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Investigation of Noise Source Mechanisms in Subsonic Jets

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The precise nature of the origin of jet noise remains in question to this day. Apart from the scientific importance of gaining a better understanding of the noise sources, there is the practical consideration of our ability to alter/manipulate the sources so as to achieve noise reduction. In this study, the sources of jet noise have been investigated with 1) the analyses of far-field spectra, and 2) the measurements of the far-field correlations, both in the polar and azimuthal directions. Two geometries were used: a round nozzle and a beveled nozzle. The acoustic characteristics of these nozzles exhibit interesting trends at different jet velocities (V_j/a), thereby permitting a better understanding of the nature of the noise sources. The far-field spectra from unheated round jets at extremely low Mach numbers conform to the large-scale similarity shape at angles close to the jet axis; there is a gradual progression from the fine-scale similarity shape to the large-scale similarity shape for all jet velocities. This seems to be a fundamental characteristic of jet noise and is a new finding. The far-field correlations indicate that there is very little correlation at the lower polar angles; in the peak aft radiation sector, high correlations prevail. It is established with both the round and beveled nozzles that low correlations are associated with fine-scale-similarity-shaped spectra and high correlations with large-scale-similarity-shaped spectra. Experimental evidence for the importance of the noise from large coherent structures even at low velocities is offered. The data indicate the existence of two independent sources in both high-speed and low-speed jets, with the coherent large structures radiating to the aft angles and the random turbulence radiating to the lower angles. It is shown that the noise reduction of the beveled nozzle is due to the alteration of the noise from the coherent structures. The beveled nozzle thus provides indirect evidence for the importance of large coherent structures.

I. Introduction

THERE is currently no consensus on the sources of jet noise. Several theories have been proposed in the last 50 years; however, depending on the theoretical approach and the assumptions invoked, different descriptions of the noise sources have resulted. The frameworks of Lighthill [1] or Lilley [2] have been used to derive models for the source terms, with a combination of simple theoretical considerations supplemented by limited experimental data. The precise nature of the origin of jet noise remains in question to this day. Apart from the scientific importance of gaining a better understanding of the noise sources, there is the practical consideration of our ability to alter/manipulate the sources so as to achieve noise reduction. The acoustic analogy requires the description of the two-point space-time correlation of the entire turbulence field, which is difficult, if not impossible, to measure. There have been several attempts in the past, with different measurement techniques, to quantify the stress tensor. These have concentrated on both single-point measurements and two-point correlations of the different fluctuating quantities of turbulence within the jet plume; see [3–7] for example.

A second approach has consisted of measuring the correlations of the flow fluctuations with the far-field noise spectra; a variety of measurement techniques have also been adopted. See [8–15] for a partial list. Several interesting results have been obtained from these measurements: the variation of the correlation coefficients as a function of the polar angle and the azimuthal angle as a function of jet operating conditions, the modal content of the source field, the axial and the radial location of the dominant source (either on the jet axis or the peripheral shear layer), the onset of Mach wave emission, etc.

Other techniques have also been employed for source measurements since the 1960s. An interesting test setup to estimate the noise produced by different slices of a jet is the so-called wall isolation technique, first introduced by Potter [16] and further refined by MacGregor and Simcox [17]. The jet is progressively retracted behind a wall and into an insulated test cell in small incremental steps. Microphones are located downstream of the solid wall, with measurements of the noise produced by the exposed jet at various radiation angles. Thus, the difference between two successive measurements yields the noise emitted by the length of the jet retracted. A comprehensive set of data from heated subsonic and supersonic jets from convergent, convergent–divergent, and a variety of suppressor nozzles was obtained in [17]. Microphone array techniques have also been used in source investigations since the 1970s: the acoustic telescope of Billingsley and Kinns [18], the polar correlation technique of Fisher et al. [19], and several phased array measurements more recently.

There have also been several near-field measurements of pressure, with the goal of identifying the acoustic or propagating components of pressure. Analyses of the spectra, from near-field circular arrays at various axial locations downstream of the nozzle exit plane, with various signal processing techniques, have yielded information about the possible source fields. Many studies in the past have indicated that the lowest order modes dominate the near field of a jet; a very small list of these types of studies may be found in [20–24]. More recently, these types of measurements have been carried out at NASA Glenn Research Center and Laboratoire d'Etudes Aérodynamiques (LEA) Poitiers for a variety of nozzle geometries; for more details, see [25,26] and the references therein.

