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Elegant Concept for Reduction of Jet Noise from Turbofan Engines

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Jet noise is a major component of total aircraft noise at takeoff, even for modern aircraft powered by high-bypass-ratio (BPR) turbofan engines with BPR of around five. The reduction of jet noise at fixed BPR has proven to be a formidable challenge, and no practical design that produces substantial aeroacoustic benefit has evolved despite significant effort. A simple concept of a beveled nozzle is adapted for realistic engine geometries. The strategy for noise reduction in the peak sector of noise radiation is based on our understanding of the characteristics of the noise sources in a dual-stream exhaust system. Specifically, the noise generation mechanisms of the inner shear layer are modified by beveling the primary nozzle to achieve noise reduction. Detailed aeroacoustic measurements are carried out statically and in the presence of a flight stream to assess the noise benefit of the modified exhaust system, relative to a conventional arrangement, at realistic engine cycle conditions. Two beveled nozzles of bevel angles 24 (bevel24) and 45 deg have been evaluated. The bevel24 nozzle has a low performance penalty (∼0.2%) at cruise power and produces substantial reduction in noise levels in the aft quadrant. The reduction in overall sound pressure levels is ∼5 to ∼7 dB near the spectral peak in the angular sector ≥110 deg. There is a slight increase (∼1 dB) in the overall sound pressure levels at the lower polar angles. The magnitude of noise reduction is strongly dependent on the velocity of the inner stream. The reduction in levels occurs over a wide frequency range; there is no increase at the higher frequencies, which is a typical trend for other noise reduction concepts. The effects of forward flight on the measured spectra are different at different azimuthal angles; further, the flight effects in the azimuthal plane are a function of the bevel angle. A total noise reduction of ∼4 dB effective perceived noise level is demonstrated at takeoff (sideline and overhead) at realistic flight Mach numbers with the bevel24 nozzle.

I. Introduction

THE introduction of the turbofan engine revolutionized commercial aviation and facilitated the explosive growth of air travel over the past three decades. The improved fuel efficiency of the turbofan engine, coupled with the lower level of engine noise, has made air travel affordable and aircraft operations more acceptable. However, because of population growth near airports and the perception that aircraft noise is a nuisance, there is tremendous pressure on the aviation industry to reduce aircraft noise. Even for modern aircraft powered by high-bypass-ratio (BPR) turbofan engines with BPR of around five, jet noise is a major component of total aircraft noise at takeoff and, hence, must be reduced further. Focused programs on jet noise research and the development of nozzle designs for low noise have been underway in both Europe and the USA for the last 10 years. Unlike a turbojet, the turbofan engine with separate nozzles for core and fan flows offers many more possibilities for noise reduction because noise reduction strategies can be applied to either stream or both simultaneously. Numerous concepts such as the incorporation of vortex generators, tabs and other mixing devices, offset and nonconcentric nozzles, thermal shielding, etc., have been investigated. However, none of these devices has produced the level of noise reduction necessary to provide a substantial and noticeable relief for the surrounding population. The reduction of jet noise from a turbofan engine at fixed BPR presents a formidable challenge as evidenced by the lack of any viable concept in the last three decades.

Viswanathan[1] proposed a simple concept, a beveled nozzle, for the reduction of turbulent mixing noise from single jets. It was demonstrated that the beveled nozzle introduces a strong azimuthal variation of the noise field. Whereas the noise from large-scale structures is radiated principally to the aft angles in a round jet, this component of noise is radiated to shallower polar angles for a beveled nozzle. (Polar angles are measured from the jet inlet axis.) Of greater relevance vis-à-vis noise reduction is the observation that this noise is radiated toward the shorter side of the beveled nozzle. Therefore, through proper orientation of the beveled nozzle, it is possible to enhance the emission skyward and, hence, reduce the noise that reaches the ground from an aircraft. For a single jet, it was shown that most of the noise reduction occurs in a polar angular region that spans from ∼110 to ∼145 deg. Within this angular sector, reduction in spectral levels at all frequencies was observed. The magnitude of the noise reduction was directly proportional to the jet velocity. The reduction achieved at certain azimuthal angles below the longer lip of the beveled nozzle could be because of significant radiation of noise from the large-scale structures to lower polar angles (especially above the shorter lip) possibly leading to less acoustic energy being available for radiation to the aft angles. This hypothesis needs to be verified in the future, with experimental measurements as well as computational fluid dynamics (CFD), to quantify the modifications to the large-scale turbulence in the jet plume.

The noise generation and radiation processes in a dual-stream nozzle are more complex. The measurements of the source characteristics and the far-field spectra by Lu[2] established the many features of the noise generation mechanisms, the frequency content, and the principal radiation directions of the different sources. For normal-velocity-profile jets, as in practical high-BPR turbofan engines, the following trends have been observed. Specifically, the outer shear layer between the fan (or secondary) flow and the ambient stream is responsible for the generation of the high-frequency noise radiated to all angles. The inner shear layer between the core (or primary) flow and fan flow is responsible for the peak levels in the spectra and the lower frequencies in the peak radiation angles. These two characteristics, also confirmed in the experiments of Ref. 3 as well as in other studies, are pertinent to the strategy adopted here for the reduction of jet noise from dual-stream nozzles.

The objective of the current study is to develop a practical concept for the reduction of jet noise for turbofan engines. A comprehensive

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parametric investigation of noise from dual-stream nozzles carried out by the author and reported in Ref. 3 includes a selected list of prior studies. The current study is an extension of the research performed in Ref. 3 and focuses specifically on noise reduction, with emphasis on concepts that are not too complex and that are easily adapted. In this paper, the characteristics of the turbulent mixing noise are presented. The noise at supercritical pressure ratios are examined in a companion paper.[4]

II. Concept Description and Test Details

From the foregoing discussion, it is clear that to achieve noise reduction in the peak radiation angles, similar to that seen for a single jet, one should modify the noise characteristics of the inner shear layer. Therefore, a beveled nozzle is used for the primary nozzle alone. There is another important reason as well for not altering the fan nozzle. Engine nacelles are designed carefully to provide good external aerodynamics, with minimization of cruise drag as the main design consideration. Further more, modifications to the nacelle usually tend to be very expensive, and a reoptimization of the engine/pylon/wing installation would be necessary. Hence, any change to the nacelle for the purpose of noise reduction is not a viable option for retrofits for current engine installations.

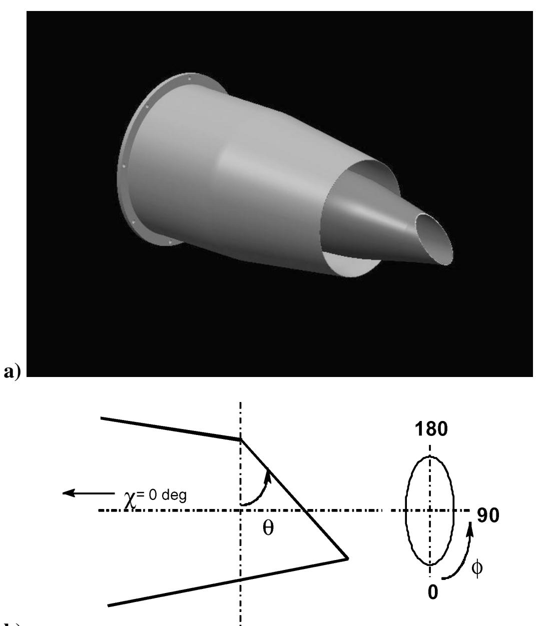

Fig. 1 Beveled nozzle concept for noise reduction from dual-stream nozzles: a) design drawing and b) convention for measurements of polar angle χ, bevel angle θ, and azimuthal angle ϕ.

Figure 1a shows the exhaust system with a beveled primary nozzle. Figure 1b defines the various angles and their measurement conventions: θ is the bevel angle, χ is the polar angle measured from the inlet, and ϕ is the azimuthal angle measured counterclockwise from the bottom dead center. The performance of two beveled primary nozzles with bevel angles of 24 and 45 deg (bevel24 and bevel45) is assessed against a conventional dual-stream nozzle with a simple round primary nozzle. The area ratio, defined as the ratio of secondary to primary area, As/Ap, is 3.0 for the reference nozzle, with the primary nozzle area being 4.714 in.[2] (30.41 cm^2), $D = 2.45$ in. (6.2 cm) (The subscripts p and s refer to primary and secondary, respectively.) As noted in Ref. 1, this area ratio is altered slightly because the effective areas for the beveled nozzles are lower than that for the round nozzle.

