra are somewhat distracting and a clearer visual picture is provided by one-third data. In Fig. 27, we examine the noise reduction due to the beveled nozzles, with a transonic primary stream and a supersonic secondary stream at an azimuthal angle of 0 deg. The cycle conditions are NPRp = 1.96, $T_p/T_a = 2.46$, and NPRs = 3.0, and the tunnel Mach number is 0.32. Spectral comparisons are shown only at the aft angles. There is a reduction in levels for the beveled nozzles at the lower frequencies, where mixing noise is dominant. However, there is a substantial increase in the shock peak at the higher frequencies for bevel45, whereas there is no change for bevel24. A comparable increase in levels (as for bevel45) is observed at an azimuthal angle of 90 deg, but for both beveled nozzles.

Now, when shocks are established in the primary stream with a subsonic secondary stream, the trends are quite different in Fig. 28. The cycle conditions are as follows: NPRp = 3.0, $T_p/T_a = 3.04$, NPRs = 1.8, and $M_t = 0.32$. There is a substantial reduction in levels for the beveled nozzles over a wide range of frequencies, with a small increase at the higher frequencies. The magnitude of reduction is not quite as large as is seen for the static case in Fig. 12, but it is still significant. Finally, we examine the noise benefit with shocks in both streams by increasing NPRs to 3.0. It was mentioned earlier that for cabin noise applications, one should be concerned with noise levels around an azimuthal angle of 90 deg. The modified nozzle with bevel24 was shown to be superior for community noise reduction. Hence, spectral comparisons at the four aft angles are presented in Fig. 29 only for bevel24. It is readily apparent that there is a ~3–4 dB reduction at the spectral peak, with no elevated levels at the higher frequencies. Note that there are multiple sources that contribute to high noise levels at the aft cabin: the noise due to the turbulent boundary layer, the engine exhaust, and the environmental control system. Usually, it is harder to reduce the cabin noise at

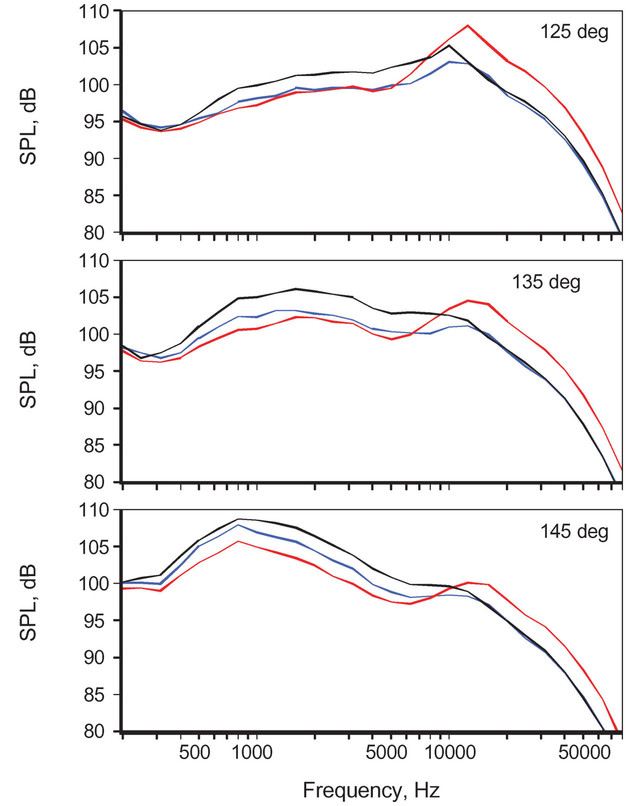

Fig. 27 Performance of beveled nozzles relative to round nozzle: NPRp = 1.96, $T_p/T_a = 2.46$, NPRs = 3.0, azimuthal angle = 0 deg, and $M_t = 0.32$; black, round; blue, bevel24; and red, bevel45.