In a different approach adopted in the early 1970s, ellipsoidal and spheroidal dish-microphone systems were used for mapping the aeroacoustic noise sources. Extensive studies on supersonic and subsonic jets were carried out by the research group at the University of Southern California under the direction of Laufer et al. [27,28] and Schlinker et al. [29]. A parallel study was carried out by Grosche [30] with an elliptic mirror. It should be kept in mind that no particular technique is perfect; there are advantages and limitations associated with all of these approaches with regard to resolution, assumptions

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involved in the interpretation of the data, requirement for a priori knowledge of the source characteristics, omnidirectivity of the noise sources, etc., as noted by Fuchs [31]. However, the collective information gleaned from these source measurements has proved to be valuable.

II. Scope of Current Study

It is now widely believed that the turbulence in free shear layers is not completely random but more coherent and orderly, and turbulent flows contain both fine-scale and large-scale structures. Both fine-scale (random) turbulence and large-scale turbulence generate noise. The coherent large-scale structures have been modeled as instability waves and their importance in noise radiation has been recognized since the early 1970s. For supersonic jets, and subsonic jets at high temperatures, as in practical jet engine applications, the large-scale structures propagate downstream at supersonic speeds relative to the ambient speed of sound. These structures are efficient generators of noise and constitute the dominant noise sources, especially in the downstream direction. There have been several experimental and theoretical developments related to the measurement and modeling of the source mechanisms associated with the large-scale structures: Tam [32], McLaughlin et al. [33], Morris [34], Ffowcs Williams and Kempton [35], Tam and Morris [36], and Tam and Burton [37], to name just a few.

Experimental measurements have shown that the mean flow as well as the turbulence statistics exhibit self-similarity in the mixing layer and in the fully developed jet. Based on these observations, Tam and Chen [38] and Tam et al. [39] proposed that, because noise is generated by the turbulence of the jet, the noise spectra generated by fine-scale and large-scale turbulence should also exhibit self-similarity. By examining a large set of supersonic jet noise data acquired at NASA Langley, Tam offered evidence that the turbulent mixing noise of high-speed jets does consist of two independent self-similar components. These were termed the fine-scale similarity (FSS) spectrum and large-scale similarity (LSS) spectrum. The relative contributions of these two noise sources are dependent on the jet Mach number, the jet temperature, and the radiation angle.

All of the preceding investigations and the salient observations on large-scale structures vis-á-vis noise generation have been restricted to high-speed jets, with supersonic convective velocities. For subsonic jets, especially at low and moderate temperatures, the large turbulence structures propagate downstream at subsonic speeds relative to the ambient speed of sound.

In a recent study, Viswanathan [40] proposed that the noise from large-scale structures could be important even for low-speed jets. Based on spectral analysis, he showed that the typical spectral shape associated with the large-scale turbulence is observed down to a very low jet velocity of 440 ft/s for an unheated $M = 0.4$ jet. Viswanathan [40] pointed out that the instability waves at low Strouhal numbers amplify more gradually than waves at high Strouhal numbers, and attain their peak amplitudes close to the end of the potential core. In addition, low-velocity jets have higher growth rates than those of high-speed jets. Just beyond the potential core, these waves have no mechanism to extract energy from the mean flow and lose their energy through nonlinear processes; see also [35,37]. This process would occur over a region that is a few diameters in extent, downstream of the end of the potential core. The modulation of the amplitude of the instability waves due to the growth/decay cycle could trigger low-wave-number components with potentially supersonic phase speeds relative to the ambient speed of sound. Given the low velocities, though, this radiation would be confined to angles close to the jet axis. Thus, the large-scale structures could be a source of noise for low-velocity jets as well. The physical process outlined here could also explain the puzzling observation of why the LSS shape, extracted from jets with velocities of 3450 ft/s (1050 m/s), is seen for such a low-velocity jet.

