AIAA JOURNAL
Vol. 43, No. 5, May 2005

Nozzle Shaping for Reduction of Jet Noise from Single Jets

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There is a wide body of evidence that suggests that the turbulent mixing noise from high-speed jets consists of two components. These two components are generated by sources/mechanisms associated with the fine-scale turbulence and the large-scale structures of the jet plume. The noise generated by the large-scale structures radiates predominantly to the aft quadrant and typically peaks at angles close to the jet axis. The noise from the fine-scale turbulence is dominant in the forward quadrant and at near-normal angles to the jet axis. The initial objective of this study is to find a means to alter this basic radiation process in a high-speed jet. The ultimate goal of this study, however, is the achievement of noise reduction by accomplishing the preceding objective. A simple concept, a beveled nozzle, is proposed, and detailed aeroacoustic measurements are performed on two nozzles of different bevel angles. Noise measurements, over a wide range of polar angles, are made at several azimuthal angles to map the azimuthal variations. The performances of the beveled nozzles are assessed against a reference round nozzle. The beveled nozzles introduce significant azimuthal variations in the spectra, resulting in major differences in the polar directivities of the overall sound pressure levels at different azimuthal angles; these differences become pronounced when the jet velocity is increased. It is demonstrated that significant noise reduction is achieved in the azimuthal directions below the longer lip of the beveled nozzle, principally in the polar angular range of ~110 to ~140 deg. Furthermore, this reduction is observed at all frequencies, with a low performance penalty of ~1%. The magnitude of the noise reduction is a strong function of the jet velocity, with progressively higher reductions as the jet velocity is increased. With proper orientation of the nozzle, the noise footprint on the ground can be reduced. It is shown that the noise reduction is caused by the modification of the noise generated by the large-scale structures in the jet plume. Thus, noise reduction is achieved through the manipulation of the generation mechanisms.

I. Introduction

THERE is a wide body of evidence that suggests that the turbulent mixing noise from high-speed jets consists of two components. These two components are generated by sources/mechanisms associated with the fine-scale turbulence and the large-scale structures of the jet plume. The noise generated by the large-scale structures radiates predominantly to the aft quadrant and typically peaks at angles close to the jet axis. The noise from the fine-scale turbulence is dominant in the forward quadrant and at near-normal angles to the jet axis. As the jet velocity is increased, there is a broadening of the angular sector in which peak radiation occurs, with more noise being radiated to lower polar angles. (All polar angles are measured from the jet inlet axis, with the jet exhaust axis corresponding to 180 deg.) Seiner and Krejsa,[1] Tam and Chen,[2] and Tam,[3,4] among others, have proposed this view of the sources of jet noise, especially for supersonic jets. The experiments of Seiner et al.[5] established the angular ranges where these two components are clearly dominant. Tam et al.[6] examined a large database of jet noise obtained at the Jet Noise Laboratory at NASA Langley and identified two distinct spectral shapes for the two components of noise; these were termed the fine-scale similarity spectrum (FSS) and large-scale similarity spectrum (LSS). Typically, the spectral shapes correspond to that of the FSS for angles ≤110 deg. Even for the highly heated supersonic jet of Seiner et al.[5] at a Mach number M of 2.0 and a total temperature ratio Tt/Ta of 4.89, the lowest angle at which the LSS shape could be unambiguously identified was ~125 deg. Tam and Chen[2] showed that this highly directional noise in the peak radiation angles is generated directly by the large-scale structures/instability waves of the jet flow. Tam et al.[6] also reasoned that in the intermediate angles of 110–125 deg the contributions from both components would be important. Figure 1 captures the essence of these noise components and their dominant sectors. Also shown in this figure are typical measured spectral shapes and comparisons with the empirical similarity spectra.

A comprehensive study of subsonic unheated and heated jets by Viswanathan[7] indicated that the noise characteristics of these jets are also similar to those of the supersonic jets. Specifically, the spectral shapes at the lower angles fit the fine-scale similarity spectrum for all jet temperatures. Figure 2 shows the directivities of the overall sound pressure levels (OASPL) for six jets of Mach numbers 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0, at a temperature ratio of 3.2. Whereas there is a noise increase of ~10 dB in the peak direction relative to the levels at the forward quadrant for $M = 0.5$, this magnitude jumps to ~20 dB at a Mach number of 1.0. This is because of the increasing importance of the noise from the large-scale structures as the jet Mach number is increased for these highly heated jets. However, given the lower jet velocities relative to supersonic heated jets, the angular range where the LSS component is dominant is confined to a smaller sector closer to the jet axis. A surprising finding of this study is that the spectral shapes at 155 deg and higher angles from unheated jets at as low a Mach number as 0.4 conform to that of the LSS. Though there is no consensus on the reason for this phenomenon at lower Mach numbers, the preceding description encompasses the general view of the mechanisms associated with the generation and radiation of jet noise, especially from simple round jets.

Jet noise continues to be an important component of aircraft noise at takeoff, and significant research and development efforts to reduce jet noise are underway at the aircraft and engine companies as well as at NASA and many universities. These efforts include measurements of turbulence in the jet plume, optical diagnostic studies, improved theoretical models and prediction methods, better descriptions of the noise sources, etc. The objectives of the current study are somewhat different. The questions that we ask ourselves are as follows: 1) Can we somehow modify the basic radiation process in a jet? 2) Will the achievement of this objective lead to jet noise reduction? 3) Is there a way of adapting the findings of this endeavor for practical application to turbofan engines? This

Presented as Paper 2004-2974 at the AIAA/CEAS 10th Aeroacoustics Conference, Manchester, England, United Kingdom, 10–12 May 2004; received 7 June 2004; revision received 11 October 2004; accepted for publication 30 November 2004.

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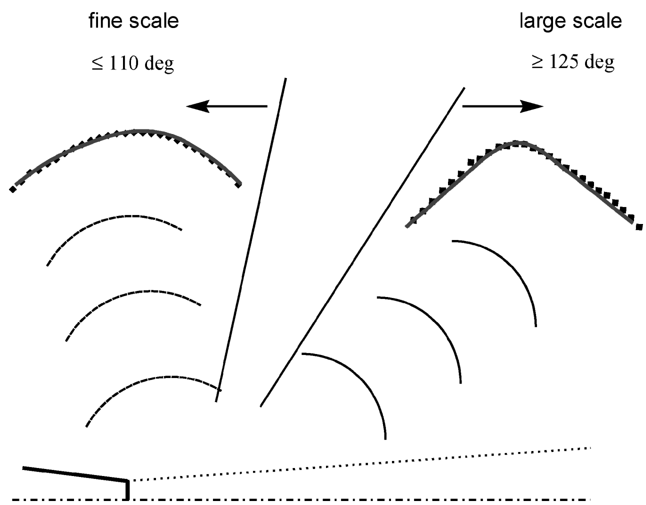

Fig. 1 Conceptual sketch of the noise generation mechanisms in a jet: symbols, measured spectra and ——, similarity spectra.

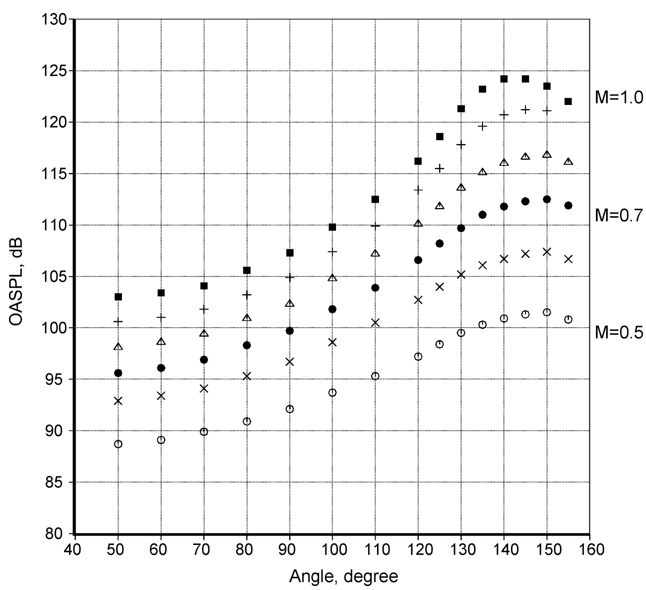

Fig. 2 Measured overall directivity of jet noise: $Tt/Ta = 3.2$; ○, $M = 0.5$; ×, $M = 0.6$; ●, $M = 0.7$; △, $M = 0.8$; +, $M = 0.9$; and ■, $M = 1.0$.

paper addresses the first two questions, whereas a companion paper (see Viswanathan[8]) deals with question three. A simple concept is first proposed, followed by a brief description of the experimental program. Salient results are then presented and the physics of the observed noise characteristics investigated. It is demonstrated that the first two objectives are clearly met with the proposed concept.

II. Concept Description and Test Details

In the past, jet noise reductions were sought through modifications to the nozzle shape; this objective almost always involved complicated shapes. Nozzles that consisted of multitubes, multilobes, corrugations, etc., were studied extensively. The magnitude of noise reduction achievable with these devices usually correlates directly with the level of complexity. However, the higher the complexity, the greater the penalties as a result of thrust degradation, weight increase, and issues with manufacturability, which render these concepts unsuitable for aircraft application. Therefore, we seek a simple and practical concept in the quest to achieve the objectives of this study. This philosophy led to the concept of a beveled nozzle, illustrated in Fig. 3. The measurement conventions for the bevel as well as the azimuthal angles are also shown. The rationale for this geometry is stated here at the outset and then is verified experimentally.

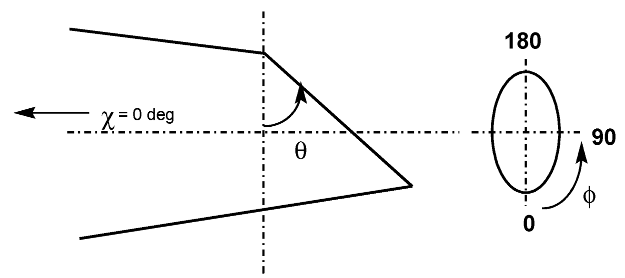

Fig. 3 Conceptual sketch of the beveled nozzle and the measurement convention for the polar angle χ, bevel angle θ, and azimuthal angle ϕ.

As noted, Viswanathan[7] provided experimental evidence that the spectral shapes from unheated jets at even a very low Mach of 0.4 at angles close to the jet axis conformed to the LSS shape extracted from heated supersonic spectra by Tam et al.[6] Further, it was hypothesized in Ref. 7 that the rapid decay of the instability waves through a nonlinear process downstream of the potential core, with severe enough modulation of the amplitude of the instability waves, could generate low-wave-number components with supersonic phase speeds relative to the ambient speed of sound. This radiation process, of course, would be weak at low jet velocity Vj/a, where a is the ambient speed of sound. Implicit in this hypothesis is the supposition that the noise from large-scale structures could be important even at lower Mach numbers. This belief, in fact, led to the current concept of a beveled nozzle for the alteration of the noise generated by the large-scale structures in the jet plume. For the sake of what is to follow, it is emphasized that even for a Mach 2.0 jet at an extremely high jet temperature ($Vj/a \sim 2.5$), the FSS is dominant at angles ≤ 110 deg, and the LSS is dominant at angles ≥ 125 deg.

The aeroacoustic characteristics of two such nozzles of bevel angles 45 and 24 deg have been evaluated experimentally, over a wide range of jet Mach numbers M and total temperature ratio Tt/Ta. These characteristics are compared against those of a round nozzle. The experiments were performed in the Low Speed Aeroacoustic Facility at Boeing, with simultaneous measurement of thrust and noise. Detailed descriptions of the test facility, the jet simulator, the data acquisition and reduction process, etc., can be found in Viswanathan.[9] The jet simulator is embedded in an open-jet wind tunnel, which can provide a maximum freestream Mach number of 0.32. Bruel and Kjaer Type 4939 microphones (newer type that replaced Type 4135) 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. Because we anticipate significant azimuthal variation, two microphone arrays 30 deg apart in the azimuthal direction are employed. The microphones in each array are laid out at a constant sideline distance of 15 ft (4.572 m) from the jet axis. All angles are measured from the jet inlet axis, with a polar angular range of 50–150 deg. Given the large distance to the microphones, the discrepancy in polar angle between the top and bottom of the beveled nozzle is negligible. Narrowband data with a bandwidth of 23.4 Hz are acquired and synthesized to produce 1/3-octave spectra, up to a center band frequency of 80,000 Hz. For comparisons at model scale, the data are corrected to a common distance of 20 ft (6.096 m) from the center of the nozzle exit (coordinate system with origin at the center of the nozzle exit) and 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.[10]

No flowfield surveys or visualizations were performed. However, several video cameras were installed in the anechoic chamber. The pictures indicated that the plume is deflected toward the shorter side of the beveled nozzle, with the deflection angle being more pronounced for the nozzle with a bevel angle of 45 deg, especially at higher nozzle pressure ratios. Thus, the thrust axes for these nozzles do not coincide with the geometric centerline of the nozzle, and additional forces are produced in the normal directions in the cross-sectional plane, as discussed in the next section.