A brief overview of the aeroacoustic tests with simultaneous measurements of thrust and noise is provided here; a comprehensive description of the jet simulator, the freejet wind tunnel, the force balance, the anechoic facility, data acquisition, etc., may be found in Refs. 1, 3, and 5. For the sake of completeness, a photograph that shows the jet rig, the freejet wind tunnel, and some of the microphones is included here (Fig. 2). The freejet wind tunnel at the Boeing low speed aeroacoustic facility (LSAF) can reach a maximum Mach number of 0.32; the geometric details of the wind tunnel can be found in Ref. 5. A six-component force balance is used to measure the three forces in the three coordinate directions as well as the roll, pitch, and yaw moments. Acoustic data are acquired with several microphones on two arrays 30 deg apart in the azimuthal plane. Bruel & Kjaer Type 4939 microphones are used for free-field measurements. The microphones are set at normal incidence and without the protective grid, which yields a flat frequency response up to 100 kHz. Narrowband data with a bandwidth of 23.4 Hz are acquired and synthesized to produce one-third-octave spectra, up to a center band frequency of 80,000 Hz. The two arrays are at a constant sideline distance of 15 ft (4.572 m), and the polar angular range spans 50–150 deg. For spectral comparisons, data are corrected to a common distance of 20 ft (6.096 m) and to standard day conditions: ambient temperature of 77°F (298 K) and relative humidity of 70%. The atmospheric attenuation coefficients are obtained from the method of Shields and Bass.[6] The acoustic field in one quadrant and at four azimuthal angles of 0, 30, 60, and 90 deg has been acquired. Measurements with two different orientations of the primary nozzle are necessary for each test point to cover the four azimuthal angles. No acoustic measurements have been made at the azimuthal angles of 150 and 180 deg because of time constraints; even though one is only concerned with the noise that would reach the ground from an engine (with a beveled nozzle) installed on an airplane, it would be desirable to have a complete picture of the azimuthal variations.

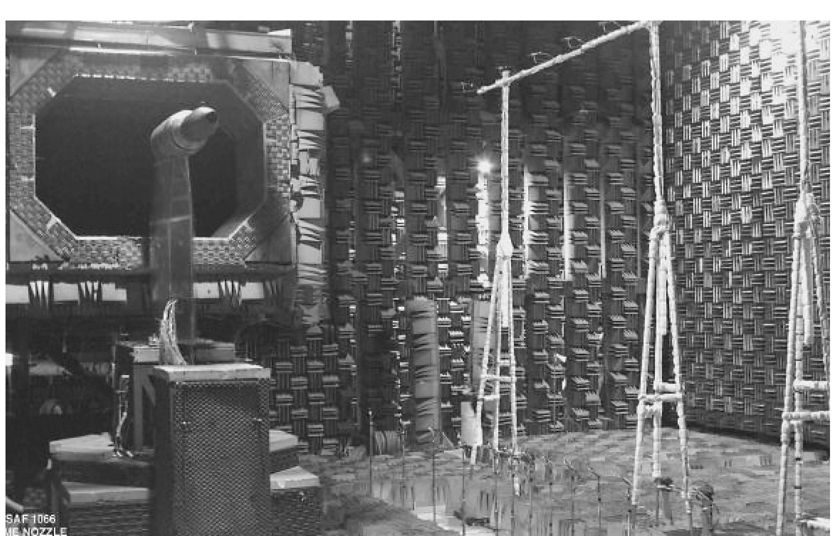

Fig. 2 Photograph of LSAF showing anechoic chamber, jet rig, wind tunnel, and some of the microphones.

To ensure practical relevance, a typical engine cycle that has a fixed temperature for a specified nozzle pressure ratio (NPR) is chosen for the primary stream. The NPR of the primary stream spans a range of 1.4–3.0, with a corresponding stagnation temperature ratio range, Tp/Ta, of 2.14–3.04. At every cycle point for the primary flow, the NPR in the secondary stream is systematically varied over a range of 1.4–3.0. The secondary stagnation temperature ratio is always maintained at unity. This is the same test matrix adopted in the experiments of Ref. 3. (See Fig. 2 in Ref. 3.) However, data have been acquired at a smaller subset of the test points in the large test matrix studied in Ref. 3. Thus, the foregoing chosen nozzle geometry with an extended primary nozzle and the engine cycle represent typical turbofan engines and operating conditions in current-day service with large passenger jetliners.

III. Nozzle Aerodynamics

Viswanathan[1] showed that the effective flow areas for the beveled nozzles were smaller than that for the round nozzle. Specifically, the corrected mass flow rates were lower by ~8% for bevel24 and ~13% for bevel45 for all NPR. It is important to understand the distinction between the nozzle discharge coefficient and the nozzle thrust coefficient. The discharge coefficient pertains to the amount of mass that can be passed through a given flow area for the nozzle. In a jet engine, this flow area is determined to ensure an engine match, whereby the nozzle is properly sized to allow smooth operation of the fan without causing pressure surges or engine stall. Thus, an ~8% increase in the throat area of bevel24 would ensure the proper operation of the fan and maintain the correct mass flow rates and thrust levels. (Note that the geometric area of bevel24 is 3.1% smaller than that for the round nozzle.) The thrust coefficient, on the other hand, is a measure of the propulsive efficiency and impacts directly the specific fuel consumption. Therefore, it is essential to minimize the adverse thrust impact of any concept for noise reduction. Complex nozzle geometries, such as multitube mixers, lobed mixer/ejector, etc., usually degrade thrust from ~3% to ~4% and entail an increase in weight. The thrust coefficient for the dual-stream nozzle is defined as,

$$C_f = \frac{F_{\text{measured}}}{(W_{p,\text{measured}} * V_{ip} + W_{s,\text{measured}} * V_{is})}$$

F is the measured axial force and W_p and W_s are the actual mass flow rates in the two streams. V_{ip} and V_{is} are the ideal velocities of the two streams, calculated from the plenum stagnation conditions.

Let us now examine the thrust performance of the beveled nozzles. Figure 3 shows the variation of thrust coefficient with secondary NPR (NPRs), for a fixed primary NPR (NPRp) of 1.8. Data are presented in this fashion because this allows one to assess the influence of NPRs independently and because the chosen cycle does not correspond to that of any particular engine. The trends for the round, bevel45, and bevel24 nozzles are similar, with the peak values of the thrust coefficient occurring for a NPRs value of ~2.3.

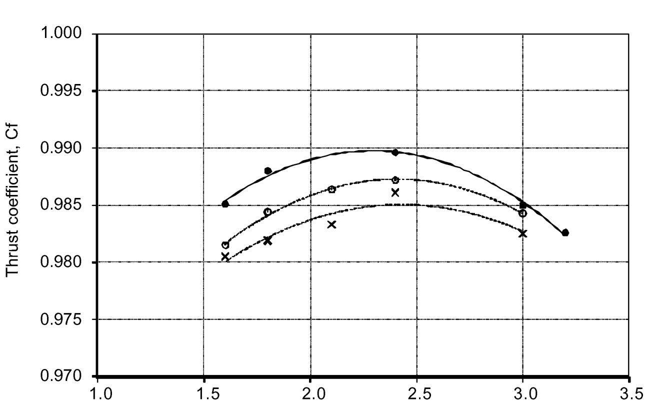

Fig. 3 Variation of thrust coefficient with NPRs: NPRp = 1.8 and T_p/T_a = 2.37; ●, round primary; ○, bevel24; and x, bevel45.

In general, the thrust coefficient of bevel24 is ~0.3% lower than that for the round nozzle at the lower NPRs. The thrust degradation for bevel45 is higher, ~0.6%. When NPRp is increased to 1.96, similar trends prevail, as shown in Fig. 4, with the exception that the degradation of performance for bevel24 is reduced to ≤0.25%. These values for NPRp are representative of typical conditions at takeoff with maximum power. However, the thrust coefficient at cruise conditions is more important because this value impacts the specific fuel consumption and the block fuel requirement for a given mission. The variation of thrust coefficient with NPRs for a typical cruise NPRp of 2.4 is shown in Fig. 5. In the range of typical NPRs at cruise, the thrust coefficient of bevel24 is ~0.2% worse than that for the conventional nozzle.

For a conventional nozzle, the axial force or the thrust is the only component of interest, and not much attention is paid to the forces in the normal directions to the jet. The values of these components are typically close to zero. It was noted in Ref. 1 that for the single-stream beveled nozzles, the jet plume is deflected toward the shorter side of the beveled nozzle and that the thrust axis does not coincide with the geometric centerline of the nozzle. This deflection of the plume (thrust vectoring) introduces forces in the normal directions that have been measured in the current test. Unlike for a single jet, the secondary jet constrains the magnitude of the deflection of the primary jet in a dual-stream nozzle. The influence of the cycle conditions on plume deflection and the thrust coefficient is discussed briefly. In a dual-stream exhaust system with a fixed area ratio, one can change the BPR in several ways. For example, for a fixed secondary NPRs and temperature ratio, hold NPRp constant and progressively increase the primary temperature ratio T_p/T_a. With this approach, the thrust is maintained essentially at a constant level (except for a negligible effect due to a change in the ratio of specific heats γ), whereas BPR is increased due to a lowering of the

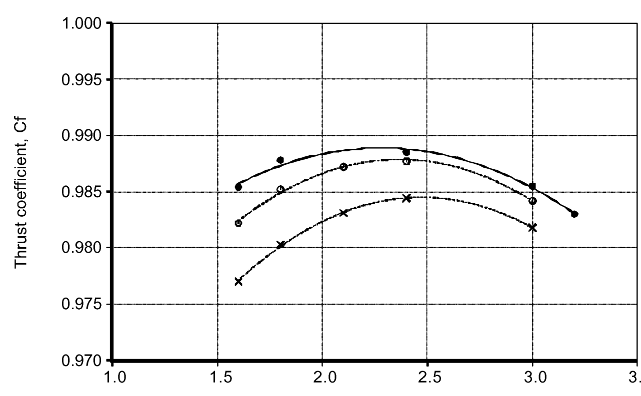

Fig. 4 Variation of thrust coefficient with NPRs: NPRp = 1.96 and T_p/T_a = 2.46; ●, round primary; ○, bevel24; and x, bevel45.