The fundamental question that remains unanswered to date is this: are large-scale structures important noise generators at very low jet velocities? In this study, we investigate this question with two approaches: 1) analyses of far-field spectra, especially from unheated low Mach number jets, and 2) inspection of far-field polar and azimuthal correlations at various radiation angles and at various jet velocities. It is well known that the spectral shape changes from a gradual rise and fall (FSS) at the lower polar angles to a sharp peak with a rapid roll off (LSS), as the radiation angle is increased progressively. The connection between correlations, both in the polar and azimuthal directions, and the far-field spectral shapes is examined. The modifications to the spectral shapes and the correlations due to the beveling of a round nozzle are investigated to gain insights into the noise from the large coherent structures of the jet flow.

III. Overview of Experimental Measurements

A. Far-Field Spectra

The tests were carried out at the Low-Speed Aeroacoustic Facility at Boeing. Detailed descriptions of the test facility, the jet simulator, the data acquisition and reduction process, etc., may be found in Viswanathan [41]. Figures 1a and 1b in [41] provide a schematic sketch of the anechoic facility and the jet rig, with the layout of the far-field microphones also included. Therefore, only an overview of the tests is provided here. The jet simulator is embedded in an open-jet wind tunnel, which can provide a maximum freestream Mach number of 0.32. Both acoustic and thrust measurements were made simultaneously. Typically, several microphone arrays at different azimuthal angles were used. The microphones were at a constant sideline distance of 15 ft (4.572 m) from the jet axis, except the microphone at 155 deg, which was at a distance of 12.75 ft (3.886 m). All angles are measured from the jet inlet axis, with a polar angular range of 50–155 deg. For some of the test points, additional microphones at a sideline distance of 9.17 ft (2.79 m) were also located at large polar angles so as to minimize interference with the exhaust collector; these microphones were at a different azimuthal angle. Although this was the general microphone layout adopted, other microphone installations were employed for answering specific issues as discussed later. Bruel & Kjaer Type 4939 quarter-inch microphones were used for free-field measurements. The microphones were set at normal incidence and without the protective grid, which yields a flat frequency response up to 100 kHz. Narrowband data with a bin spacing of 23.4 Hz were acquired and synthesized to produce one-third-octave spectra in the range of centerband frequencies of 200–80,000 Hz. Spectral measurements have been made at extremely low jet velocities from unheated jets with a nozzle of diameter 2.45 in. (6.2 cm); Table 1 provides a summary of the test points. NPR is the nozzle stagnation pressure ratio, M is the jet Mach number, (T_t/T_a) is the jet stagnation temperature ratio, and (V_j/a) is the acoustic Mach number or the jet velocity normalized by the ambient speed of sound. The test points in Table 1 complement an existing larger database described in Viswanathan [40,41].

B. Far-Field Correlation Measurements

Measurements of the far-field correlations of jet noise have been carried out in the past, as already noted. Here, two far-field

Table 1 Summary of test points for low-velocity jets

NPR	M	T_t/T_a	(V_j/a)
1.00	0.00	1.0	0.00
1.01	0.12	1.0	0.12
1.02	0.17	1.0	0.17
1.03	0.21	1.0	0.21
1.04	0.24	1.0	0.24
1.05	0.26	1.0	0.26
1.06	0.29	1.0	0.29
1.07	0.31	1.0	0.31
1.08	0.33	1.0	0.33
1.09	0.35	1.0	0.35
1.12	0.41	1.0	0.40
1.15	0.45	1.0	0.44

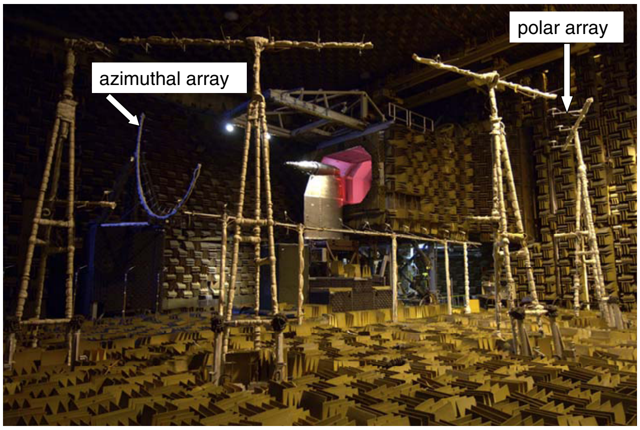


Fig. 1 Photograph of polar and azimuthal microphone arrays. The jet rig and wind tunnel are also shown.