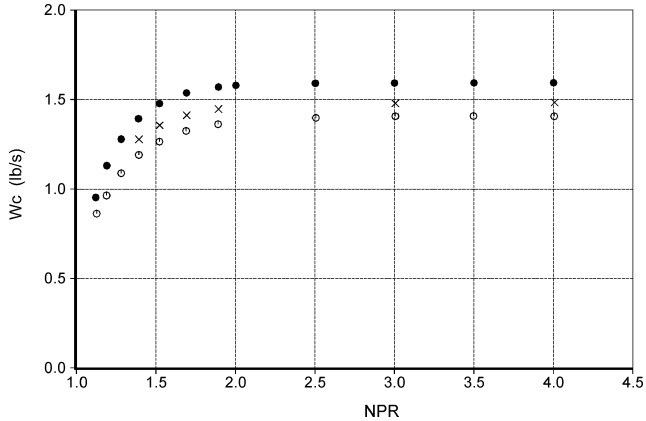

Fig. 4 Variation of the corrected mass flow rates with NPR: ●, round nozzle; ×, bevel24; and ○, bevel45.

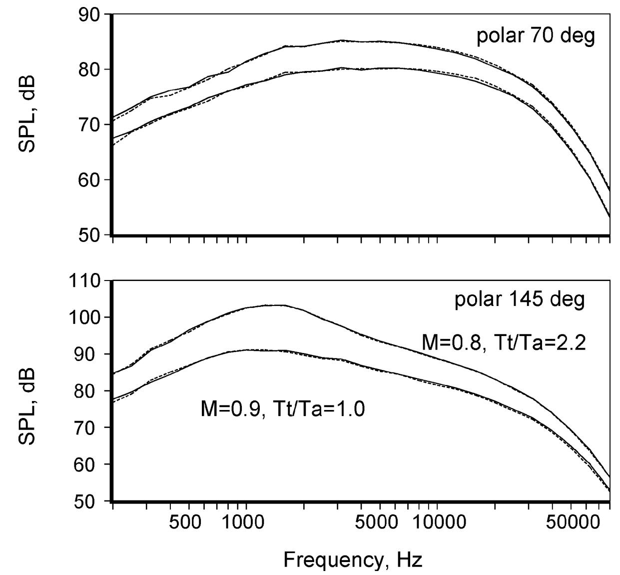

Fig. 5 Comparison of spectra at two azimuthal angles from an unheated and heated round jet: ——, azi = 90 deg and – – –, 60 deg.

III. Aerodynamic Performance

It is not clear what value of the exit area characterizes a beveled nozzle shown in Fig. 3. For the sake of convenience, the exit areas along the exit plane (slanted) of the nozzle are reported here. Every effort was made in the design of the nozzle to match the equivalent diameter D_e of the beveled nozzle to that of the reference round nozzle of 2.45-in. (6.223-cm) diam. The corresponding D_e for the two beveled nozzles of 45 and 24 deg (hereafter referred to as bevel45 and bevel24) are 2.526 in. (6.416 cm) and 2.412 in. (6.127 cm), respectively. Thus, the first nozzle has a geometric area that is 6.3% larger, while the second one is smaller by 3.1%. As it turns out, the geometric area is not the effective flow area. Figure 4 shows the corrected mass flow rates as a function of the nozzle pressure ratio (NPR) for the three nozzles. The corrected mass flow rates are calculated as per the usual definition at standard day conditions of T_{std} and p_{std} as

$$W_c = \frac{W_{\text{actual}} * \sqrt{T_t/T_{\text{std}}}}{p_t/p_{\text{std}}}$$

The mass flow rates for the beveled nozzles are lower than that for the round nozzle by ~8% for bevel24 and ~13% for bevel45 for all nozzle pressure ratios. Figure 3 indicates that the flow would actually reach the nozzle exit sooner at the top than at the bottom, thus establishing a more complex flowfield. This phenomenon could explain the drop in the flow rates for the beveled nozzles, with the more severe bevel angle producing a greater reduction.

It was noted earlier that because of plume deflection the thrust axes for the beveled nozzles do not coincide with the geometric centerline of the nozzle and additional forces are produced in the normal directions in the cross-sectional plane. In general, two factors are responsible for the reduction of the axial thrust coefficient: the plume deflection and the loss in propulsive efficiency caused by the geometry itself. The forces in the three coordinate directions are measured with a six-component force balance incorporated with the jet simulator. From the force vectors, the deflection angle can be calculated. These measurements indicate that the deflection angle is more or less constant for a fixed bevel angle when the NPR is subcritical, with an estimated value of ~10 deg for bevel45 and ~7 deg for bevel24. At subsonic jet Mach numbers, the thrust loss relative to a round nozzle is <1% for bevl24 and <1.8% for bevel45. The inclination of the thrust vector accounts for a sizable portion of the reduction in axial thrust. The loss of propulsive efficiency as a result of the change in exit geometry is deemed to be low. The implications of the reduction in discharge coefficient and the propulsive efficiency of the beveled nozzles are discussed in detail in Ref. 8.

IV. Acoustics

The noise characteristics of the beveled nozzles are now presented. It is clear that in comparing the noise levels of the beveled nozzles with those of the round nozzle there is a small effect as a result of the reduced effective flow areas. Because of the lower flow areas, the sound pressure levels would be lower by 0.33 and 0.53 dB for the bevel24 and bevel45, respectively. In the following, these discrepancies are neglected because of the small magnitudes. Further, the small change in Strouhal number caused by different nozzle diameters is also ignored, as it does not alter the main results. First of all, it is shown that there is no azimuthal variation in the radiated field for a round nozzle. Figure 5 shows spectral comparisons at the two azimuthal angles at two polar angles of 70 and 145 deg for an unheated jet with $M = 0.9$ and an 0.8 jet at a temperature ratio of 2.2. There is excellent agreement between the two sets of spectra at all frequencies; there is similar agreement at other polar angles as well. Thus, any azimuthal variation observed for the beveled nozzles is caused by geometric modifications and not because of any inherent differences in the measurements.

A. Azimuthal Directivity

First we examine the azimuthal directivity of the beveled nozzle as a function of jet velocity, before presenting noise reduction relative to the reference round nozzle in Sec. IV.B. Repeat measurements, in which the orientation of the beveled nozzles was changed, permitted the mapping of the azimuthal content of the radiated acoustic field. Typically, data were acquired at two orientations so as to quantify the field at azimuthal angles of 0, 30, 60, and 90 deg. Note that there is only one axis of symmetry, the plane through the major axis in Fig. 3, for the beveled nozzle. For the bevel45, data were also acquired at azimuthal angles of 150 and 180 deg, thereby acquiring data at six angles on one side of the symmetry plane. Figure 6 shows spectral comparisons at three azimuthal angles of 0, 30, and 90 deg from an unheated $M = 0.9$ jet for bevel45. It is immediately apparent that there is some azimuthal directivity, with the spectral levels being the lowest at 0 deg and a progressive increase with increasing azimuthal angle at all polar angles. The spectra at an azimuthal angle of 60 deg are typically higher than at 30 deg and lower than at 90 deg. Figure 7 shows a comparable plot at a temperature ratio of 3.2. There are dramatic differences when the jet is heated at the same Mach number of 0.9. There is a modest reduction of ~2 to 3 dB (relative to the levels at an azimuthal angle of 90 deg) at the higher frequencies at an azimuthal angle of 0 deg in the forward quadrant (polar angle of 70 deg). However, as we move aft, the azimuthal directivity is more pronounced. At 130 deg, there is a noise reduction of ~7 dB near the spectral peak and a slightly lower reduction at the higher frequencies. As we move further aft, there is less noise reduction at the lower frequencies while the larger reduction at the higher frequencies is still maintained. Similar trends are observed at other Mach numbers and temperature ratios. The magnitude of the azimuthal directivity

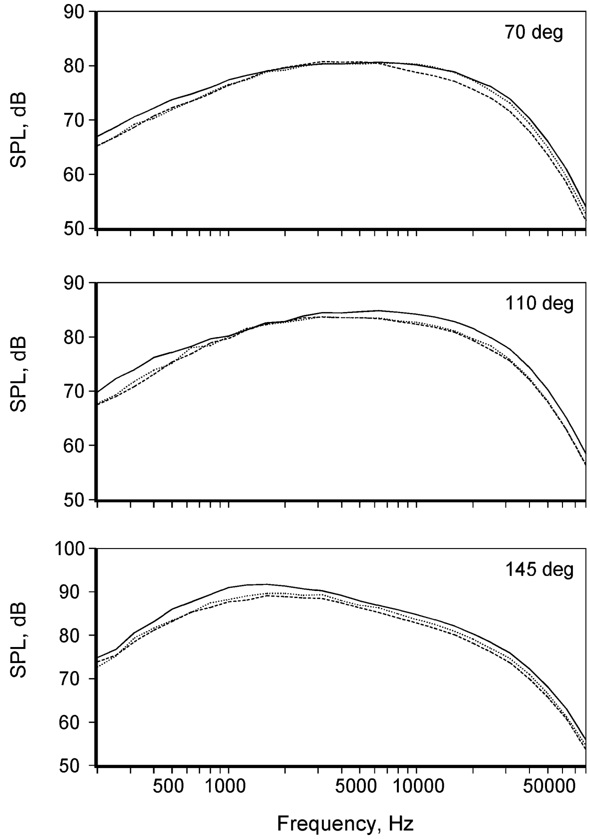

Fig. 6 Azimuthal directivity of bevel45: $M = 0.9$; $Tt/Ta = 1.0$; ——, azi = 90 deg; . . . ., 30 deg; and – – –, 0 deg.

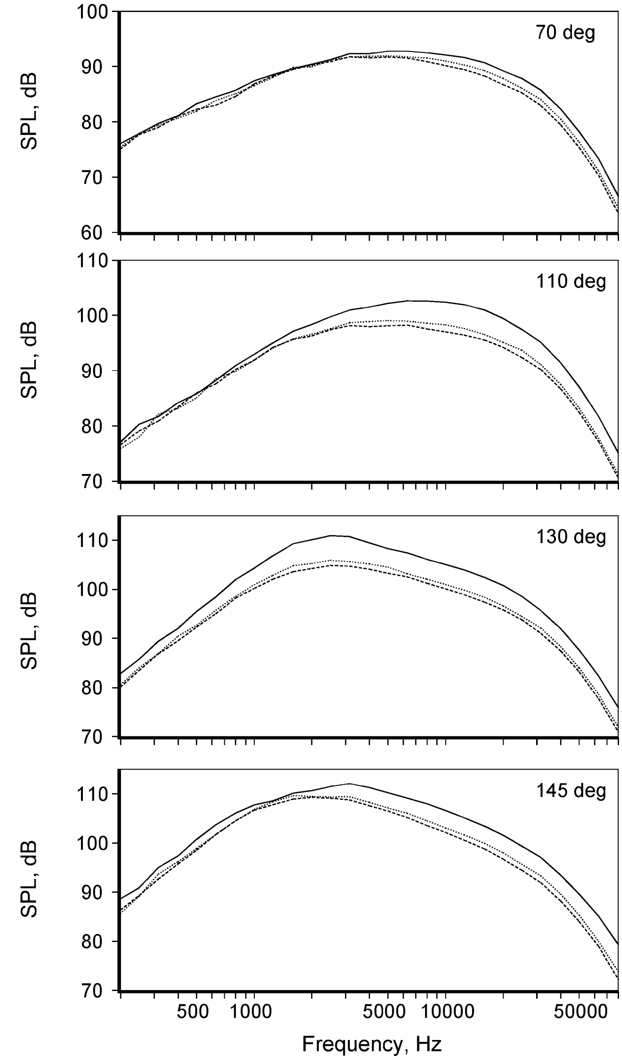

Fig. 7 Azimuthal directivity of bevel45: $M = 0.9$; $Tt/Ta = 3.2$; ——, azi = 90 deg; . . . ., 30 deg; and – – –, 0 deg.

depends strongly on the velocity ratio Vj/a. At low Mach numbers from unheated jets, the magnitude of reduction in sound pressure level at an azimuthal angle of 0 deg, relative to 90 deg, is quite small, whereas it is the largest at higher Mach numbers from highly heated jets. Regardless, the levels are always lower at 0 deg across the spectra.