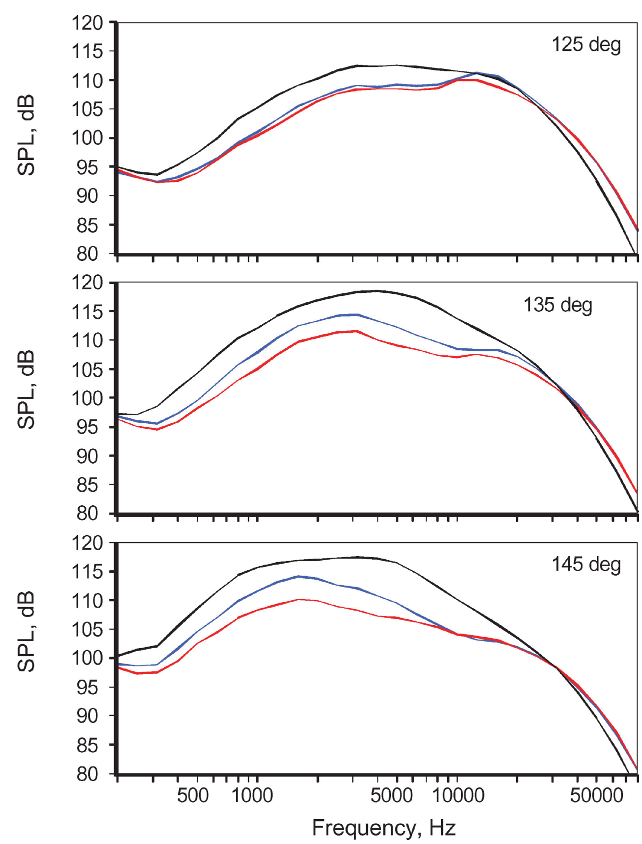

Fig. 28 Performance of beveled nozzles relative to round nozzle: NPRp = 3.0, $T_p/T_a = 3.04$, NPRs = 1.8, azimuthal angle = 0 deg, and $M_t = 0.32$; black, round; blue, bevel24; and red, bevel45.

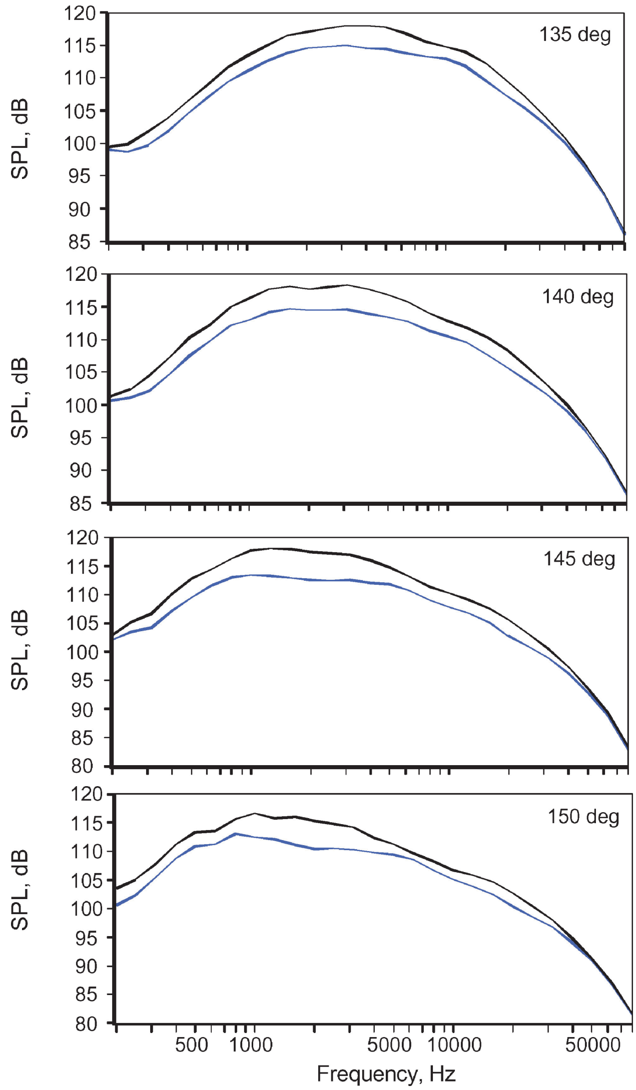

Fig. 29 Performance of beveled nozzle relative to round nozzle: NPRp = 3.0, T_p/T_a = 3.04, NPRs = 3.0, azimuthal angle = 90 deg, and M_t = 0.32; black, round and blue, bevel24.

the lower frequencies because of the longer wavelengths; the noise at the higher frequencies is more amenable to acoustic treatment of the fuselage. Furthermore, it is believed that the sources of jet noise, being more correlated than those of the turbulent boundary layer, are more efficient in exciting the fuselage structure. Given the complex acoustic environment on the outside of the fuselage, it is hard to quantify the noise benefit inside the cabin due to the beveled nozzle. However, the reduction of source noise, especially at the lower frequencies (confirmed by data extrapolated to engine scale but not shown), should have a salutary effect for cabin noise reduction. Only internal measurements in a flight test would confirm the magnitude of the anticipated noise benefit in the aft cabin of an aircraft.