microphone arrays are deployed: a polar array which spans the angular range of 60–150 deg, and an azimuthal array that spans an angular range of 180 deg. Figure 1 shows a photograph of the two arrays. The azimuthal angle is measured counterclockwise from the bottom dead center (toward the ground), which corresponds to 0 deg. To facilitate measurements from both of these arrays simultaneously, a semicircular azimuthal array with 19 microphones at 10 deg intervals was constructed; these microphones are located at azimuthal angles from 240 to 60 deg. The azimuthal array was mounted on the same traversing cart/platform used for the elliptic mirror, thereby providing the flexibility to obtain azimuthal correlation measurements at any desired polar angle. Time-series data were recorded from all of the microphones for different nozzles at several test conditions. These data have been processed to produce some basic correlation plots and coherence spectra. A more comprehensive analysis of the data is currently underway and will be reported in the future. The coherence function $\gamma^2(f)$ between any two microphones is defined by

$$\gamma_{12}^2(f) = \frac{|G_{12}(f)|^2}{G_{11}(f)G_{22}(f)}$$

where G_{11} and G_{22} are the one-sided autospectra, and G_{12} is the cross spectrum between the two signals. Similarly, the cross-correlation coefficient function $\beta_{12}(\tau)$ is defined by

$$\beta_{12}(\tau) = \frac{R_{12}(\tau)}{[R_{11}(0)R_{22}(0)]^{1/2}}$$

where R_{11} and R_{22} are the autocorrelation functions, R_{12} is the cross-correlation function, and τ represents the time delay. The signals from the array microphones are time synchronized; because the distances to the microphones in each array have a fixed value, no corrections related to the weather conditions are applied in the processing of the correlation data. Attention is drawn to the fact that the same microphone models are used; thus, offsetting identical type corrections would be applied to the signals. Therefore, no microphone type corrections are applied.

IV. Results and Discussion

First, we establish some fundamental characteristics of jet noise through the examination of the experimental data. A new trend is identified from the far-field spectra; the properties associated with it are investigated using far-field correlations. Modifications of the basic radiation characteristics are effected through changes to the nozzle geometry and the implications are discussed.

A. Fundamental Characteristics of Jet Noise

1. *Far-Field Spectra*

The spectra from unheated low-velocity jets, listed in Table 1, are examined. It is extremely difficult to obtain accurate spectral measurements from very low-velocity jets, as discussed in great detail in [40,41]. The issues with 1) the proper choice of the instrumentation system that would lead to accurate measurements at the higher frequencies of interest in model scale tests, and 2) the stringent requirements for model and engine tests, as they pertain to data repeatability, etc., have been addressed in Viswanathan [42,43]. It was clearly demonstrated that with adequate care, 1) highly repeatable data with a scatter within ± 0.25 dB is obtainable (see Fig. 10 in [42]), and 2) it is possible to match spectra obtained at disparate weather conditions and from different jet simulators (see Sec. III.D in [43]). Therefore, the accuracy of the current database has already been established.

First, the measured narrowband spectra along with the noise floor at an angle of 165 deg are shown in Fig. 2. The noise floor is made up of the sum of the ambient noise and the electronic noise, and is denoted by the thick black line at the bottom. The jet Mach number is progressively increased and the spectra for jets with $M = 0.21, 0.24, 0.26, 0.29, 0.31, 0.33, 0.35, 0.41, 0.45$, and 0.60 exhibit the expected monotonic increase in level. The spectra from the lowest two Mach numbers of 0.12 and 0.17 virtually coincide with the noise floor and therefore are not shown. The spectrum for the noise floor peaks at 200 Hz, decreases as the frequency is increased, and flattens out with a level between ~10 dB and ~15 dB for the frequency range of ~3–80 kHz. The spectrum for the $M = 0.21$ jet is very close to the noise floor for most of the frequencies. As the Mach number is increased, there is an enlarging separation between the measured levels and the noise floor at the lower frequencies, which is ≥ 6 dB for $M > 0.26$. However, at the higher frequencies, the measured data eventually run into the noise floor, with the range of resolvable frequency becoming larger with the Mach number. When the narrowband spectra are synthesized to produce one-third-octave spectra, there is a tail-up at the higher frequencies because of the contamination due to the noise floor and the ever-increasing bandwidth with frequency. This point should be kept in mind when the following figures are examined.