What happens at 180 deg? The spectra at the azimuthal angles of 0 and 180 deg from an $M = 0.9$ unheated jet are shown in Fig. 8. The Mach number of 0.9 is chosen to facilitate comparison between the many spectral plots presented here; however, it is noted that similar trends are observed at other Mach numbers, with the jet velocity playing an important role in the magnitude of the observed trends. Though the levels at 0 deg are lower at all frequencies at the lower angles, the difference at the higher frequencies decreases gradually as we move aft, to zero at 110 deg and is substantially higher, by ~7 dB, at 145 deg. At the same Mach number of 0.9 and at a higher temperature ratio of 3.2, the noise picture is different in Fig. 9. At the lower angle, there is a modest reduction of ~3 dB below the longer lip. In the midangular range of 110–130 deg, there is a substantial difference in peak noise of ~8 dB. At larger aft angles, more noise is radiated below the longer lip at the higher frequencies. When we increase the Mach number to 1.0 at the same temperature ratio, the preceding trends are more exaggerated. Possible explanations of these characteristics are explored in Sec. IV.C.

The polar directivity of the overall levels (OASPL) at three azimuthal angles of 0, 90, and 180 deg are shown in Fig. 10 at a Mach number of 1.0, with temperature ratios of 1.0 and 3.2. This figure displays the characteristic features of the azimuthal directivity and its dependence on (Vj/a). At lower Vj/a, the magnitude of the azimuthal variation is not very pronounced at lower angles. There is an angular sector, ~110 to ~140 deg, where the azimuthal effects are most pronounced. However, at the higher Vj/a, there is substantial azimuthal variation. At large polar angles there is less noise radiated at an azimuthal angle of 180 deg. The reduction in level at an azimuthal angle of 0 deg is ~7 dB relative to that at 90 deg at the midangles; further, the polar angular sector over which this reduction occurs expands as (Vj/a) is increased. The reasons for the observed trends are explained in a later section.

B. Noise Reduction of Beveled Nozzles

Next we examine the acoustic performance of the beveled nozzle relative to a round nozzle. For practical applications, the beveled nozzle would be oriented with the longer lip at the bottom-dead-center position as shown in Fig. 3. The importance of certain azimuthal angles for aircraft noise certification is first highlighted in Fig. 11, which shows the noise measurement locations and typical flight profiles for takeoff and approach. Note that two of the locations, at approach and flyover conditions, are directly under the flight path, while the third one is laterally displaced by 1476 ft (450 m) from the center of the runway. The sideline (or lateral) noise level is taken to be the maximum level that occurs anywhere along a line at that lateral distance. An examination of the certification database of all aircraft, with two or four engines and at any takeoff gross weight (and corresponding thrust setting for the engines), indicates that the altitude of the airplane that corresponds to peak sideline noise lies within a narrow range of (~1000 ± 50) ft. That is, regardless of the airplane type and weight, the azimuthal angle for the sideline measurement point is ~34 deg, which is pictorially depicted in Fig. 11. The choice of the second azimuthal microphone array (30 deg from the first one) was dictated by the preceding consideration. Therefore, comparisons are shown at azimuthal angles of 0 and 30 deg, corresponding to the two certification points at takeoff.

Figure 12 shows spectral comparisons at several polar angles for an $M = 0.7$ unheated jet at an azimuthal angle of 0 deg. The solid

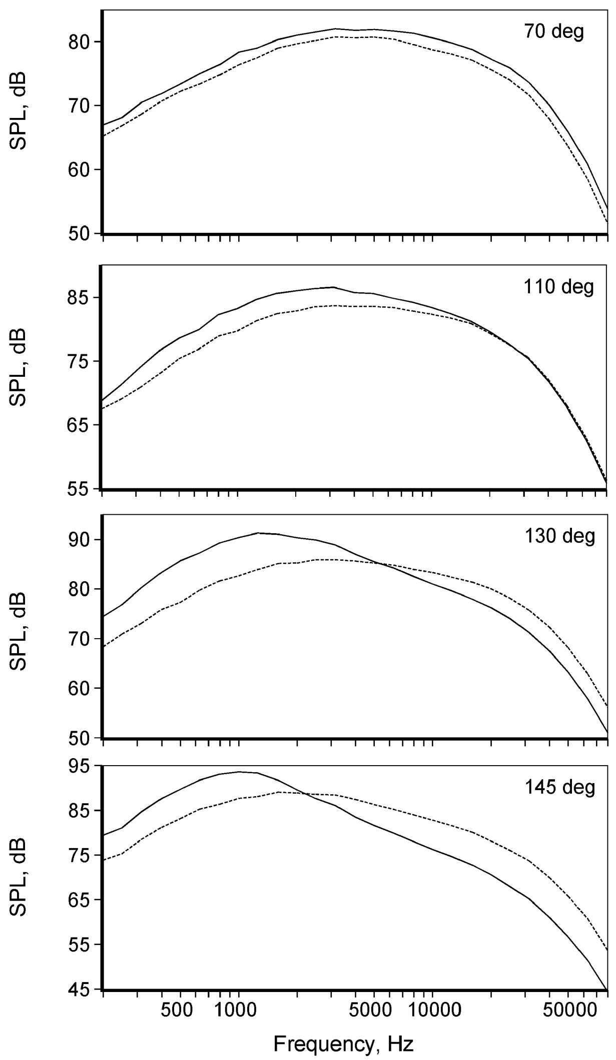

Fig. 8 Azimuthal directivity of bevel45: $M = 0.9$; $Tt/Ta = 1.0$; ——, azi = 180 deg and – – –, 0 deg.

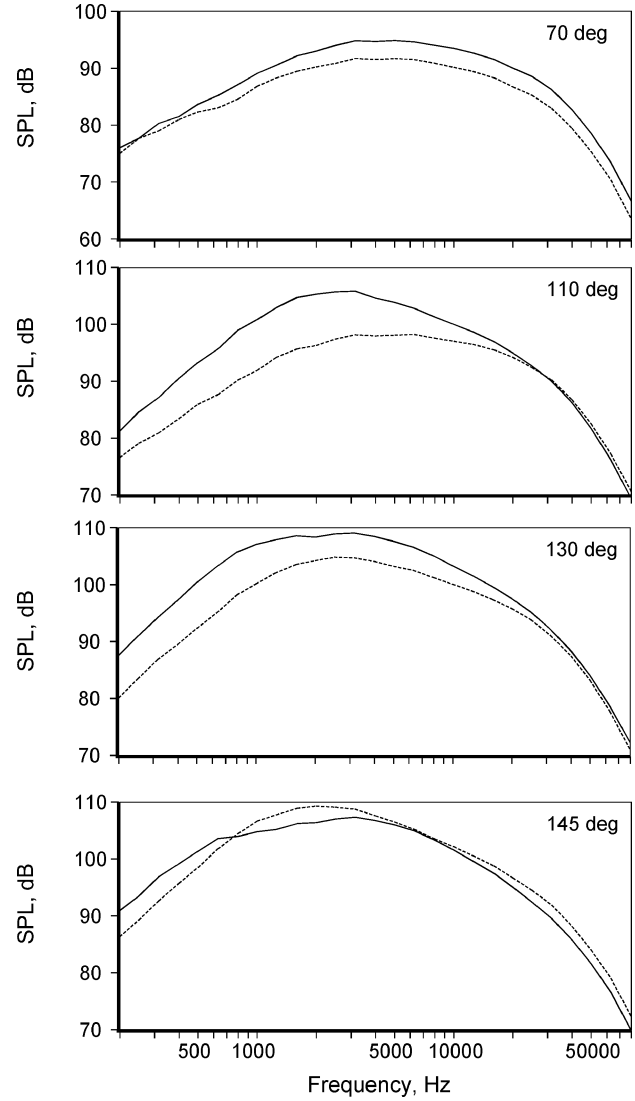

Fig. 9 Azimuthal directivity of bevel45: $M = 0.9$; $Tt/Ta = 3.2$; ——, azi = 180 deg and – – –, 0 deg.

line represents the round nozzle, while the dashed lines the two beveled nozzles. At the lower angles, there is a reduction of ∼2 dB across the spectrum, and the magnitude of the noise reduction is larger for the bevel45. At the aft angles, there is a slightly larger noise reduction at the lower frequencies with no appreciable benefit at the higher frequencies. Figure 13 shows a similar plot for an $M = 1.0$ jet with a temperature ratio of 2.2. Again, there is a noise reduction at all of the frequencies at the lower angles; however, the magnitudes are larger than those for the cold jet at lower (Vj/a). At the aft angles, there is a substantial reduction of ∼5 to ∼7 dB near the spectral peak and the lower frequencies, with only a slight reduction at the higher frequencies. Let us examine what happens when the jet temperature ratio is further increased to 3.2, in Fig. 14. There is no appreciable change in levels at the forward quadrant. There is a substantial reduction of ∼5 dB across the spectrum at the aft angles where the jet noise peaks. A comparable plot at an azimuthal angle of 30 deg is shown in Fig. 15. There is a slight noise increase of <1 dB at certain frequencies at the lower angles. In the peak sector of noise radiation, there is a large noise benefit for the beveled nozzles. Figures 12–15 also indicate that more noise reduction is achieved with bevel45 than with bevel24. Figure 16 shows a polar directivity of OASPL for the round and bevel45 nozzles at an azimuthal angle of 0 deg. As seen, there is a noise reduction at the aft angles for the two Mach numbers shown. At the higher (Vj/a), the magnitude of noise reduction is more pronounced.

In summary, the beveled nozzles yield substantial noise benefits over a round nozzle over a certain range of azimuthal angles. As

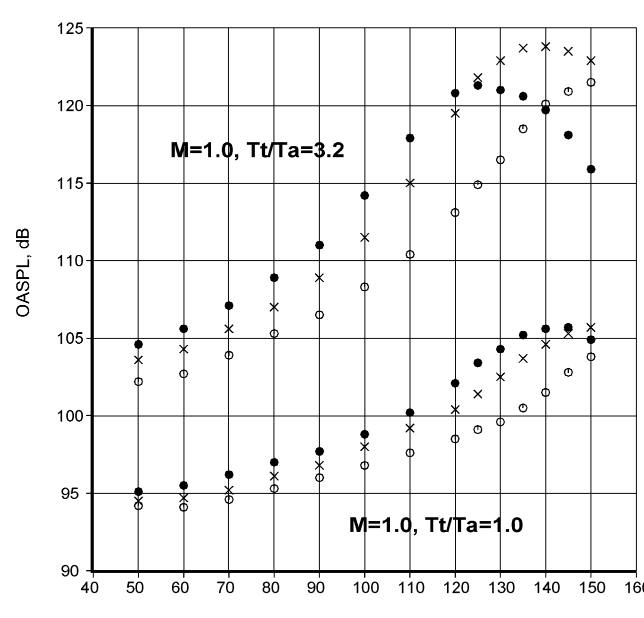

Fig. 10 Polar directivity of OASPL: $M = 1.0$; $Tt/Ta = 1.0$ and 3.2; ●, azi = 180 deg; ×, 90 deg; and ○, 0 deg.

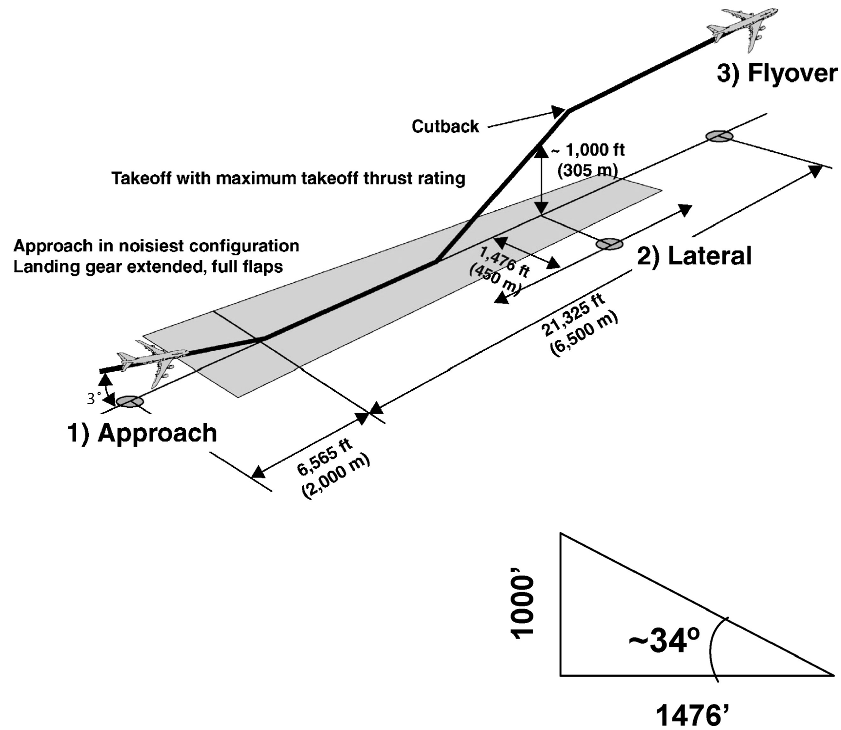

Fig. 11 Noise measurement locations (1–3) for aircraft certification.