Thus, there is a strong potential for the reduction in cabin noise levels in addition to the benefit demonstrated for community noise. For the sake of information, note that there is a higher magnitude of noise reduction at an azimuthal angle of 0 deg (not shown). These trends are not too surprising because the primary velocity is high, and similar reductions were observed at static conditions.

IV. Summary

Experimental measurements of noise from dual-stream nozzles with a beveled primary nozzle have been presented for supersonic jet Mach numbers, both at static conditions and in the presence of a flight stream. Two different beveled nozzles with bevel angles of 24 and 45 deg have been evaluated. This study represents the first step in gaining a better understanding of the physics of noise generation. The experimental results indicate that, in general, the changes in spectral levels at supercritical pressure ratios due to the beveled nozzles are not significant when compared with conventional round nozzles at lower polar angles. Similar trends have been observed for single beveled jets and dual-stream beveled jets at subsonic jet Mach numbers. At a polar angle of 50 deg, where shock-associated noise is dominant, there is a slight increase in OASPL of ~1 dB for the beveled nozzles relative to a convention dual-stream nozzle, regardless of the jet Mach numbers in the two streams.

Under static conditions, significant levels of noise reduction are achieved with the beveled nozzles at large polar angles in the aft quadrant. The maximum reduction is observed in the polar angular range from ~130 to ~140 deg and drops gradually as we move away from this angular sector. The magnitude of the noise reduction as well as the azimuthal effects, depend on the primary jet velocity. At the polar angle of 150 deg where the turbulent mixing noise is dominant, the noise reduction of bevel45 relative to the conventional round nozzle system increases with primary Mach number. At low subsonic primary Mach numbers, there is a negligible noise benefit. At higher primary jet velocities, the noise benefit is ~9 dB at an azimuthal angle of 0 deg when the Mach number of the secondary stream is 0.96 and drops to ~5 dB at a secondary Mach number of 1.36, pointing to the increasing importance of the noise from the secondary stream at higher Mach numbers. Thus, the balance between the different sources dictates the noise reduction achievable with the beveled nozzles. It is clear, however, that there is a reduction in the levels of the jet exhaust noise that impinges on the rear fuselage, which is then transmitted into the aft cabin.

The effects of forward flight are influenced by the jet operating conditions, the bevel angle, and the azimuthal angle. Note that the results reported here have been obtained at a maximum freestream Mach number of 0.32, whereas the cruise Mach number is ~0.8. At lower V_p, the noise levels for the beveled nozzle relative to a conventional dual-stream round nozzle are higher for the aft-radiating shock component. When shocks are present in the primary stream (and higher V_p), there is a reduction in spectral levels over a wide range of lower frequencies (up to 40 kHz) and, hence, in OASPL for bevel24 in the aft angles in the entire azimuthal angular range of 0–90 deg. Note that spectra have been presented here only at two azimuthal angles, 0 and 90 deg, even though data have been acquired at two other azimuthal angles, 30 and 60 deg.

For the bevel24 nozzle, the magnitude of reduction in OASPL is from ~3 to ~4 dB at the aft polar angles at an azimuthal angle of 90 deg, due to reduction over a wide range of lower frequencies with no increase in levels at the higher frequencies. Thus, bevel24 could provide a benefit for cabin noise, in addition to the observed benefit at takeoff conditions. One could take advantage of the azimuthal variations of the noise field to optimize the noise benefit for community noise at takeoff and cabin noise at cruise by suitably orienting the longer lip of the beveled nozzle.

There is no theory or an empirical model for the generation of shock noise from conventional dual-stream nozzles; the azimuthal effects for the beveled nozzles make this problem even more complex. A major study is needed to investigate the mechanisms of noise generation and radiation from these types of geometries. A model for the shock-cell structures and shock-cell strengths must be developed, and the role of the inner shear layer must be investigated by theoretical and computational studies. A prediction method would follow when the relevant physics are understood better.

Screech tones are not a major concern for commercial turbofan engines; however, broadband shock-associated noise and, in particular, the aft-radiating component, is important for cabin noise. The usual means for the alleviation of noise levels in the aft cabin consists of adding acoustic treatment, which adds unnecessary weight to the airplane. Any design that reduces source noise levels is, therefore, highly desirable. The beveled nozzle concept described here and the results presented here and in Refs. 2 and 3 demonstrate clearly that this approach is far superior, in terms of simplicity and the potential for greater noise reduction, to any design that has been proposed so far for jet noise reduction. Therefore, the beveled nozzle represents a viable design with major noise benefit and low thrust penalty (as discussed in the companion paper), with the added advantage of easy retrofit of existing commercial turbofan engines.

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