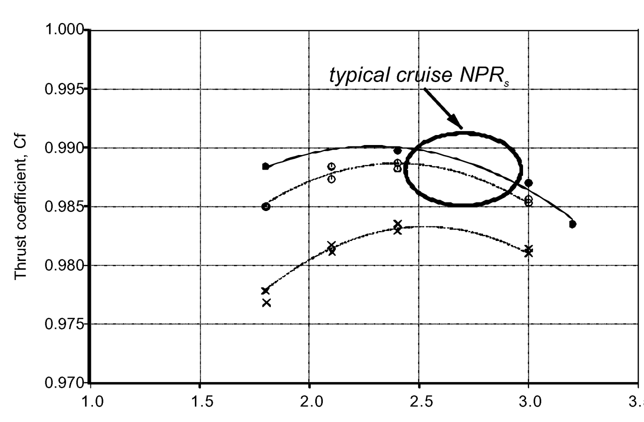

Fig. 5 Variation of thrust coefficient with NPRs at typical cruise conditions: NPRp = 2.4 and T_p/T_a = 2.70; ●, round primary; ○, bevel24; and x, bevel45.

primary mass flow rate. The plume deflection angle is insensitive to changes in the BPR and has a value of ∼4 deg for bevel45 and ∼2.5 deg for bevel24, for pressure-balanced jets. Alternately, one could maintain the same NPRp and T_p/T_a and progressively increase NPRs. The value of the axial thrust increases progressively with this approach; the normal force remains, however, more or less unaltered. Hence, the plume deflection angle calculated from the force triangle keeps decreasing with increasing BPR. The reduced degradation of the thrust coefficient of the beveled nozzles relative to that of the conventional nozzle system in Figs. 3–5 with increasing NPRs reflects the aforementioned trend and highlights the rising importance of the thrust generated by the secondary stream. Finally, in a third approach, one could hold NPRs constant, increase both NPRp and T_p/T_a, and follow the cycle line for the primary jet. Both the thrust and BPR are altered. In all the preceding variations, the plume deflection angle spans a range from ∼3 to ∼5 deg for bevel45 and from ∼1.2 to ∼3 deg for bevel24. Anyway, the impact of the deflection is considerably less when there is a fan stream. It might be possible to reduce the magnitude of the thrust degradation due to the beveled nozzles further, as follows. If one were to install the primary nozzle with a slight cant or tilt of ∼2 deg downward from the geometric centerline of the jet, or redesign the primary nozzle with a suitable contouring of the internal flow lines to align the plume axis with the engine axis, some of the thrust loss associated with the plume deflection could be recovered. This implementation would require a careful analysis of the airplane attitude, engine pitch angle, etc., as well as the cycle conditions at cruise, to arrive at an optimum tilt angle for the primary nozzle for a given engine/airplane combination.

In a high BPR turbofan engine (with BPR ≅ 5), the secondary jet generates ∼75% of the total engine thrust. This is why there is only a slight degradation of the thrust coefficient for the beveled nozzles. This is another powerful reason, in addition to cost and complexity, not to attempt anything that would compromise the aerodynamic performance of the fan nozzle. In summary, one can regain the proper level of thrust through appropriate sizing of the throat area of the beveled primary nozzle. Second, it is worth noting that the bevel24 degrades thrust by ∼0.25% relative to a round nozzle over a wide range of nozzle pressure ratios. As noted, this low level of thrust loss could be mitigated further.

IV. Acoustics

For airplane certification, the noise metric of importance is the effective perceived noise level (EPNL), which is an integrated quantity that includes the importance of both the maximum noise level and the duration of the noise exposure at the measurement point produced by an aircraft flyover. There are two certifications points for takeoff; one is the sideline measurement point, with the sideline level defined as the maximum noise level measured by a microphone located at a lateral distance of 1476 ft (450 m), irrespective of the altitude of the aircraft. (See Fig. 11 in Ref. 1.) The other one is directly under the flight path (0-deg azimuthal angle), usually referred to as the cutback microphone location. An examination of the certification database for several aircraft indicates that, regardless of the takeoff gross weight of the aircraft and the number of engines, the altitude at which maximum noise is measured at the sideline microphone location falls within the range 1000 ± 50 ft. The azimuthal angle that corresponds to these altitudes is ∼34 deg. Thus, the noise level at an azimuthal angle of 30 deg in the current experiments is representative of the level that would occur at the sideline measurement location in a flyover test because there is no drastic variation in the azimuthal directivity. Note that the effective flow area of the beveled nozzle is slightly less than that for the reference round primary nozzle. Therefore, the BPR and thrust of the modified dual-stream exhaust system are not the same as those for the baseline exhaust system. However, it is not possible to account directly for these minor variations through scaling of the acoustic data. The effect of these variations is assessed with an empirical prediction procedure in a later section. Noise spectra from the beveled primary nozzles are compared with those from the conventional dual-stream nozzle at the same operating conditions, and the effect of slightly different BPR is neglected for the time being.

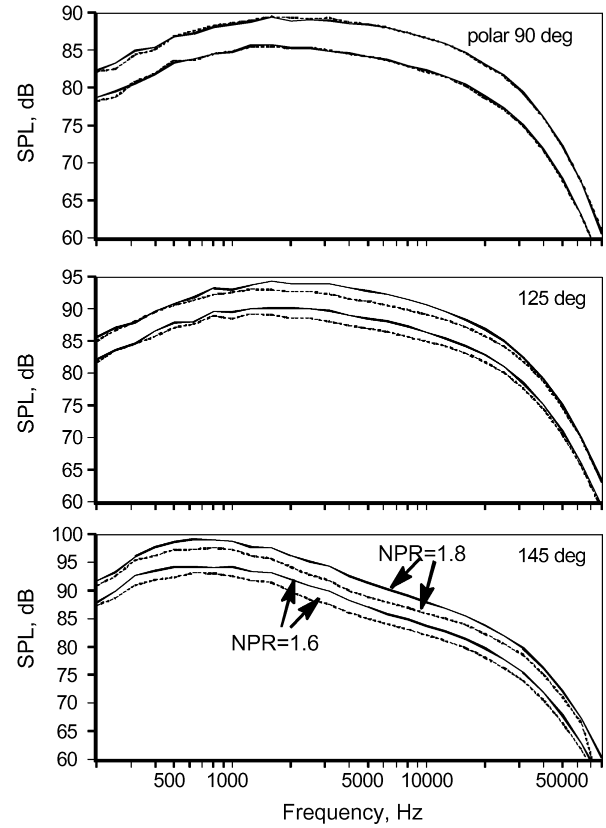

Fig. 6 Comparison of spectra at two azimuthal angles from unheated and pressure-balanced jets with bevel45: $M_t = 0.0$; ——, azimuthal angle = 90 deg; and – – – –, azimuthal angle = 0 deg.

A. Noise Characteristics at Static Conditions

First, we examine the azimuthal variation of the noise from the dual-stream nozzle with primary bevel45, operated pressure balanced and unheated. This essentially eliminates the inner shear layer, except for the small effect due to the boundary layer on the inner and outer surfaces of the primary nozzle. Figure 6 shows spectral comparisons at two azimuthal angles of 0 and 90 deg at several polar angles and at two NPR of 1.6 and 1.8. There is no azimuthal variation at 90 deg and lower polar angles. However, as we move aft to higher polar angles, the noise level at the azimuthal angle of 0 deg is ∼2 dB lower across the spectrum compared with the levels at an azimuthal angle of 90 deg. When the same nozzle is operated at one of the engine cycle points with NPRp = 1.96, $T_p/T_a = 2.46$, and NPRs = 1.8, there is a pronounced azimuthal variation as shown in Fig. 7. Again, at the lower polar angle of 90 deg, there is only a small difference in the spectral levels at the two azimuthal angles of 0 and 90 deg. At a polar angle of 125 deg, there is a reduction of ∼5 dB in the peak noise level at the azimuthal angle of 0 deg (underneath the longer lip) relative to the level at the azimuthal angle of 90 deg. There is a substantial reduction of ≥10 dB over a broad frequency range at the higher aft angles. At a lower power setting with NPRp = 1.6, $T_p/T_a = 2.26$, and NPRs = 1.8 (not shown), the reductions in noise levels at the azimuthal angle of 0 deg are in between those observed for the two cases shown in Figs. 6 and 7. Thus, the azimuthal trends for the dual-stream nozzle with the beveled primary are similar to those for the single jet shown in Ref. 1 in that the velocity of the inner stream plays a significant role in the level of asymmetry in the acoustic field.