The spectral shapes at large aft angles and at various Mach numbers are compared with the similarity spectra of [39]. Figure 3 shows a typical comparison at an angle of 150 deg; there is excellent agreement between the data and the LSS spectrum for the higher Mach numbers of 0.7–1.0. At the lowest Mach number of 0.3, the spectrum corresponds to the FSS shape. Similar comparisons at two further aft angles of 160 and 165 deg are shown in Figs. 4 and 5, respectively, at lower Mach numbers. These are solely qualitative comparisons; no claim about the good quality of the spectra is made or implied. Careful analysis reveals that there is contamination at the low frequencies due to rig noise, in addition to the noise floor issue at

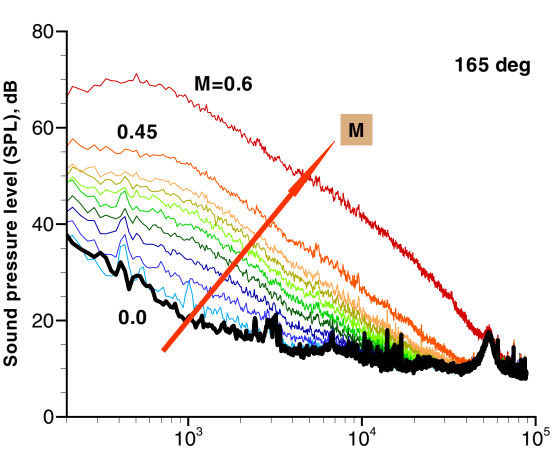


Fig. 2 Measured spectra from unheated jets at 165 deg; $M = 0.6, 0.45, 0.41, 0.35, 0.33, 0.31, 0.29, 0.26, 0.24, 0.21$.

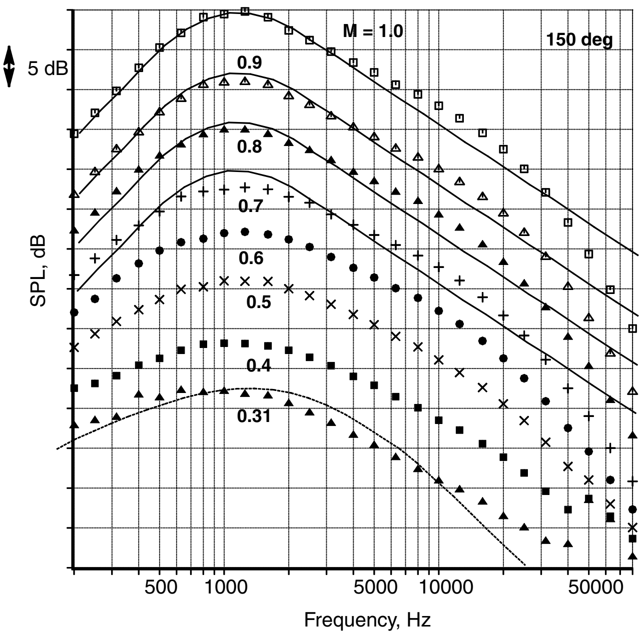


Fig. 3 Comparison of one-third-octave spectra from unheated jets with similarity spectra. Solid lines: LSS; dashed: FSS.