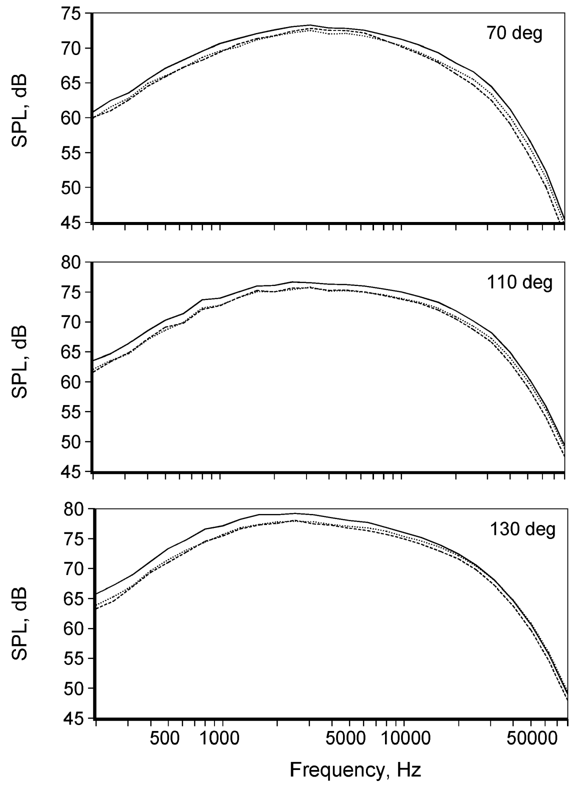

Fig. 12 Noise reduction of the beveled nozzle: $M = 0.7$; $Tt/Ta = 1.0$; azimuthal angle = 0 deg; ——, round nozzle; – – –, bevel45; and . . . ., bevel24.

with the azimuthal directivity, the jet velocity (Vj/a) plays an important role in the magnitude of noise reduction achievable with the beveled nozzle. The question that remains to be answered is whether a beveled nozzle produces less overall power (OAPWL) than a round nozzle. Because noise measurements were made at six azimuthal angles for the beveled nozzle, we have the opportunity to assess the azimuthal directivity of power level as well. For every orientation of the beveled nozzle, the power level is calculated over an azimuthal angular sector of 30 deg; though a proper definition of power level requires integration over all the azimuthal angles, the preceding quantity provides a useful cumulative measure of the noise radiated to different azimuthal directions. For lack of a better terminology, this quantity is referred to as a sector power level. No information is available at the azimuthal angle of 120 deg. The acoustic power is quoted in decibels relative to 10^{-12} W.

The comparison of OAPWL requires consideration of one more factor. The mass flow rate for the bevel45 is ~13% less than that for the round nozzle. To facilitate comparison at constant thrust, the factor [10*log (A)] is subtracted with the appropriate nozzle flow areas. Thus, the power levels are quoted for unit flow area, and no unwarranted noise benefit would be claimed for the beveled nozzle. Figure 17a shows the azimuthal variation of sector power level for an $M = 1.0$ jet at a temperature ratio of 3.2. The dashed horizontal line represents the power for the round nozzle. As seen in the spectral plots, the power level is the lowest at the azimuthal angle of 0 deg, with a reduction of ~4 dB relative to the round nozzle. Also, there is a strong azimuthal variation of power. However, the overall power levels for the round and bevel45 nozzles are 154.96 and 153.84 dB, yielding a noise reduction of ~1.1 dB. The change in OAPWL at lower jet velocities is even lower; these changes do not constitute a significant difference when we consider the slight experimental variability. Therefore, it is fair to say that the beveled nozzles do not reduce the overall power radiated (or only slightly so); rather, there is an uneven distribution of power in the azimuthal plane, and we exploit this feature to achieve noise reduction at desired azimuthal angles.

It is recognized that there is some ambiguity in the comparisons of spectra because the polar angles are slightly different for the beveled nozzles at different azimuthal angles. However, any uncertainty is eliminated when the noise benefit is quantified in terms of integral quantities such as the sector power level and the effective perceived noise level (EPNL). For flyover noise measurements for aircraft certification, the noise metric of interest is the EPNL. In Fig. 17b, the variation of the perceived noise level (PNL) with time is shown. This is the typical noise measurement in a flight test. The EPNL is computed from the PNL variation; it accounts for the maximum PNL level as well as the duration effect, which is defined as the time period over which there is a 10-dB reduction from the peak PNL level. The timescale on the x axis is somewhat arbitrary

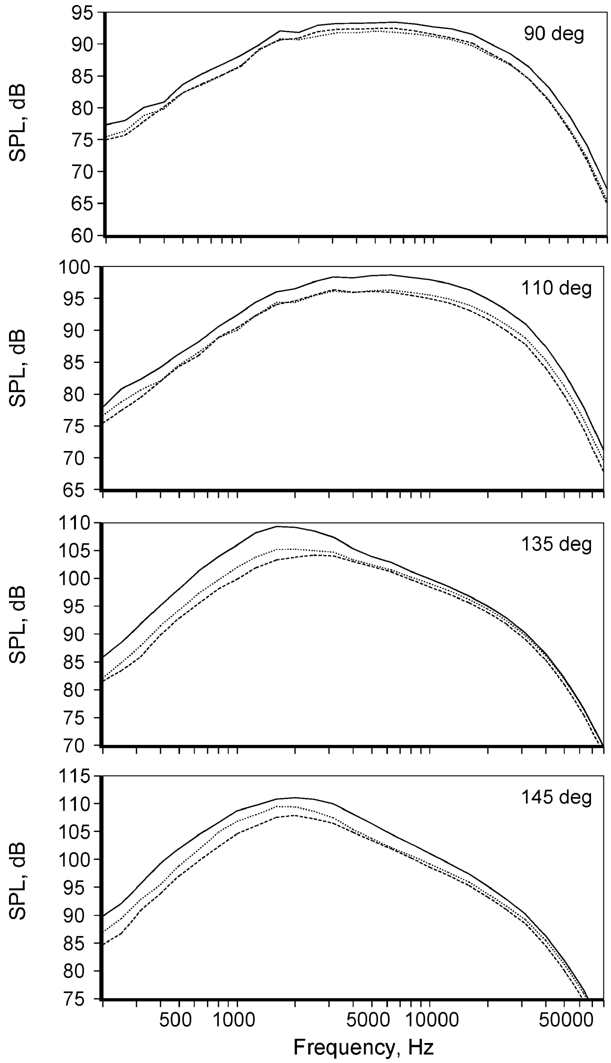

Fig. 13 Noise reduction of the beveled nozzle: *M* = 1.0; *Tt*/*Ta* = 2.2; azimuthal angle = 0 deg; ——, round nozzle; – – –, bevel45; and . . . ., bevel24.

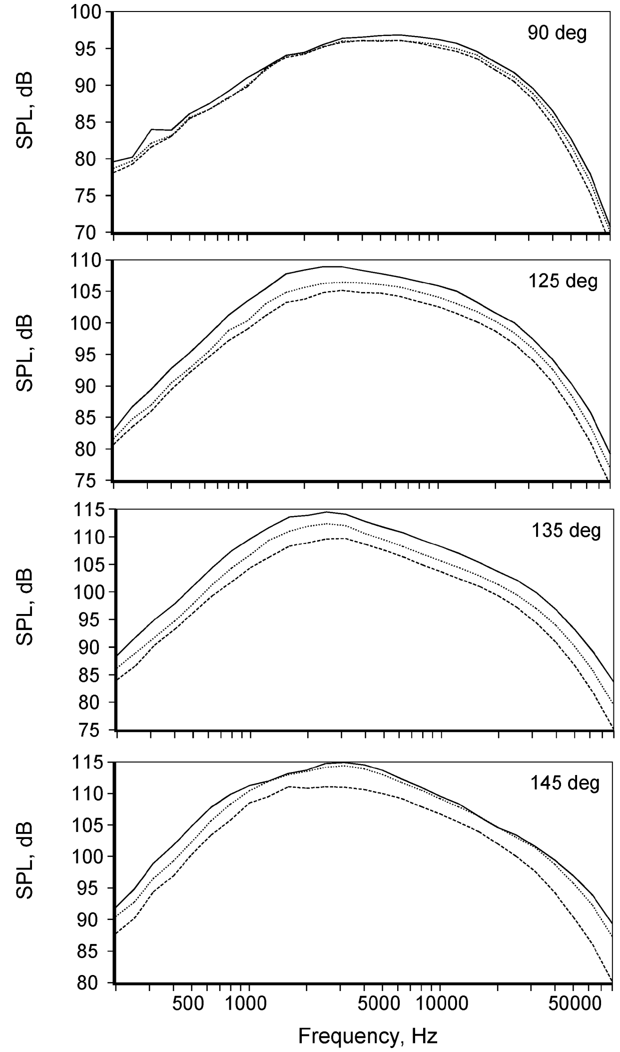

Fig. 14 Noise reduction of the beveled nozzle: *M* = 1.0; *Tt*/*Ta* = 3.2; azimuthal angle = 0 deg; ——, round nozzle; – – –, bevel45; and . . . ., bevel24.

because the shape of the PNL variation alone determines the EPNL level. That is, the timescale has no great significance, and sliding the curves to the left or right would result in the same EPNL. In Fig. 17b, the PNL variations are shown for the round nozzle and the bevel45 at an azimuthal angle of 0 deg; the jet conditions are $M = 1.0$ and $Tt/Ta = 3.2$. The model-scale data have been extrapolated to engine scale with a linear scale factor of 10.0 and corrected for constant thrust. Clearly, the peak PNL for the beveled nozzle is ~5 PNdB lower than that for the round nozzle, yielding a noise benefit in EPNL of 3.5 EPNdB.

In Fig. 17a, there is a reduction in power level of ~4 dB for the beveled nozzle; in Fig. 17b, there is a reduction of 3.5 EPNdB for the same test case at an azimuthal angle of 0 deg. Therefore, it has been clearly demonstrated that there is a significant noise benefit for the beveled nozzle. It is emphasized that these two results remove the effects of the plume deflection on the calculated noise benefit and therefore allay any doubts about the efficacy of the beveled nozzle.

C. Noise Generation Mechanisms of Beveled Nozzles

A detailed spectral analysis is carried out to uncover the reasons for the observed noise reduction, especially in the polar angular range of ~110 to ~145 deg. Figures 18a–18d show measured spectra in the polar angular range of 90–150 deg, from a heated jet at a Mach number of 1.0 and temperature ratio 3.2. The four plots correspond to the round nozzle and the bevel45 at azimuthal angles of 0, 90, and 180 deg, respectively. Also presented in these figures are comparisons of the data with the FSS or LSS empirical spectra. For the round nozzle (Fig. 18a), there is excellent agreement between the measured spectra and the FSS at all the angles from 90 to ~120 deg. As we move aft, the spectral shape begins to change and gets peakier. Presumably, the contribution from the large-scale structures becomes important, and there is good match between the data and the LSS at a polar angle of 150 deg. Note that the data in the intermediate angular range of ~125 to ~140 deg cannot be characterized by either of the empirical spectrum by itself.

For the bevel45 at an azimuthal angle of 0 deg (Fig. 18b), the measured spectra start deviating from the FSS at a lower polar angle of ~120 deg, and a LSS shape is observed at a polar angle of 130 deg. As we go around the periphery of the beveled nozzle to an azimuthal angle of 90 deg, we notice that the LSS shape is seen for the spectra at a polar angle of 125 deg and higher. At an azimuthal angle of 180 deg, the spectral characteristics are dramatically different from that for the round nozzle. Even at 90 deg there is a slight hump near the peak; at 100 deg this hump is more pronounced, and there is major deviation from the FSS shape. The most surprising feature is the observation of the LSS shape for the measured spectra at a polar angle of 110 deg.