The noise reduction potential of the dual-stream nozzle with the beveled primary, relative to a conventional, nozzle is now assessed at different operating conditions. Figure 8 shows spectral comparisons of bevel45 at azimuthal angles of 0 and 30 deg with the

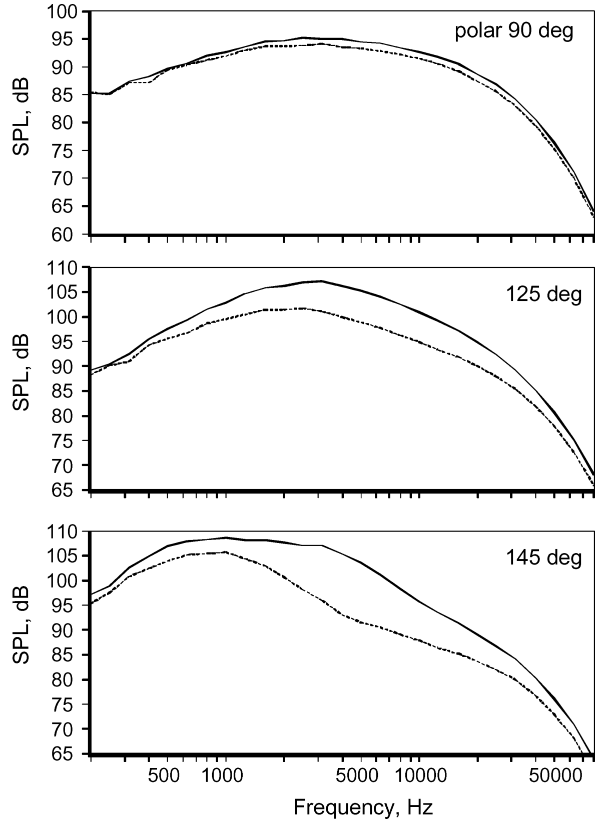

Fig. 7 Comparison of spectra at two azimuthal angles with bevel45: $M_t = 0.0$, NPRp = 1.96, $T_p/T_a = 2.46$, and NPRs = 1.8; ——, azimuthal angle = 90 deg; and – – – –, azimuthal angle = 0 deg.

corresponding spectra from an equivalent conventional dual-stream exhaust system. The cycle conditions are as follows: NPRp = 1.8, $T_p/T_a = 2.37$, and NPRs = 1.8. In the forward quadrant, at a polar angle of 60 deg, the beveled nozzle increases the noise at the peak frequencies by ~2 dB. As we move aft, the noise levels from the beveled nozzle tend to be lower. At a polar angle of ~100 deg, the levels are comparable. Farther aft, we notice a substantial decrease in levels: ~5 dB at an angle of 125 deg and more than 7 dB at higher angles. The noise reduction occurs over a very wide range of frequencies including the peak frequency of noise radiation; there is only a negligible change in levels at the very high frequencies. This is not surprising because, as stated earlier, the secondary shear layer is responsible for the generation of noise at these frequencies, and this source of noise has not been altered in any way. Another feature worth noting is that comparable levels of noise reduction are observed at the two azimuthal angles of 0 and 30 deg. That is, there is a slow variation of azimuthal directivity below the longer lip of the beveled nozzle. This trend ensures that significant noise reduction would be achieved at the sideline microphone location for a range of altitudes (azimuthal angles) at which peak noise levels occur for different aircraft/engine combinations.

The acoustic performance of both bevel24 and bevel45 in combination with a conventional secondary nozzle, at another cycle condition of NPRp = 1.96, $T_p/T_a = 2.46$, and NPRs = 1.8, is assessed in Fig. 9. The azimuthal angle is 0 deg for Fig. 9, and we examine the spectra at the same three polar angles as in Fig. 8. As at the lower power, the spectral levels from the beveled nozzles are slightly higher at a polar angle of 60 deg and in the forward quadrant. However, the increase due to bevel24 is lower in magnitude. As we move to aft angles, there is again substantial noise reduction due to the beveled nozzles, with the magnitude of reduction increasing with increasing polar angle. The noise levels for bevel24 are higher than that for bevel45 at aft angles, similar to the trends observed for the single jet. A comparable plot at an azimuthal angle of 30 deg in

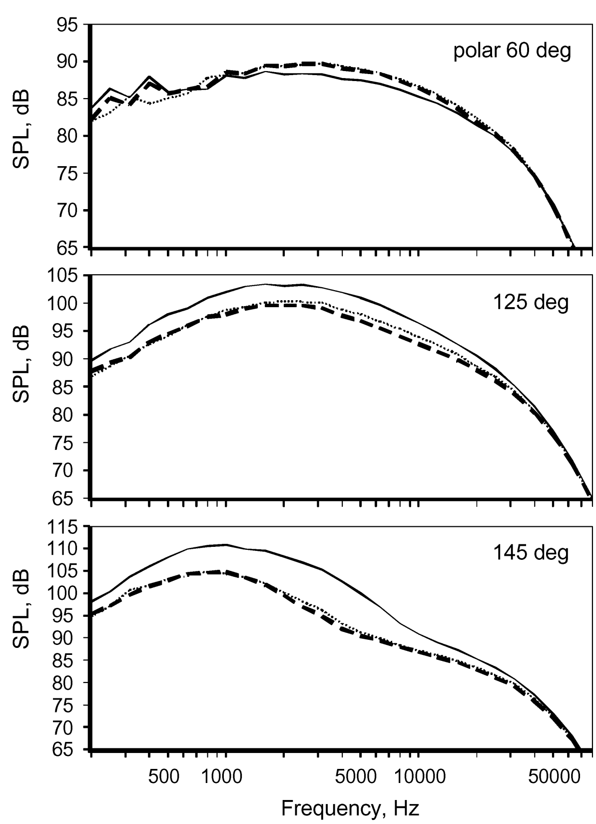

Fig. 8 Noise reduction of bevel45; $M_t = 0.0$, NPRp = 1.8, $T_p/T_a = 2.37$, and NPRs = 1.8; ——, round; – – – –, bevel45, and azimuthal angle = 0 deg; · · · ·, bevel45 and azimuthal angle 30 deg.

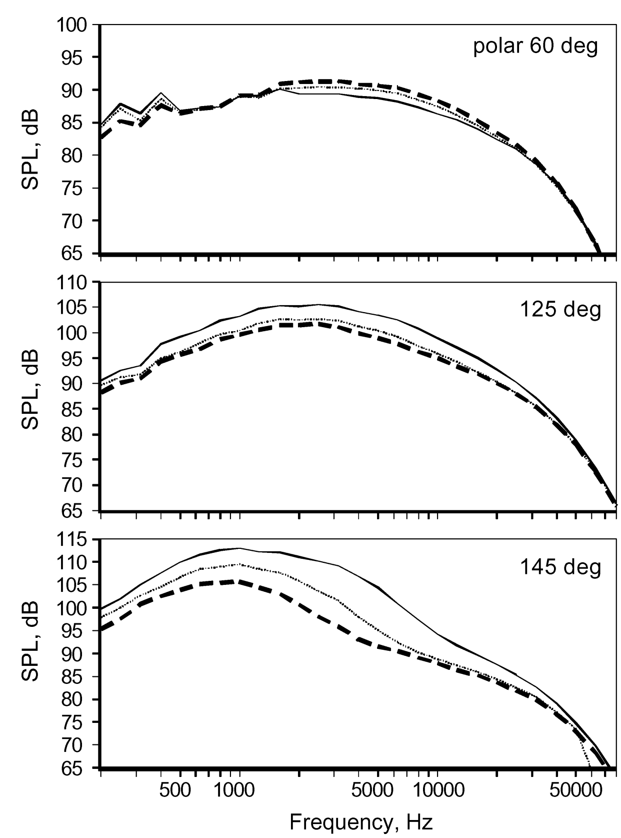

Fig. 9 Performance of beveled nozzles relative to round nozzle: $M_t = 0.0$, NPRp = 1.96, $T_p/T_a = 2.46$, NPRs = 1.8, and azimuthal angle = 0 deg; ——, round; – – – –, bevel45; and · · · ·, bevel24.

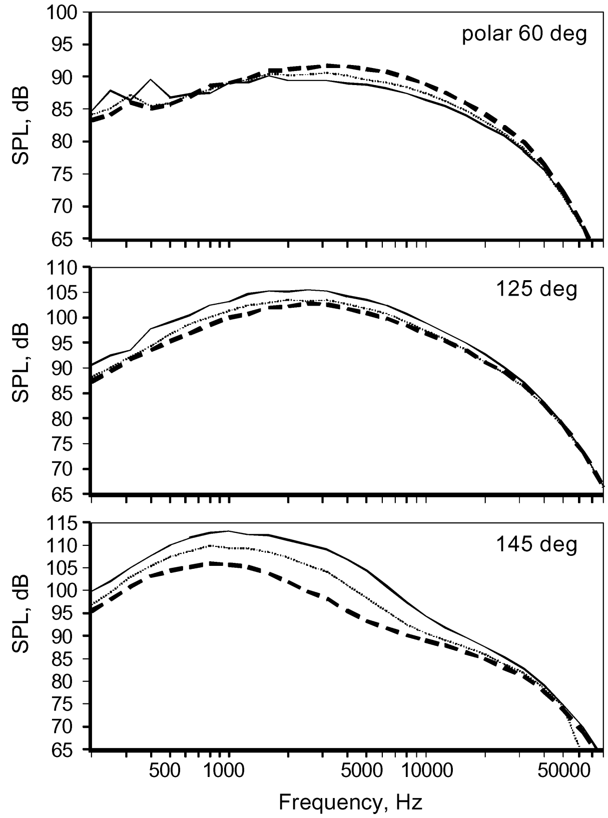

Fig. 10 Performance of beveled nozzles relative to round nozzle: $M_t = 0.0$, NPRp = 1.96, $T_p/T_a = 2.46$, NPRs = 1.8, and azimuthal angle = 30 deg; ——, round; – – – –, bevel45; and · · · ·, bevel24.

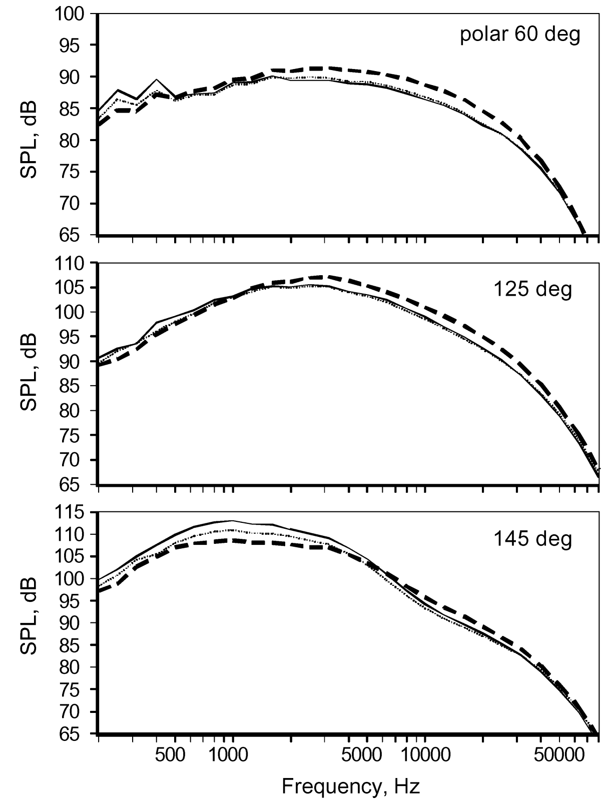

Fig. 11 Performance of beveled nozzles relative to round nozzle: $M_t = 0.0$, NPRp = 1.96, $T_p/T_a = 2.46$, NPRs = 1.8, and azimuthal angle = 90 deg; ——, round; – – – –, bevel45; and · · · ·, bevel24.

Fig. 10 provides a similar picture to that seen at an azimuthal angle of 0 deg in Fig. 9. Therefore, substantial noise reduction for all polar angles ≥110 deg has been realized for a dual-stream jet with the concept of a beveled primary and a standard round secondary nozzle at static conditions. For the sake of completeness, a comparable plot is shown at the azimuthal angle of 90 deg in Fig. 11. It is clear that the bevel45 radiates higher levels than the reference nozzle, especially at the higher frequencies at all polar angles. There is a reduction in level at the lower frequencies at the aft angles. In contrast, bevel24 produces lower noise levels (at the lower frequencies) in the aft angles without a noise increase at the higher frequencies at all polar angles.

It is instructive at this point to examine the spectral variations introduced by chevrons on a round nozzle. Figure 12 shows spectral comparisons of a baseline nozzle with two chevron designs at typical takeoff power, at two polar angles of 90 and 140 deg. The solid line represents the baseline round nozzle and the broken lines the chevrons. At 90 deg, one observes a reduction of ~2 dB at the lower frequencies. However, there is a considerable increase of ~5 dB over a wide range of higher frequencies. In the aft direction, similar trends are observed, though the noise increase at the higher frequencies is not quite as pronounced as at the lower angles. Thus, the chevrons alter the shape of the spectra with a decrease in level at the lower frequencies accompanied by an increase in level at the higher frequencies. The crossover frequency is particular to a given design (and the cycle conditions to a lesser degree) and is generally controlled by the number, geometry, and immersion of the chevrons. Because of the noise increase at the higher frequencies, the net benefit in EPNL is usually minimal at best. These trends have been observed in all chevron tests. For a detailed discussion of the importance of the noise at the higher frequencies, see Viswanathan.[5] Let us contrast this trend with the spectra from the beveled nozzles shown in Figs. 8–10. First of all, in the angular region in which peak noise reduction occurs (≥110 deg), there is substantial reduction in spectral level over a wide range of frequencies, and there is no increase in level at any frequency. It is believed that the noise reduction of the beveled nozzles has been achieved through the manipulation of the noise generated by the large-scale structures in the inner shear layer. For additional discussions, see Ref. 1. This process is very different from that for a chevron, which simply redistributes energy from the lower frequencies to higher frequencies at each angle, with no guarantee that there would be a net benefit in EPNL.

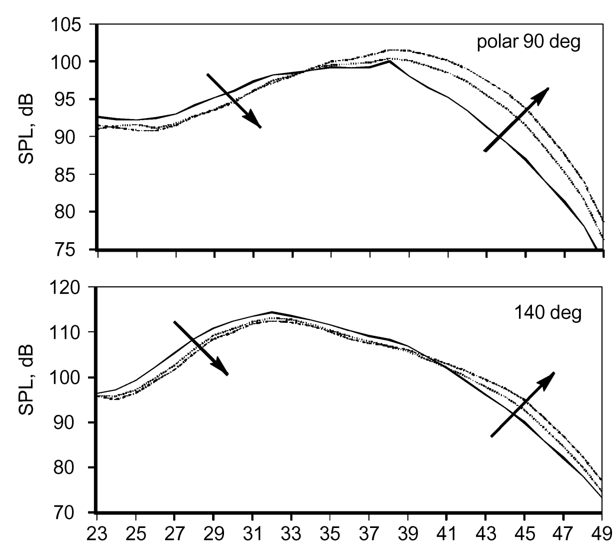

Fig. 12 Spectral modifications due to chevrons at typical takeoff power: ——, baseline; – – – –, and · · · ·, chevrons.

B. Effect of Forward Flight

It is essential to prove the worth of any concept for noise reduction in the presence of a freestream. Often, the observed benefits at static conditions fail to hold up under flight conditions. Let

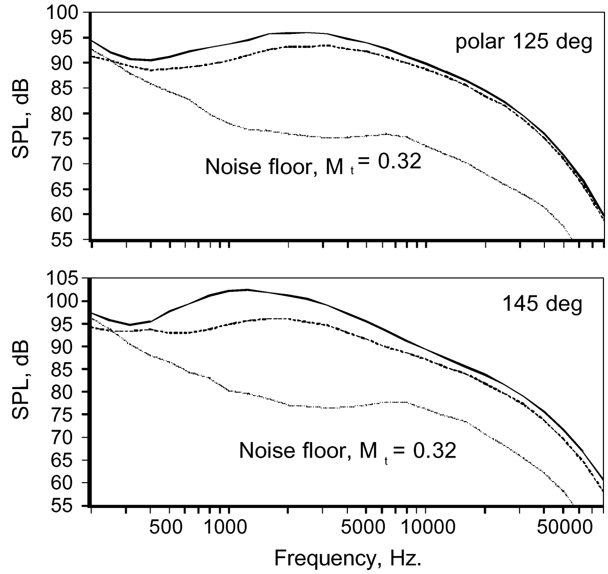

Fig. 13 Performance of beveled nozzles relative to round nozzle: $M_t = 0.32$, NPRp = 1.8, $T_p/T_a = 2.37$, NPRs = 1.8, and azimuthal angle = 0 deg; ——, round and – – – –, bevel45.

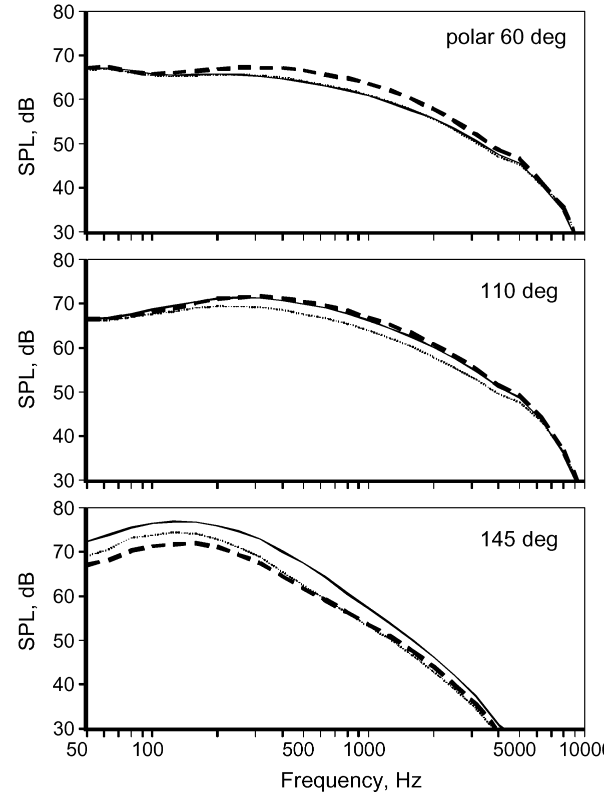

Fig. 14 Performance of beveled nozzles relative to round nozzle, engine scale: $M_t = 0.32$, NPRp = 1.96, $T_p/T_a = 2.46$, NPRs = 1.8, and azimuthal angle = 0 deg; ——, round; – – – –, bevel45; and · · · ·, bevel24.

us first examine the acoustic performance of the bevel45 nozzle at a freestream Mach number of 0.32, at an azimuthal angle of 0 deg, in Fig. 13. The nozzle operating conditions are NPRp = 1.8, $T_p/T_a = 2.37$ and NPRs = 1.8. A similar comparison with no external flow was presented in Fig. 8. The background noise floor due to the tunnel flow is also shown to point out the influence of the tunnel noise on the spectra at the lowest frequencies. The noise reduction due to the beveled nozzle at an angle of 125 deg is more modest, from ∼2 to ∼3 dB instead of ∼5 dB for the static case, in the presence of an external flow. There is a similar erosion of noise benefit due to the beveled nozzle at 145 deg. It is clear that one cannot assume that a given concept would work equally well under flight conditions.