We next show similar behavior for an unheated jet with a Mach number of 1.0 in Fig. 19. As before, spectra at different polar angles are compared with either the FSS or the LSS for the round nozzle and bevel45 at an azimuthal angle of 180 deg. For the round nozzle, the FSS shape is maintained until a polar angle of 130 deg, and the LSS shape is reached at an angle of 150 deg and higher. (Contrast

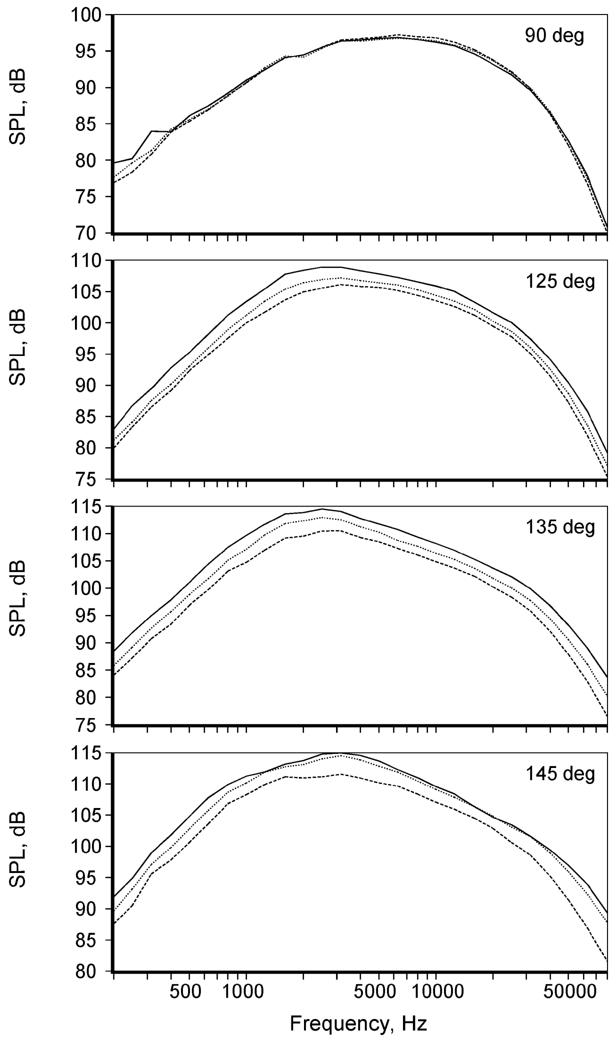

Fig. 15 Noise reduction of the beveled nozzle: $M = 1.0$; $Tt/Ta = 3.2$; azimuthal angle = 30 deg; ——, round nozzle; – – –, bevel45; and . . . ., bevel24.

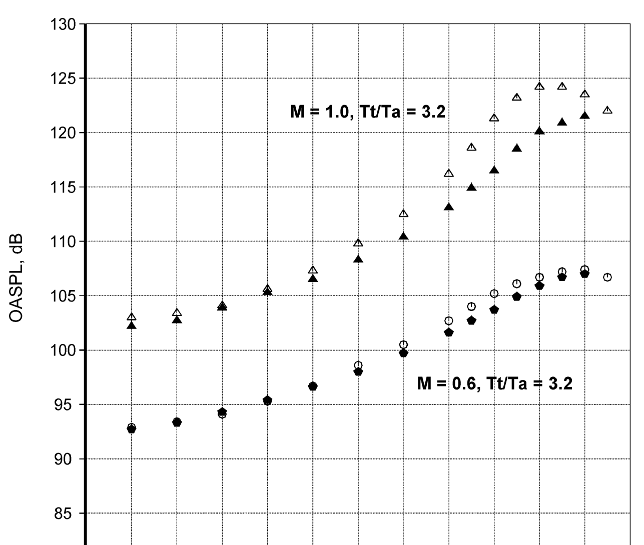

Fig. 16 Polar directivity of OASPL: $M = 0.6$ and 1.0; $Tt/Ta = 3.2$; ○, △, round nozzle; and ●, ▲, bevel45; azimuthal angle = 0 deg.

these trends with those in Fig. 18a to recognize the effect of jet velocity for the heated and unheated round jets.) For the beveled nozzle, however, the spectral shape begins to change even at a polar angle of 110 deg. In the polar angular range of 120 deg and higher, there is excellent agreement with the LSS even for this unheated jet at a lower (Vj/a)! To put this in perspective, the LSS shape is not seen at angles lower than 150 deg for the round nozzle. For the sake of information, it is also mentioned that the LSS shape is observed only at 145 deg and higher for bevel45 at the azimuthal angles of 0 and 90 deg (comparisons not shown). These figures lead to an important conclusion that the observed trends are not caused by a simple change in the directivity pattern due to the deflection of the plume. The estimated plume deflection of 10 deg does not account for the drastic change in the spectral shapes at an azimuthal angle of 180 deg. This point is also reinforced by the azimuthal variation in Fig. 17a of the sector power level; the power level is an integrated quantity and hence removes the effect of changes to the polar directivity.

It was shown in Ref. 7 that there is excellent agreement between the LSS and measured spectra from unheated round jets at very low Mach numbers at 155 deg and higher. Figure 20 shows a comparison of spectra for bevel45 at an azimuthal angle of 180 deg but at a polar angle of 135 deg. There is surprising agreement with the LSS even at a Mach number of 0.5, and the peak frequency is independent of jet velocity, a trend observed for round nozzles at angles close to the jet axis. This is quite unexpected because we do not anticipate the noise from the large-scale structures to be dominant at the lower polar angle of 135 deg, especially at low Mach numbers from a round nozzle.

Next we examine the spectra of heated jets in Figs. 21 and 22. In Fig. 21 we present spectra from heated jets of Mach numbers 0.6, 0.7, 0.9, and 1.0 with $Tt/Ta = 3.2$. The spectra from bevel45 at an azimuthal angle of 180 deg and a polar angle of 110 deg conform to the LSS shape. (For the sake of information, at a temperature ratio of 2.2 the spectra from jets of Mach numbers 0.6, 0.7, 0.8, 0.9, and 1.0 attain the LSS shape at a polar angle of 120 deg.) Figure 22 shows a comparable plot for a round nozzle at the same temperature ratio, but at two polar angles of 110 and 120 deg, to allay any doubts about the change in directivity caused by plume deflection. At both of these angles, the spectra at all Mach numbers conform to the FSS shape. (At the higher Mach numbers the spectral shape just begins to change at 120 deg.) Therefore, it is obvious that the radiation pattern has been completely altered with the preceding concept. It is generally accepted that the large-scale structures do not radiate noise at an angle of 90 deg. When we examine the spectra at 90 deg, it is obvious that the FSS by itself does not fit the measured data even at a Mach number of 0.6 in Fig. 23. The LSS component must be added, as shown symbolically, to fit the spectral peak. For a round nozzle, the angular sector where both components are important occurs at much larger polar angles. In fact, for the beveled nozzle one would have to be at a very low angle of 60 deg to recover the FSS shape, as shown in Fig. 24.

The picture that emerges from the preceding analysis indicates the reason for the observed noise reduction in the aft directions with the beveled nozzle. First, the noise generated by the large-scale structures, which is beamed preferentially to angles close to the jet axis for a round nozzle, is radiated to lower polar angles for a beveled nozzle. Of greater significance is the fact that this component is radiated towards the azimuthal direction with the shorter side of the beveled nozzle. With the longer lip of the beveled nozzle at the bottom dead center, this means that the noise is radiated up into the sky. The fact that the large-scale structure noise is radiated to lower polar angles (at an azimuthal angle of 180 deg) is confirmed by the observations that the spectral shapes are very different from those from the round nozzle and the surprising conformity with the LSS at the lower polar angles. It has been shown that the spectral shapes at an angle of 135 deg from unheated jets of Mach numbers ≥ 0.5 conform to the LSS shape, whereas such a trend is confined to angles ≥ 155 deg for a round nozzle. In heated jets, a perfect fit with the LSS shape is attained even at 110 deg for an $M = 0.6$ jet. This trend is markedly different from that for a round nozzle: recall that even

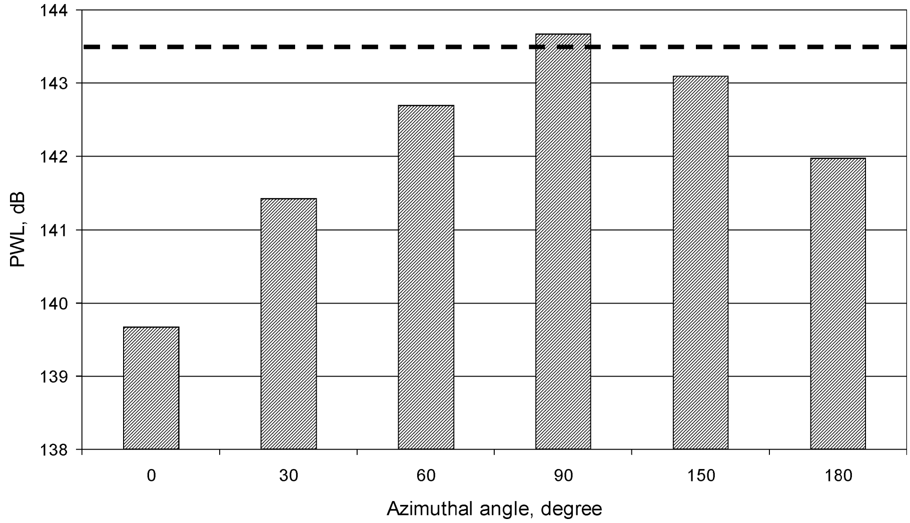

Fig. 17a Azimuthal directivity of power level: $M = 1.0$, and $Tt/Ta = 3.2$. Power level calculated per 30-deg azimuthal sector: – – –, equivalent level for round nozzle.

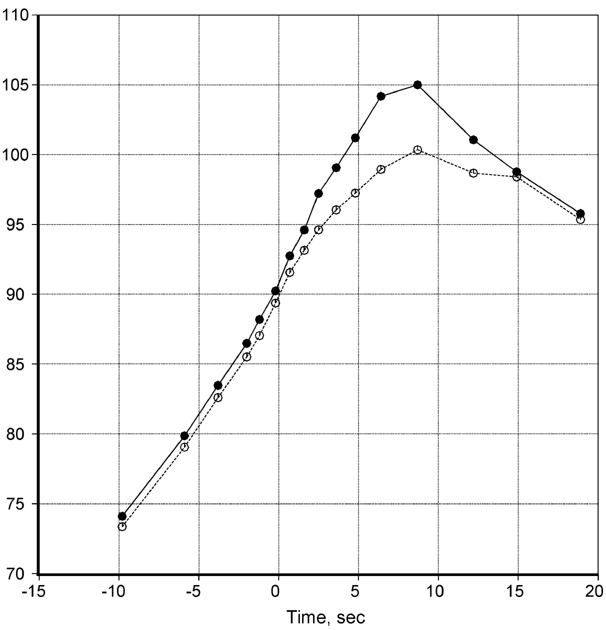

Fig. 17b Variation of perceived noise level with time; $M = 1.0$; $Tt/Ta = 3.2$; ● and ——, round nozzle and ○ and – – –, bevel45, azimuthal angle of 0 deg.

for a highly heated supersonic round jet with $M = 2.0$ significant noise from the large-scale structures is confined to angles ≥ 125 deg. The reason for the observed noise reduction (below the longer lip) is now postulated: because of significant radiation from large-scale structures to lower polar angles (above the shorter side), less acoustic energy is perhaps available for radiation to the aft directions, where peak noise radiation occurs for a round nozzle. This scenario would explain why we see a reduction in level across the spectra at all frequencies. It is not surprising then that the magnitude of noise reduction is greater at higher (Vj/a) because the noise from the large structures is more pronounced.

It is worthwhile at this time to discuss another unresolved issue: why does the spectral shape change from a broad peak with gradual roll off at 90 deg to one with a narrow peak and sharp roll-off at angles close to the jet axis? As per Lighthill's theory[11] and subsequent extension by Ffowcs Williams,[12] the effect of the convection of the sources tends to increase the radiated levels in the direction of the jet flow. The theoretical estimate for the radiated noise intensity includes a factor $(1 - M_c \cos ß)^{-5}$, with the angle ß measured from the jet exhaust axis. However, as noted by Lush[13] and Ahuja and Bushell[14] initially and subsequently by others, the measured spectra at angles close to the jet axis did not support the contention of convective amplification. Spectral analysis by Lush[13] indicated that there was no convective amplification at the higher frequencies, whereas the measured levels at the lower frequencies were higher than those predicted by theory. The experimental measurements of Atvars et al.[15] indicated that refraction of sound by the mean flow creates a cone of silence around the direction of jet flow. Lilley[16,17] developed an acoustic analogy that accounted for the equivalent sources immersed in a parallel sheared flow and derived a third-order convected wave equation. Effects caused by mean flow/acoustic interaction and refraction have been generally believed to be responsible for the large reduction in noise at the higher frequencies at aft angles. This viewpoint, wherein there is an increase in level at lower frequencies as a result of convective amplification and a reduction at the higher frequencies as a result of mean flow/acoustic interaction, represents one school of thought and has formed the basis for many theoretical methods.

The second point of view, advanced by Tam and Morris,[18] Tam and Burton,[19] and Tam,[20] among others, is that the noise radiation in the aft directions is generated directly by the large-scale structures/instability waves. This mechanism of Mach wave radiation is especially valid for highly heated supersonic jets, with supersonic convective velocities relative to the ambient speed of sound. A key observation in Refs. 18–20 is that there is a direct coupling between the instability wave solution (in the immediate vicinity of the jet shear layer) and the acoustic wave solution (in the far field). The transition from the inner to the outer solution occurs near the edge of the jet, and therefore the sound field is regarded as being generated near the edge of the jet shear layer. As such, this component of noise would not be subject to the effects of mean flow/acoustic interaction.