To examine the net benefit in terms of the EPNL, the model scale data have been extrapolated to engine scale. Typically, the extrapolation process is carried out with one-third-octave spectra. The proper choice of the scale factor that could be used for extrapolation is first discussed briefly. As noted earlier, acoustic data have been acquired up to a one-third-octave band with center frequency of 80,000 Hz. This frequency range would enable the use of a scale factor of 8 for the resolution of the entire range of frequencies at engine scale. Viswanathan[5] provides a detailed discussion of the nozzle size requirements and the consequences of using large nozzles. Several linear scale factors of 8, 10, and 11 were used in the extrapolation. With a scale factor of eight, the engine thrust at takeoff power is ∼24,000 lbf. First of all, it has been verified that the change in noise benefit in terms of EPNL is negligible for two scale factors of 8 and 10. Therefore, a linear scale factor of 10 has been assumed in the spectra presented in this section. This implies that the spectral level at a one-third-octave centerband frequency of 10 kHz at the engine scale is obtained by extrapolation because model scale data have been acquired up to a frequency of 80 kHz. Because the spectral shapes due to the beveled nozzle at the higher frequencies are not different from those from conventional nozzles, and because their shapes are well established, one could use a slightly higher scale factor in the range of 11.0–11.5 in the extrapolation procedure to obtain an engine thrust of ∼50,000 lbf. For these larger scale factors, the maximum frequency at engine scale for which measured data are available with the test nozzle is ∼7000 Hz, and, hence, one would not incur large errors in the calculation of the EPNL. For a discussion on the proper choice of the nozzle size for a given jet rig, see Ref. 5. In the computation of the EPNL, the model scale data are extrapolated to engine scale, again at standard day atmospheric conditions. A level flight profile for the airplane at a constant altitude of 1000 ft (305 m) is assumed. The slant distance (or the hypotenuse) to the sideline microphone is 1783 ft (544 m), which is a typical value for the cutback altitude for many aircraft. Note that the cutback altitude varies widely (unlike the altitude for the sideline measurement point) and is strongly dependent on the number of engines and takeoff gross weight.

Comparisons at engine scale are presented, with the frequencies in the range from 50 Hz. to 10 kHz. In the results presented so far, both for single- and dual-stream jets under static conditions, a common trend for all the cases is that the noise reductions due to bevel24 are much less than those for the bevel45. Let us see if the same trends prevail for wind-on conditions. The comparisons of spectra from the round and beveled nozzles at a freestream Mach number of 0.32 and at an azimuthal angle of 0 deg are shown in Fig. 14. The jet operating conditions are NPRp = 1.96, $T_p/T_a = 2.46$, and NPRs = 1.8. (See Fig. 9 for static comparisons.) There is no noise increase due to bevel24 at any angle. However, at a polar angle of 60 deg there is a ∼3 dB increase in the spectral level at the spectral peak and a wide range of midfrequencies for bevel45. As we move aft, the magnitude of this increase becomes less pronounced at 110 deg, and noise reductions are observed only at angles ≥120 deg for the larger bevel angle. In contrast, the bevel24 retains its noise benefit even at lower polar angles. At large aft angles, the noise reduction at the peak due to bevel45 is greater than that due to bevel24. Similar spectral trends (not shown) were observed at an azimuthal angle of 30 deg.

The directivities of the perceived noise levels with tone correction (PNLT, PNdB) for the three nozzles at the same jet conditions are shown in Fig. 15, at the two azimuthal angles of 0 and 30 deg. The consequence of the noise increase at the lower angles for the bevel45 (dashed line) is clearly identifiable, with an increase in the perceived noise levels at angles ≤120 deg at both azimuthal angles. Even though the bevel45 produces larger noise reduction at the higher aft angles, bevel24 yields reductions in the perceived noise level over a wider range of angles and without any increase in the forward quadrant. Consequently, the reductions in EPNL due to bevel45 are 1.79 dB effective perceived noise level (EPNdB) and

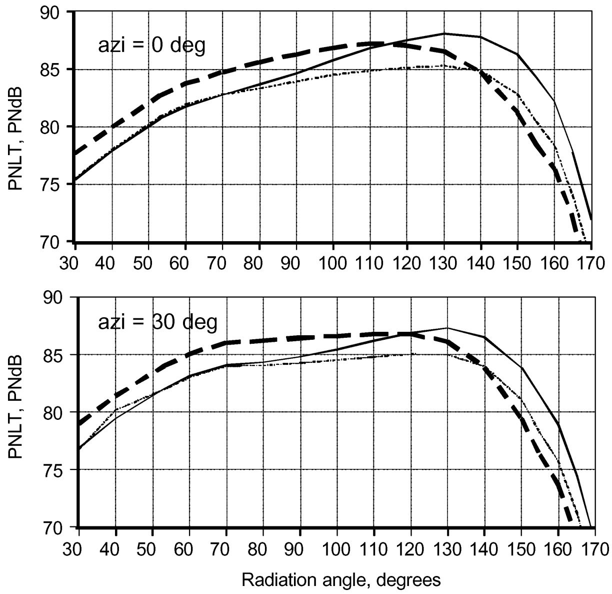

Fig. 15 PNLT directivity: $M_t = 0.32$, NPRp = 1.96, $T_p/T_a = 2.46$, and NPRs = 1.8; ——, round; – – – –, bevel45; and · – · –, bevel24.

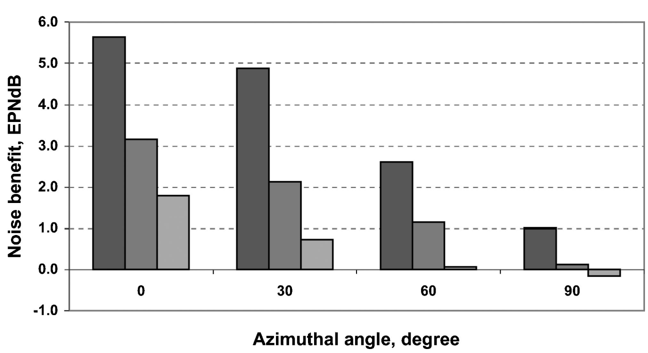

Fig. 16 Reduction in EPNL relative to round primary for bevel45 at various azimuthal angles: NPRp = 1.96, $T_p/T_a = 2.46$, NPRs = 1.8; vertical lines, $M_t = 0.0$; blank: $M_t = 0.20$; and slanted lines, $M_t = 0.32$.

0.72 EPNdB at the azimuthal angles of 0 and 30 deg, respectively, whereas they are 2.50 EPNdB and 1.72 EPNdB for bevel24. At lower freestream Mach numbers and at static conditions, bevel45 outperforms bevel24. However, for realistic takeoff Mach numbers in the range from ~0.25 to ~0.28 (160–180 kn), bevel24 is seen to provide a larger noise reduction. The flight Mach numbers at the certification points are again dependent on the number of engines and the takeoff weight/thrust setting of the engines; however, they fall within the narrow range of flight velocities noted earlier. This example indicates that one could be misled easily by investigating concepts for noise reduction only at static conditions.

The effect of the flight Mach number on the performance of bevel45 at various azimuthal angles are brought out in Fig. 16, again at engine conditions of NPRp = 1.96, $T_p/T_a = 2.46$, and NPRs = 1.8. First, the greatest noise reduction is achieved at an azimuthal angle of 0 deg; this magnitude keeps decreasing with increasing azimuthal angle. Second, there is substantial reduction in EPNL at the static condition, especially below the longer lip of the beveled nozzle; this trend is suggested in the spectral comparisons shown in Figs. 9 and 10. As the flight Mach number is increased, the reductions in EPNL become more modest at all azimuthal angles. Figure 17 shows a comparable plot for bevel24. There are striking differences from Fig. 16. The most important observation is that there is no drastic erosion of the reduction in EPNL as the flight Mach number is increased. For instance, at an azimuthal angle of 0 deg, whereas there is a decrease in the effectiveness of bevel45 of 3.8 EPNdB when the flight Mach number is increased from 0.0 to

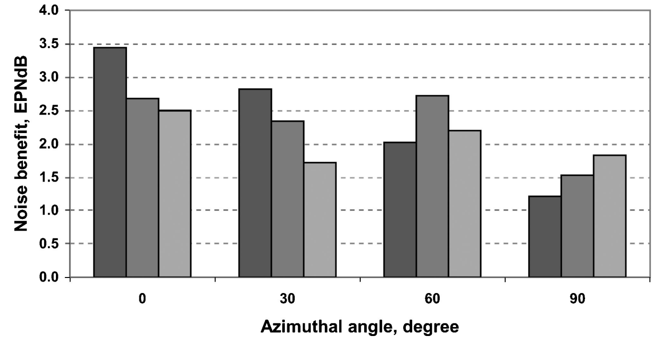

Fig. 17 Reduction in EPNL relative to round primary for bevel24 at various azimuthal angles: NPRp = 1.96, $T_p/T_a = 2.46$, and NPRs = 1.8; vertical lines, $M_t = 0.0$; blank, $M_t = 0.20$; and slanted lines, $M_t = 0.32$.

0.32, this degradation is only 0.9 EPNdB for bevel24. Further more the effect of the flight stream is asymmetric: Higher reductions in EPNL are observed at an azimuthal angle of 90 deg with an increase in flight Mach number for bevel24. The reasons for these trends are not well understood.

Figure 18 shows the cumulative reduction in EPNL at takeoff (sideline plus cutback), as a function of flight Mach number. At the static condition, the bevel45 yields a tremendous reduction of 10.5 EPNdB, which drops to 2.51 EPNdB at a flight mach number of 0.32. The performance of both beveled nozzles is comparable at a flight Mach number of 0.20. However, at the higher flight Mach number of 0.32, the bevel24 yields a reduction of 4.2 EPNdB. To allay any concerns about the extrapolation of data with a scale factor of 10.0 leading to erroneous EPNL benefits, it has been verified that comparable EPNL reductions are obtained with a scale factor of 8.0, as mentioned earlier. The reason for this becomes clear when we examine the spectra at engine scale in Fig. 14. Even at a lower polar angle of 60 deg, the spectral level at a frequency of 8000 Hz is ~30 dB below the spectral peak. In the peak radiation sector, the spectral levels at the higher frequencies are over 40 dB below the peak. Given these trends, it is not surprising that the noise benefit in EPNL is virtually unchanged.

At a lower engine power, the benefit in EPNL due to the beveled nozzles is somewhat lower, as expected from the spectral comparisons seen earlier. Figure 19 shows the performance of bevel24 at engine conditions of NPRp = 1.8, $T_p/T_a = 2.37$, and NPRs = 1.8. The trends are similar to those seen in Fig. 17 at a slightly higher power setting. The cumulative noise reduction for both the nozzles for these engine conditions are shown in Fig. 20. Even though the reduction in EPNL due to bevel24 is lower at the static condition, at a realistic flight Mach number of ~0.26, the bevel24 provides a sizeable noise reduction. Recall that these EPNL values are only for the jet component; when the contributions of the noise from the turbomachinery sources such as the fan, turbine, combustor, etc., are considered, these values would change depending on the turbofan engine.

It is appropriate to discuss another technical point now. It is frequently claimed that one would not observe the benefit of a noise reduction concept (such as mixing enhancement devices) without a flight stream, as in a static test of an engine. As seen here, the opposite could be true; that is, the benefit of a given concept could be overstated drastically in a static test, and, hence, caution must be exercised in evaluating different concepts. Flight tests are expensive; it is highly unlikely that one would observe major noise reductions in flight if a concept is not proven to work even under static conditions.

Finally, there are two additional pertinent issues to be addressed. The first one pertains to the change in BPR associated with the smaller effective area for the beveled nozzles. The variation in BPR as a function of NPRs for fixed conditions for the primary stream, NPRp = 1.8, and $T_p/T_a = 2.37$, is shown in Fig. 21 for the three nozzles. Note that the increase in BPR for the bevel24 is roughly constant as a percentage, confirming that the mass flow of the primary stream can be adjusted for thrust through a simple

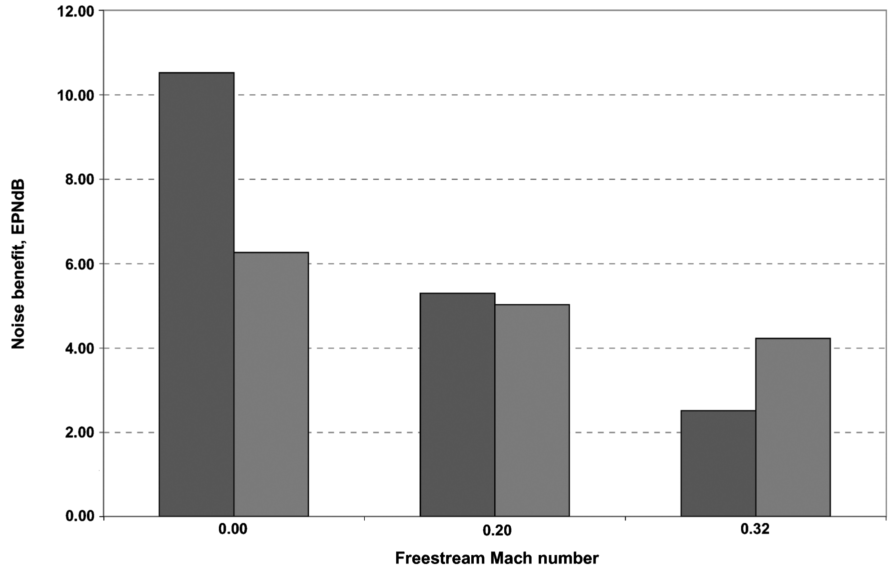

Fig. 18 Cumulative noise reduction at takeoff (sideline and cutback) for the beveled nozzles at different freestream Mach numbers: NPRp = 1.96, $T_p/T_a = 2.46$, and NPRs = 1.8; vertical lines, bevel45; slanted lines, bevel24.

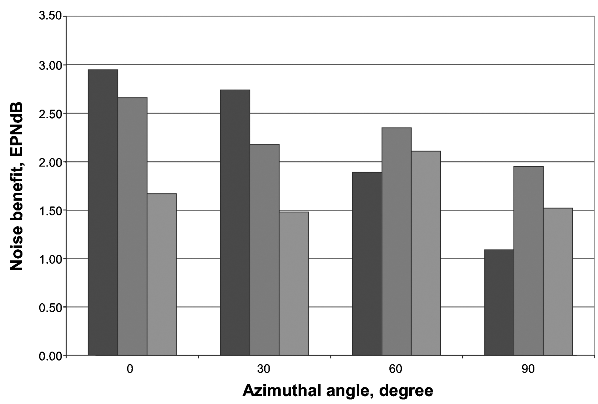

Fig. 19 Reduction in EPNL relative to round primary for bevel24 at various azimuthal angles: NPRp = 1.80, $T_p/T_a = 2.37$, and NPRs = 1.8; vertical lines, $M_t = 0.0$; blank, $M_t = 0.20$; and slanted lines, $M_t = 0.32$.

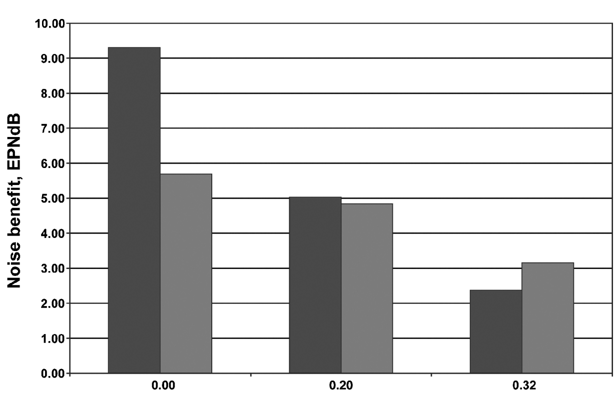

Fig. 20 Cumulative noise reduction at takeoff (sideline and cutback) for beveled nozzles at different freestream Mach numbers: NPRp = 1.8, $T_p/T_a = 2.37$, and NPRs = 1.8; vertical lines, bevel45 and slanted lines, bevel24.

increase in flow area. Of course, it is well known that the increase in BPR is beneficial for noise. This benefit, due to the higher BPR, has been estimated using the prediction method developed by Lu[7] as follows. Noise predictions were first made for the conventional nozzle; then the mass flow rate of the primary nozzle was reduced by ~8% to simulate the lower effective area for the bevel24, and a second set of predictions were made. It was found that the increase in BPR provides an EPNL reduction of ~0.3 EPNdB. Thus, most of the benefit is provided by the current concept of a beveled nozzle, with the benefit due to an increase in BPR being a very small portion of the total noise reduction.

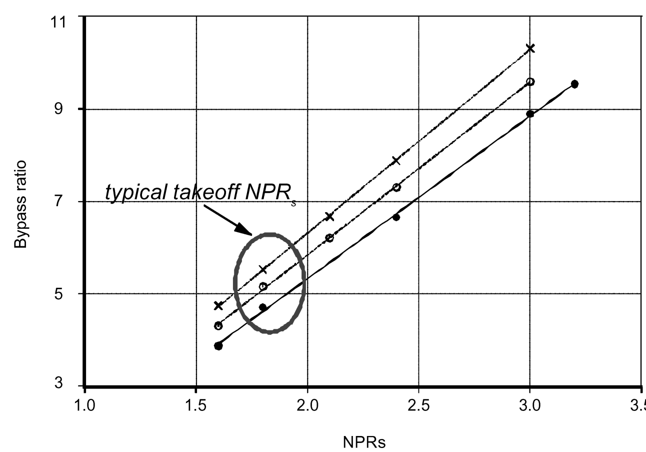

Fig. 21 Variation of BPR with NPRs for fixed NPRp = 1.8 and $T_p/T_a = 2.37$: ●, round; ○, bevel24; and x, bevel45.