Let us reexamine the spectra, specifically those presented in Figs. 21 and 22. For the round nozzle, the spectral shape has the expected broad peak and gradual roll off as identified by the FSS. However, even at a low Mach number of 0.6 and $Tt/Ta = 3.2$, the spectral shape for bevel45 at an azimuthal angle of 180 deg conforms to that of the LSS at a polar angle of 110 deg. As per the acoustic analogy and conventional thinking, the acoustic waves radiated to an angle of 110 deg would not be subjected to strong mean flow/acoustic interaction and would experience minor convective amplification. Therefore, the theory completely fails to explain the change in spectral shape at an angle that happens to be outside the cone of silence. The experimental results presented here refute the concept of convective amplification and mean flow/acoustic interaction as being the mechanism responsible for the change in spectral shape from a broad peak to a sharp peak. If on the other hand the noise from the large-scale structures is dominant in this direction and

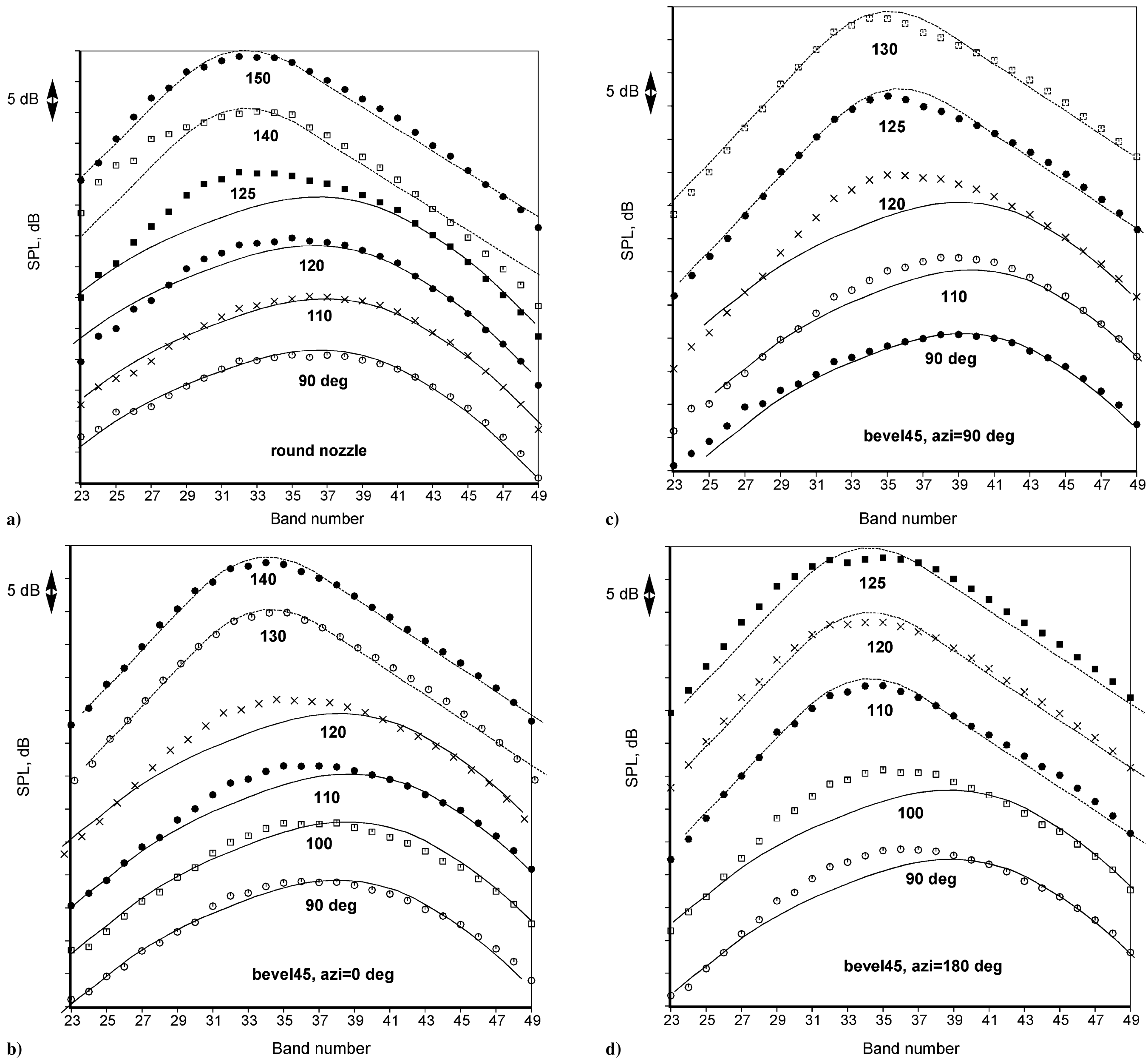

Fig. 18 Comparison of data with similarity spectra: $M = 1.0$; $Tt/Ta = 3.2$; symbols, data; ——, FSS; and – – –, LSS; a) round; b) bevel45, azi = 0 deg; c) bevel45, azi = 90 deg; and d) bevel45, azi = 180 deg.

not subject to flow/acoustic interaction, there is a ready explanation for the agreement with the LSS shape. Thus, the results shown here provide strong evidence for the presence of two distinct components for turbulent mixing noise. Recall that the supposition that the noise from large-scale structures could be important even at lower Mach numbers led to the current concept of a beveled nozzle.

It has been demonstrated that the fundamental radiation pattern of a high-speed jet has been altered with this simple concept. Convincing evidence that noise reduction in certain azimuthal directions is achievable by manipulating the radiation mechanism has been presented. It is worth remembering that there is only a slight change in the overall power levels, that is, the same small percentage of the mechanical energy of the jet is converted to noise. However, the uneven radiation of acoustic energy in the azimuthal direction makes this a winning concept. Therefore, the first two objectives of this study have been met.

D. Shock-Associated Noise from Beveled Nozzles

The mechanism for the generation of broadband shock-associated noise is different from that of the turbulent mixing noise. As per the stochastic model theory of Tam,[21] this component of noise is generated by the weak but coherent interaction between the large-scale turbulent structures in the jet shear layer and the quasi-periodic shock cell system. It is well known that the relative importance of the broadband shock-associated noise and turbulent mixing noise is a strong function of radiation angle and jet operating conditions. For a fixed Mach number, the turbulent mixing noise level increases as the jet temperature is increased, while the amplitude of the broadband shock-associated noise remains nearly unaltered. The shock noise radiation is omnidirectional, whereas the mixing noise is radiated principally to the aft directions. Furthermore, shock-associated noise is more pronounced in the forward quadrant and is distinguished easily because the levels of turbulent mixing noise are low in these directions for a round jet. However, as noted already, there is strong radiation of the component of mixing noise associated with the large-scale structures to lower polar angles. Hence, it is not clear if and how the physical processes described in Ref. 21 would be altered for the beveled nozzle.

The use of asymmetric nozzles for the elimination of screech tones and the possible alleviation of broadband shock-associated noise is not a new idea. Norum[22] tested a variety of tube nozzles with different modifications to the geometry of the trailing edge

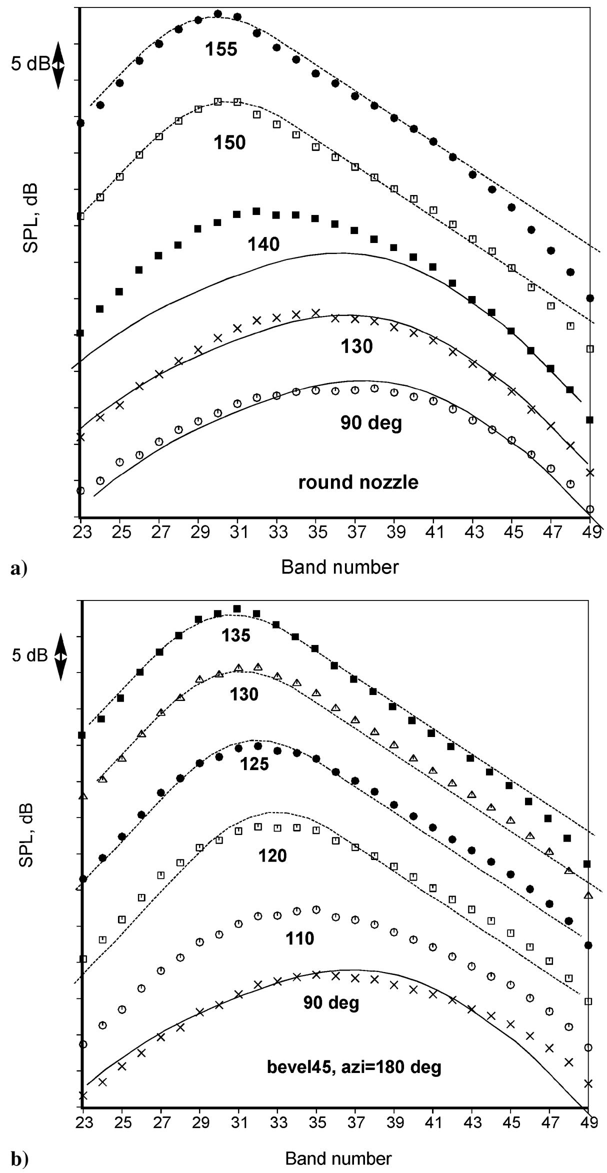

Fig. 19 Comparison of data with similarity spectra: $M = 1.0$; $Tt/Ta = 1.0$; symbols, data; ——, FSS; and – – –, LSS; a) round and b) bevel45, azi = 180 deg.

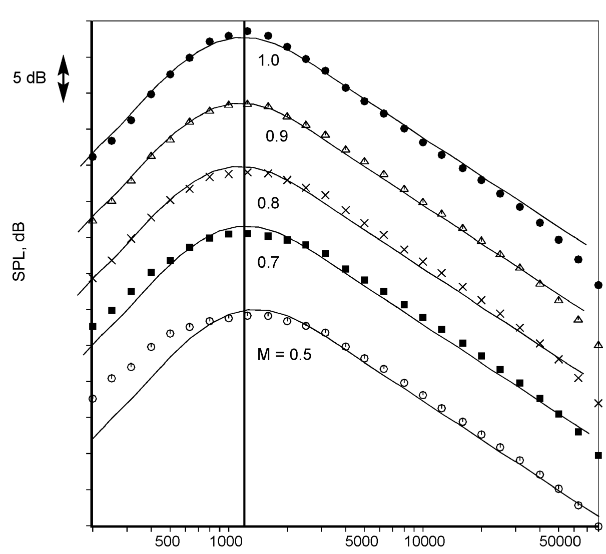

Fig. 20 Comparison of spectra with LSS: bevel45; $Tt/Ta = 1.0$; polar angle = 135 deg; azi = 180 deg; symbols, data and ——, LSS.

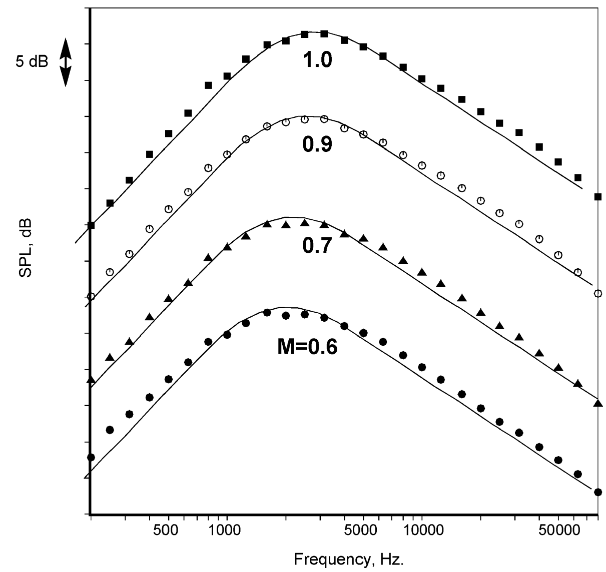

Fig. 21 Comparison of spectra with LSS: bevel45, $Tt/Ta = 3.2$; polar angle = 110 deg; azi = 180 deg; symbols, data and ——, LSS.