Note that the beveled nozzle is in no way connected to the shielding concepts that have been attempted in the last 30 years. According to the advocates of this way of thinking, the fan flow is deflected in the desired direction of noise reduction to form a thickening layer between the hot core stream and the observer. The shielding of the high-speed core stream by the thicker fan stream would presumably provide a noise benefit in the intended direction. Others have suggested that there is asymmetric or preferential mixing when the fan and core streams are at an angle to each other; however, it is not clear what mechanism is supposed to yield noise reduction. It is important to realize that, for a single jet, there is no thickening layer (or any layer for that matter) surrounding the jet. Yet, dramatic reductions in noise have been measured below the longer lip of the beveled nozzle. Therefore, the physics of noise reduction are very different here. The fan stream provides most of the thrust in a high-BPR turbofan engine; any deflection of the fan stream would lead to unacceptable loss of axial thrust. Furthermore, it has been found that the shielding layer is mixed out rapidly when there is a flight stream, thereby failing to maintain a shield and to produce any noise benefit. Given the poor acoustic performance and the potentially higher thrust loss, perhaps it is not surprising that the shielding ideas have not found application.

It has been shown that the bevel24 produces large noise reductions at takeoff and that the degradation in thrust is ≤0.3% at typical takeoff power (Figs. 3 and 4). As already noted, the thrust coefficient at cruise conditions is more important. The variation of thrust coefficient with NPRs for a typical cruise NPRp of 2.4, shown in Fig. 5, indicates that the thrust coefficient of bevel24 is ~0.2% worse than that for the conventional nozzle. As at takeoff power, the performance of bevel45 is a lot worse at cruise. As noted, by tilting the primary nozzle by a small angle downward or by contouring the primary nozzle suitably, the level of thrust degradation for the bevel24 could be mitigated further. Thus, it has been demonstrated that the bevel24 is a viable concept for the reduction of jet noise from practical turbofan engines.

V. Summary

A simple and elegant method for jet noise reduction from dual-stream exhaust nozzles of current-day turbofan engines has been described. Based on our knowledge of the characteristics of the different noise sources in a dual-stream jet, the conventional round primary (or core) nozzle is beveled to achieve noise reduction. To ensure practical relevance, typical nozzle geometries and cycle conditions have been used in this study. The aeroacoustic performance of the beveled primary nozzles has been assessed against a dual-stream nozzle with a simple round primary nozzle. Detailed aeroacoustic measurements have confirmed a total noise benefit of ~4 EPNdB at takeoff.

The effective flow area of the beveled nozzle is lower than the geometric area. A simple resizing of the throat area of the beveled nozzle would provide the correct effective flow area and ensure the proper operation of the engine. The measurement of the nozzle performance with a six-component force balance indicates that the plume deflection due to the beveled nozzle causes a reduction in the axial thrust coefficient. Not surprisingly, the higher the plume deflection (or bevel angle) the greater the thrust loss. However, unlike for a single jet, the loss in thrust efficiency is low because the secondary jet generates ~75% of the total engine thrust in a turbofan engine with a BPR of ~5. The primary nozzle with a bevel angle of 24 deg degrades axial thrust by ~0.25% relative to a round primary nozzle over a wide range of nozzle pressure ratios. It might be possible to reduce this low level of thrust loss further by canting the primary nozzle slightly downward relative to the jet centerline or by contouring the nozzle.

The acoustic benefit of the dual-stream system with a beveled primary nozzle has been evaluated under static conditions as well as in the presence of a flight stream. First, it was shown that the beveled primary introduces some azimuthal variation in the aft directions, even when the two jets are operated at the same jet velocity (pressure balanced and unheated). However, there is a noticeable reduction in levels at an azimuthal angle of 0 deg relative to those at 90 deg at realistic engine cycle conditions. The magnitude of the azimuthal variation is a strong function of the primary jet velocity V_p. The azimuthal trends for the dual-stream nozzle with the beveled primary are similar to those for the single jet in that the velocity of the inner stream plays a significant role in the level of asymmetry in the acoustic field.

The dual-stream system with a beveled primary nozzle has been shown to provide substantial reduction in noise levels relative to a conventional nozzle in the peak radiation directions in the aft quadrant. There is a significant reduction in levels, from ~5 to ~7 dB, near the spectral peak in the angular sector ≥110 deg. There is a slight increase in noise at the lower polar angles. The magnitude of noise reduction is again strongly dependent on V_p. The reduction in levels occurs over a wide frequency range, with no change at the higher frequencies. This trend is expected because the secondary shear layer is responsible for the noise generation at the higher frequencies and because this component has not been modified in any manner. The underlying mechanism for noise reduction for the beveled nozzle is very different from that for a nozzle with chevrons or other mixing enhancement devices: Whereas there is a noise reduction over a wide range of frequencies and no change in levels at the highest frequencies for a beveled nozzle, there is a reduction in level at the lower frequencies accompanied by an increase in levels over a wide range of higher frequencies for a chevron nozzle. Under static conditions (as for a single jet), the nozzle with a bevel angle of 24 deg produces a lower increase in levels at the lower polar angles (forward quadrant and near-normal angles) and a lower reduction in noise at the aft angles than the nozzle with a bevel angle of 45 deg.

The presence of a flight stream introduces significant azimuthal effects to the noise field; the azimuthal variations are very different depending on the bevel angle. The noise benefit due to the beveled nozzles could be drastically reduced when subject to the flight effect. The current results indicate that one could be easily misled in the efficacy of a new concept evaluated only under static conditions. Spectrally, there is no increase in levels at the lower angles for bevel24, whereas there is a noticeable increase for bevel45. The polar angular range over which noise reduction is observed for bevel45 is somewhat reduced; however, bevel45 yields larger noise reductions at aft angles as indicated by an examination of the directivities of perceived noise levels. In terms of the EPNL for the jet component, bevel45 provides ~10 EPNdB total benefit statically at the two certification points at typical takeoff power setting. However, the benefit is only ~2 dB when the flight Mach number is 0.32. Comparable benefits for bevel24 are ~6 EPNdB statically and ~4 EPNdB at a flight Mach number of 0.32. Clearly, bevel24 is preferable because it yields a larger noise reduction and has a lower performance penalty.

In summary, a substantial noise reduction in the aft directions has been demonstrated for a realistic engine geometry and cycle conditions. The strategy adopted here, that of modifying the noise generated by the inner shear layer, is based on the observed characteristics of the noise generation and radiation processes in a dual-stream jet. Recall that no flowfield data, such as the mean quantities and turbulent fluctuations or flow visualizations, have been acquired in the current test. CFD simulations and flow measurements that would shed light on the physical mechanisms responsible for the observed noise reduction are underway. The important issue of the optimum bevel angle is also being investigated; these results will be reported in the future.

Note that no other concept or design has yielded concurrently this level of noise reduction in EPNL with only a small reduction in thrust. Thus, it has been demonstrated that the dual-stream exhaust system with a beveled primary nozzle represents a superior design that is simple, practical, and easy to implement on existing aircraft/engine architectures. It is realized that some modifications to the noise field would occur in a typical under-the-wing engine installation. These effects would be investigated in a future study for specific aircraft geometries. Certain other issues are briefly mentioned here. One pertains to the effect of the forces produced in a plane normal to the thrust axis. If these forces were directed downward, the aircraft would need to be trimmed. It has been estimated that the magnitude of the normal force would be extremely small. This design also offers the flexibility to maximize the noise reduction at a particular azimuthal direction. For example, the bevel could be oriented toward the sideline microphone because it is hardest to reduce noise at this measurement location for most airplanes. Alternatively, another orientation that would reduce the cabin noise might be preferred. A rotatable primary nozzle would provide the ultimate flexibility, albeit with added complexities. When the nozzles on the port and starboard sides are clocked in opposite directions, it would be possible to produce antisymmetric (canceling) side forces that would require no changes to the setting of the aircraft control surfaces.

A beveled primary nozzle for the reduction of jet noise from dual-stream exhaust nozzles has been developed. A cumulative noise reduction of ~4 EPNdB at takeoff (sideline plus cutback) is achieved with a very low thrust penalty of ~0.2% at the cruise conditions for a beveled nozzle with a bevel angle of 24 deg. The jet velocity of the inner stream plays a key role in the reduction of noise in the aft directions. The strategy adopted in the development of this concept was that of modifying the mechanisms of noise radiation. The beveled primary nozzle is ideally suited for high-BPR engines with dual-stream exhaust systems; it permits easy retrofit of existing aircraft at a low cost of manufacture and installation. In addition, the move toward the use of higher BPR favors this concept even more because the thrust loss would be lower. This paper has dealt with turbulent mixing noise. The noise at supercritical pressure ratios is investigated in a companion paper.

Acknowledgments

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