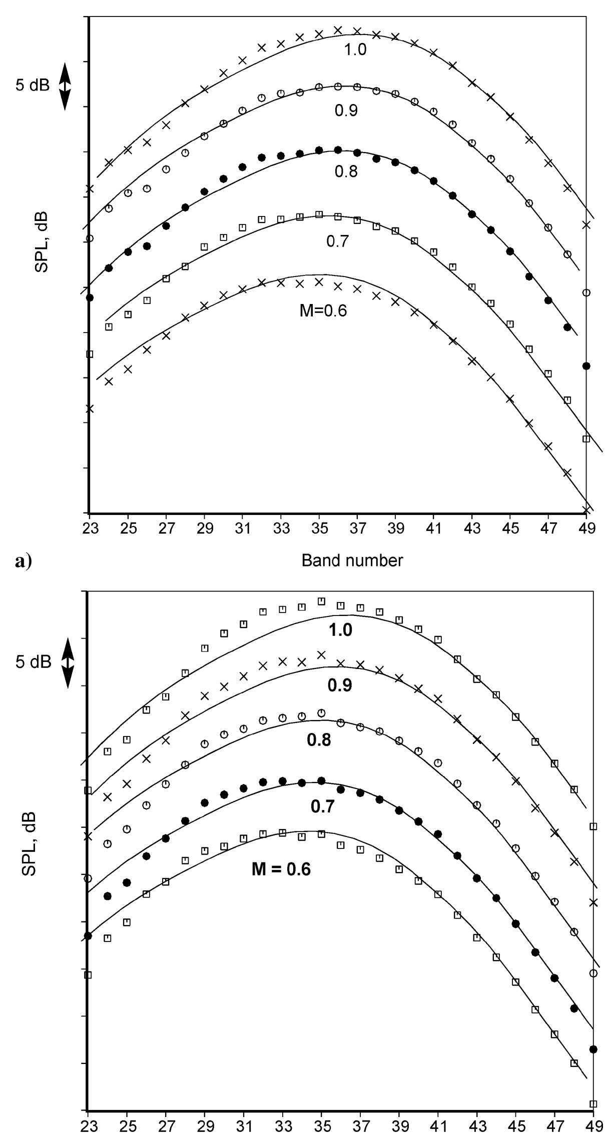

Fig. 22 Comparison of spectra with FSS: round nozzle, $Tt/Ta = 3.2$; a) polar angle = 110 deg and b) polar angle = 120 deg; symbols, data and ——, FSS.

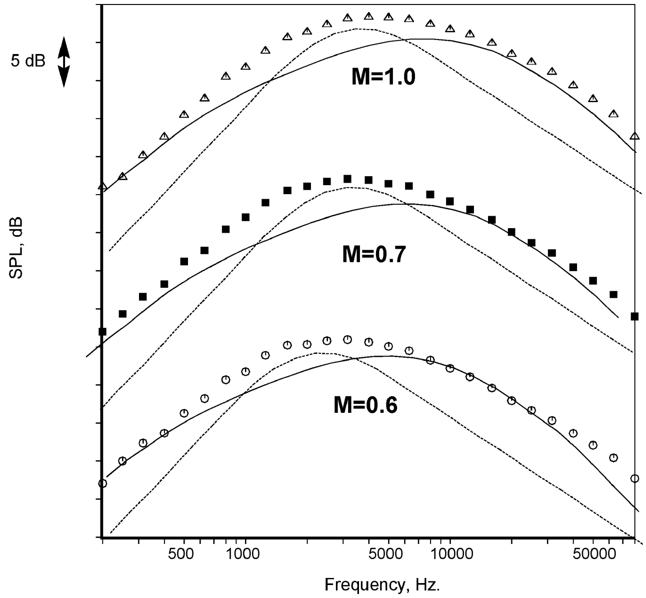

Fig. 23 Comparison of data with the similarity spectra: bevel45, *Tt*/*Ta* = 3.2; polar angle = 90 deg; azi = 180 deg; symbols, data; ——, FSS; and – – –, LSS.

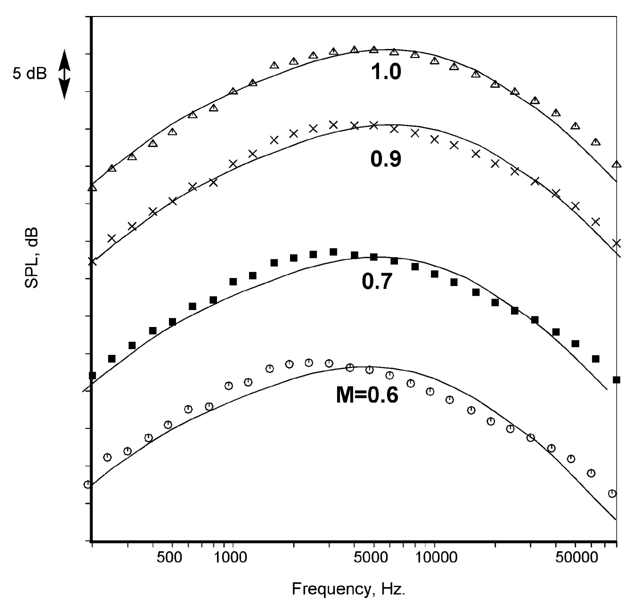

Fig. 24 Comparison of spectra with FSS: bevel45, *Tt*/*Ta* = 3.2; polar angle = 60 deg; azi = 180 deg; symbols, data and ——, FSS.

and demonstrated large reductions in screech amplitude. Wlezien and Kibens[23] investigated the flow and noise characteristics of two beveled nozzles ("inclined" nozzles in their terminology) and several tabbed nozzles and noted substantial azimuthal variation. At a polar angle of 90 deg, the asymmetry of the screech tone was found to be responsible for the azimuthal variation of OASPL. The preceding two studies were on unheated jets. Seiner and Ponton[24] evaluated the acoustic characteristics of a rectangular nozzle with an extended lower flap, termed the augmented deflector exhaust nozzle (ADEN). The rationale for the ADEN was to direct the radiated noise above the aircraft and to provide shielding to the noise radiated to the ground. Though some noise reduction was noted in the major axis plane at a Mach number of 1.5, there was no reduction in the minor axis plane. That is, the extended flap failed to provide any noise benefit in the intended direction. Rice and Raman[25,26] attempted to reduce noise from supersonic unheated jets by promoting enhanced mixing through the use of beveled nozzles and the introduction of paddles into the shear layer (thus producing intense screech tones)

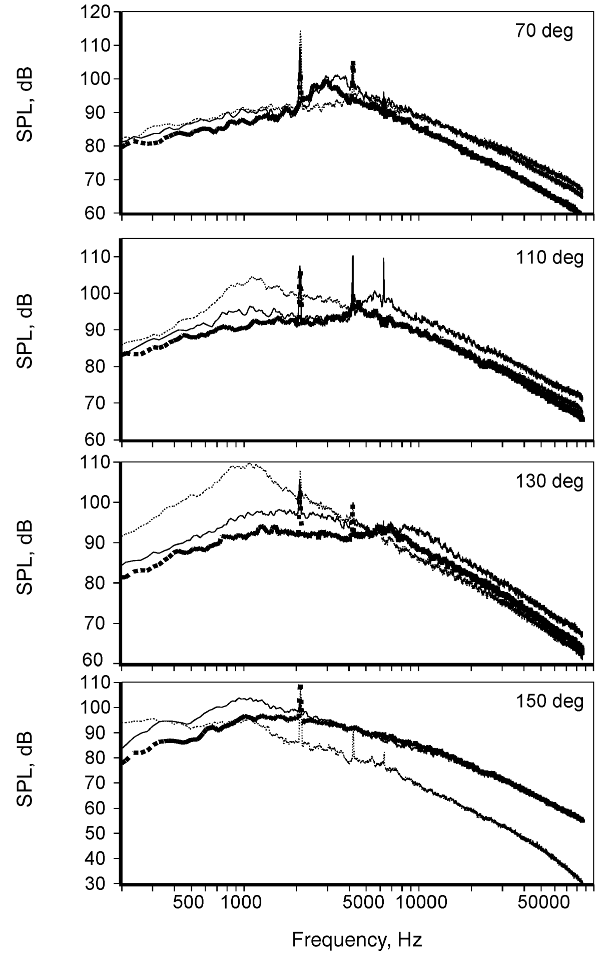

Fig. 25 Azimuthal directivity of bevel45: *M* = 1.56; *Tt*/*Ta* = 1.0; – – –, azi = 0 deg; ——, 90 deg; and · · · ·, 180 deg.

of rectangular jets. The intended application was for an ejector. Though increased mixing was observed, there was no noise benefit. They did note a change in the polar directivity and inferred that this was caused by the alteration of the noise from the large-scale structures, without offering any proof. With the beveled nozzle, even though there was a reduction in noise at the lower frequencies there was a substantial increase (∼10 dB) of broadband high-frequency noise at the lower angles. Raman[27] examined the characteristics of the screech frequencies of unheated supersonic jets from beveled nozzles; Tam et al,[28] with a theoretical/numerical approach, developed expressions for the screech frequencies from these nozzles that showed good agreement with the measurements. The main goal of the preceding studies of asymmetric nozzles was the attainment of enhanced mixing, with potential application for thrust vectoring for fighter aircraft and possible noise reduction. Even though enhanced mixing was attained and screech tones either eliminated or reduced in amplitude, all of these studies failed to yield broadband noise reduction, as demonstrated in the present study.

Some sample plots of the acoustic features at supersonic Mach numbers are presented, before comparisons with the reference round nozzle. It should be kept in mind, though, that because of the radiation of mixing noise from the large-scale structures to lower polar angles, it might not be easy to identify the shock-associated noise. Let us first examine the azimuthal spectral variation of an $M = 1.56$ jet, at unheated condition so as to keep the mixing noise levels as low as possible. Figure 25 shows spectral comparisons at several polar angles, at azimuthal angles of 0, 90, and 180 deg. At the lowest angle of 70 deg, there is not much variation in level for the mixing noise, to the left of the prominent screech tone. However, the broadband shock peak (∼3500 Hz) on the shorter side of the beveled nozzle has a lower spectral level. At a polar angle of

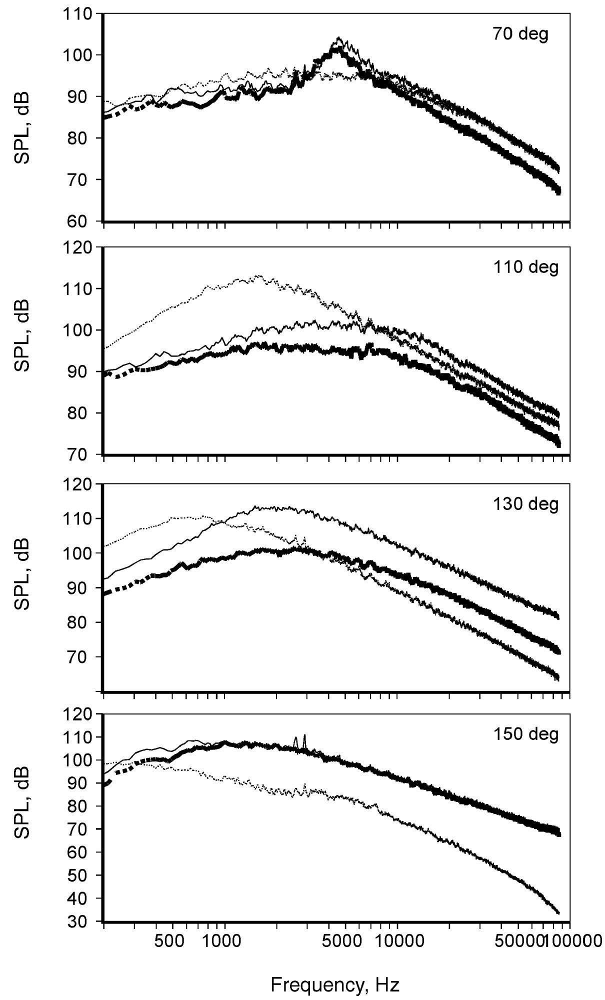

Fig. 26 Azimuthal directivity of bevel45: $M = 1.56$; $Tt/Ta = 3.2$; – – –, azi = 0 deg; ——, 90 deg; and · · · ·, 180 deg.

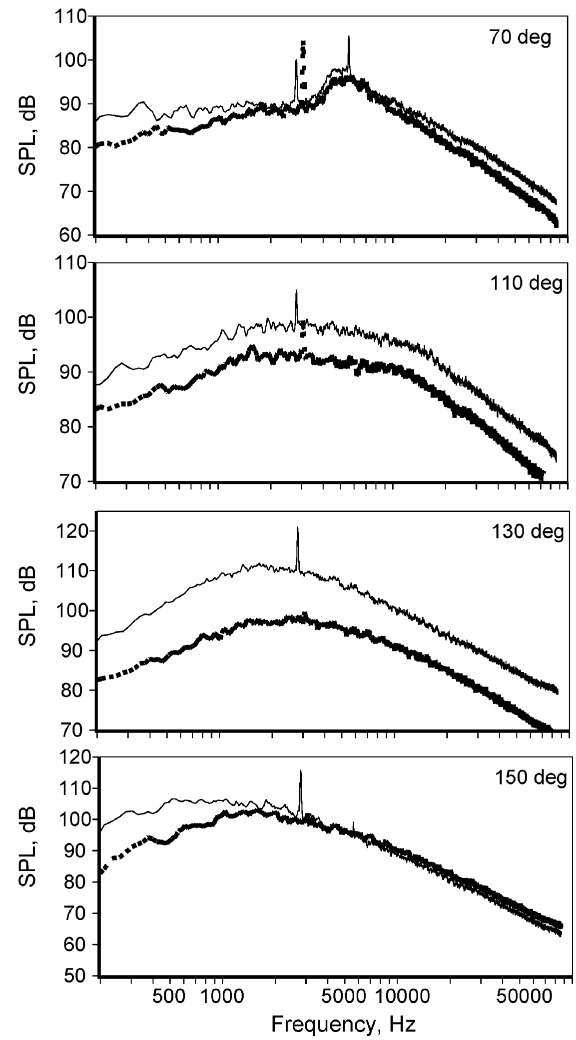

Fig. 27 Noise reduction of beveled nozzle: $M = 1.36$; $Tt/Ta = 3.2$; ——, round and – – –, bevel45, azi = 0 deg.

110 deg, there is a substantial increase in the turbulent mixing noise at an azimuthal angle of 180 deg. Given the spectral shape, one cannot discern the typical shape associated with shock-associated noise, which still prevails at an azimuthal angle of 0 deg. Because the Mach number is supersonic ($M = 1.56$), one would expect the contribution of the noise from large-scale structures to be higher than at subsonic Mach numbers. At a polar angle of 130 deg, there is a tremendous increase of >15 dB at the lower frequencies at an azimuthal angle of 180 deg. Because much of this component of mixing noise is radiated to shallower angles, the levels are substantially lower at 150 deg at this azimuthal angle.

When the jet temperature ratio is increased to 3.2 while holding the Mach number constant at 1.56, there are some interesting changes to the spectral trends in Fig. 26. First of all, the broadband hump caused by shock-associated noise at a polar angle of 70 deg has completely disappeared at an azimuthal angle of 180 deg. There is a 79% increase in jet velocity caused by the elevated temperature; this increase in jet velocity causes the peak radiation angle at an azimuthal angle of 180 deg to move forward to ~110 deg (from ~130 deg for the unheated jet). At a large aft angle of 150 deg, there is a lowering of levels by ~20 dB in the frequency range of ~1000 to ~20,000 Hz above the shorter side. At still higher frequencies, the spectral level at 180 deg keeps decreasing further; there is a ~30-dB reduction relative to that at an azimuthal angle of 0 deg. Even though the emphasis of this section is on shock-associated noise, the preceding spectral trends reinforce the proposed mechanism for noise reduction for a beveled nozzle for the following reason. Past experimental measurements indicated 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 (see Seiner[29]). That is, the turbulent mixing noise is the dominant component. For the highly heated supersonic jet ($M = 1.56$, $Tt/Ta = 3.2$, $Vj/a = 2.32$) from the beveled nozzle, there would be much stronger radiation of the turbulent mixing noise from the large-scale structures to lower polar angles, thereby reducing the amount of radiation to large aft angles, as noted in the spectral levels at 150 deg.

It remains to be demonstrated that the beveled nozzle produces lower levels of noise relative to a round nozzle at supersonic Mach numbers. Comparisons at unheated conditions are not shown because of the presence of strong screech tones, the magnitude of these being ~20 dB above the broadband noise near the tonal frequency. Experiments conducted at NASA Langley indicated that these strong screech tones lead to amplification of the turbulent mixing noise.[6,28] The tonal problem is more severe at an azimuthal angle of 90 deg, with multiple higher harmonics of comparable amplitude to that of the fundamental tone, as seen in Fig. 25. Similar trends were observed in the experiments of Ref. 23. Phase-averaged visualizations of the flow indicated that the shock system oscillates in the lateral direction, producing screech tones primarily in this direction. These pictures from Wlezien and Kibens[23] also showed the deflection and divergence of plumes from beveled nozzles, observed with video cameras here.

Spectral comparisons, at a Mach number of 1.36 with $Tt/Ta = 3.2$, from a round nozzle and bevel45 (0-deg azimuthal angle) are shown in Fig. 27. At the lowest angle of 70 deg, one can observe a reduction of ~5 dB in the turbulent mixing noise (low frequencies) with a smaller reduction at the higher frequencies. As we move aft,

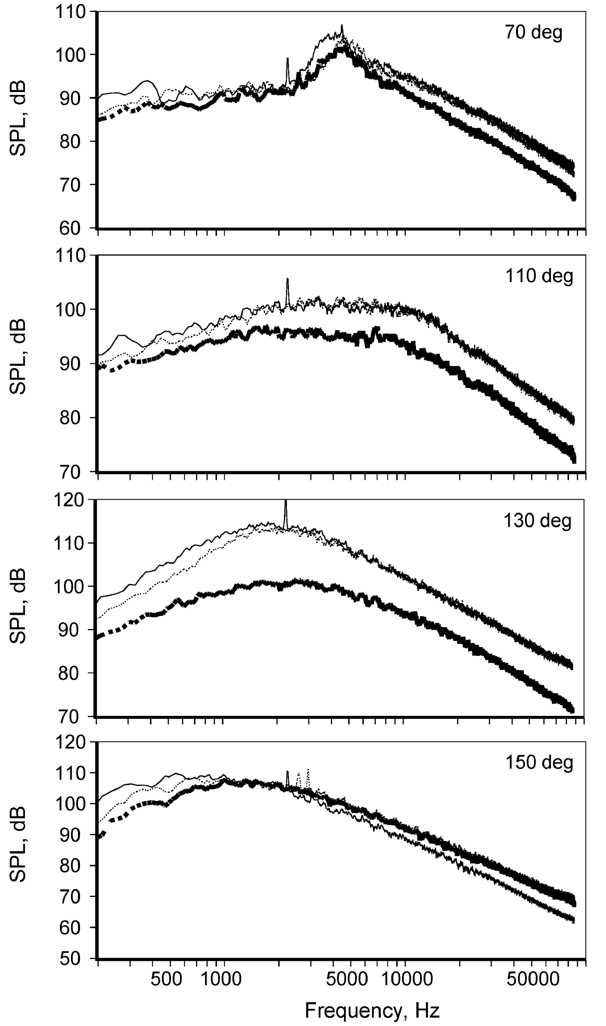

Fig. 28 Noise reduction of beveled nozzle: $M = 1.56$; $Tt/Ta = 3.2$; ——, round; – – –, bevel45, azi = 0 deg; and · · · ·, bevel45, azi = 90 deg.

there is a dramatic reduction of ~5 dB at 110 deg and ~10 dB at 130 deg at all frequencies. At angles closer to the jet axis, noise reduction is achieved only at the lower frequencies, with the magnitude being highest at the lowest frequency.

When the Mach number is increased to 1.56, with the temperature ratio maintained at 3.2, similar trends are observed in Fig. 28. For the sake of completeness, the spectra at an azimuthal angle of 90 deg are also included in this figure. The spectral levels at this azimuthal angle are no worse than those for the round nozzle, while a large reduction is seen at the midpolar angles at an azimuthal angle of 0 deg. Therefore, the beveled nozzle yields lower noise levels below the longer lip at supersonic Mach numbers as well. Finally, we examine the polar directivity of OASPL for the round nozzle and bevel45 with $M = 1.56$ and $Tt/Ta = 3.2$ in Fig. 29. The peak noise radiation angle for the round nozzle occurs at 130 deg. For the beveled nozzle, the peak direction has moved upstream to an angle of 110 deg at an azimuthal angle of 180 deg. However, the peak is at ~145 deg below the long lip. Contrast this figure with Fig. 10, which shows a similar plot for a jet at a lower Mach number of 1.0 at the same temperature ratio. At this lower Mach number, the peak radiation occurs at 125 deg at an azimuthal angle of 180 deg, while it is at 145 deg for the unheated jet with $M = 1.0$. These two figures, when examined together, establish the influence of the jet velocity (Vj/a) on the radiation process. It is recognized that shock-associated noise is also included in the OASPL at the supersonic Mach number. When we examine Fig. 16 together with Fig. 29 (symbols o and x), it is readily apparent that the noise reduction achievable with the beveled nozzle is a strong function of (Vj/a). Therefore, the spectral and directivity characteristics at supersonic

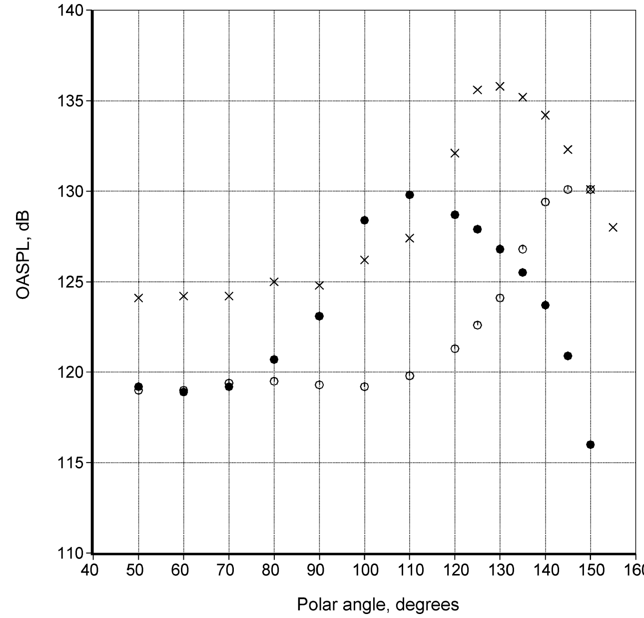

Fig. 29 Polar directivity of OASPL for the round nozzle and bevel45: $M = 1.56$; $Tt/Ta = 3.2$; ×, round; ○, bevel45, azi = 0 deg; and ●, bevel45, azi = 180 deg.

Mach numbers bolster the proposition that noise reduction is caused by the beaming of the noise component associated with the large-scale structures to lower polar angles and above the short lip for the beveled nozzle, thereby reducing the energy radiated to the aft angles. The results presented here also reinforce the contention that there are indeed two components of turbulent mixing noise.

V. Conclusions

The primary objective of this study has been to find a means to alter the inherent processes associated with the generation and radiation of noise in a high-speed jet. A simple concept, the beveled nozzle, has been shown to alter drastically the radiation pattern. First of all, a strong azimuthal variation of the noise field is introduced by the preceding concept. Second, the spectral shapes at different azimuthal angles for a given polar angle in the aft quadrant are very different. This change in spectral shapes leads to major differences in the polar directivities of the overall sound pressure levels; these differences become pronounced when the jet velocity is increased. Therefore, the primary objective of this study has been realized.

An important goal of the study, of course, is the achievement of jet noise reduction. Rather than tackle this problem directly, the noise reduction was viewed as a beneficial byproduct of the accomplishment of the primary objective. It has been shown conclusively that there is significant noise reduction for the beveled nozzle relative to a round nozzle. This noise reduction occurs in the azimuthal directions that are below the longer lip of the beveled nozzle. The noise reduction is generally confined to a polar angular sector of ~100 to ~145 deg and is observed at all frequencies. The magnitude of the noise reduction is a strong function of the jet velocity (Vj/a), with progressively higher reductions as the jet velocity is increased. The beveled nozzles reduce the overall power radiated only slightly; rather, there is an asymmetric redistribution of power in the azimuthal plane, and this feature is exploited to achieve noise reduction over certain desired azimuthal angles. The degradation in thrust caused by the beveled nozzle has been found to be low.

A spectral analysis at different azimuthal angles helped gain a physical understanding for the observed noise reduction in certain azimuthal directions. For round jets, the angular sector in which the noise generated by the large-scale turbulent structures/instability waves is dominant is confined to angles close to the jet axis. However, for a beveled nozzle this component of noise is beamed to lower polar angles. Of greater significance is the fact that this noise is radiated toward the shorter side of the beveled nozzle. Therefore, less acoustic energy is available for radiation to the aft directions and hence the observation of lower levels across the spectra.

It has been verified that the acoustic characteristics of the beveled nozzle are maintained even at supersonic Mach numbers and that significant noise reduction is obtained in the same polar angular range as for subsonic Mach numbers. Because the jet velocities (Vj/a) tend to be higher for highly heated supersonic jets, the magnitude of reduction in levels is substantial, ~10 dB across the spectra. The observations at supersonic Mach numbers bolster the mechanisms attributed for noise reduction. The current results have cast doubts about the validity of the reason traditionally attributed to the change in spectral shape at angles close to the jet axis: convective amplification and mean flow/acoustic interaction; this issue should be reexamined in light of the current data. Significant noise reduction has been achieved through the manipulation of the noise generated by the large-scale structures. These results further reinforce the proposition that the turbulent mixing noise consists of two independent components. It is worth remembering that there is no theory/methodology for the prediction of broadband mixing noise in the peak radiation directions. It would be highly desirable to develop a self-contained theory/methodology for this noise component, similar to that for the noise generated by the fine-scale turbulence. Numerical simulations that shed light on the aerodynamic features of the jet plume and the modified turbulence characteristics for the beveled nozzle are being initiated, and the results will be reported elsewhere. The application of the current concept of a beveled nozzle for typical turbofan engines that power commercial aircraft is discussed in an upcoming paper in the *Journal of Aircraft*.

Acknowledgments

It is a pleasure to thank M. C. Joshi for providing a technical critique and offering several suggestions that improved the paper. The enthusiasm and the support of the Low Speed Aeroacoustic Facility test crew are greatly appreciated.

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