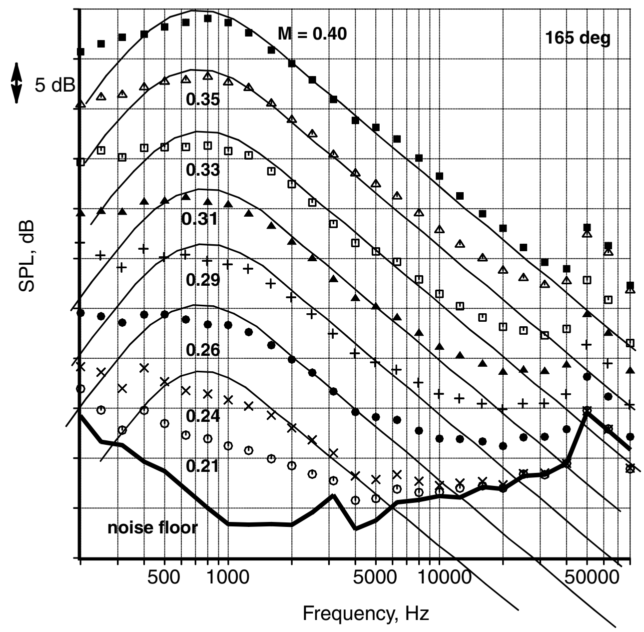


Fig. 5 Comparison of one-third-octave spectra from unheated jets with similarity spectra. Solid lines: LSS.

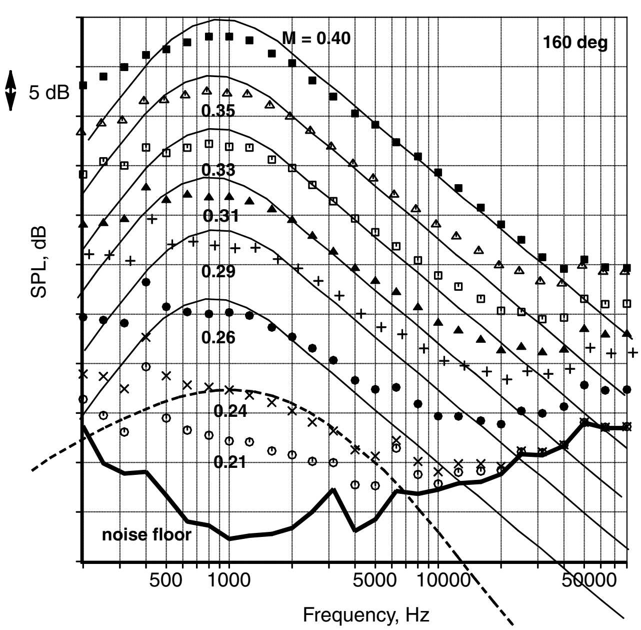


Fig. 4 Comparison of one-third-octave spectra from unheated jets with similarity spectra. Solid lines: LSS; dashed: FSS.

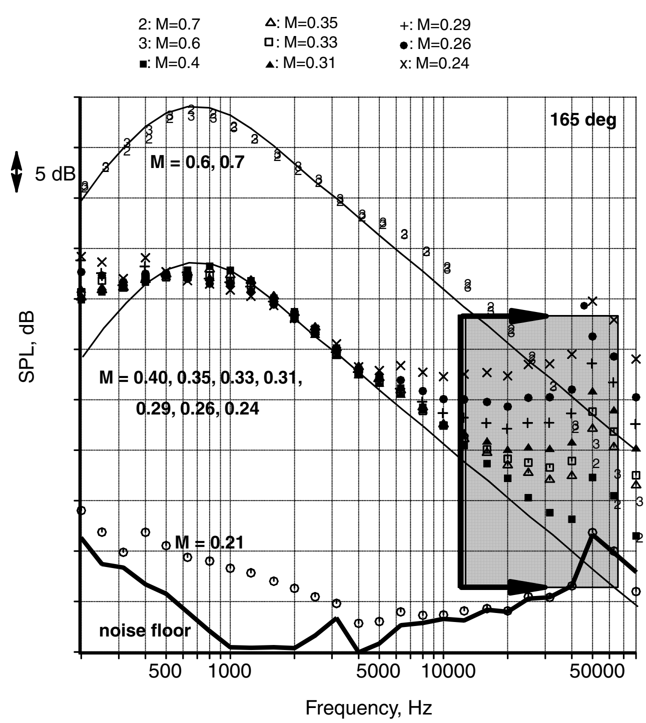


Fig. 6 Spectral collapse from unheated jets. Solid line: LSS spectrum. Symbols indicate one-third-octave data.

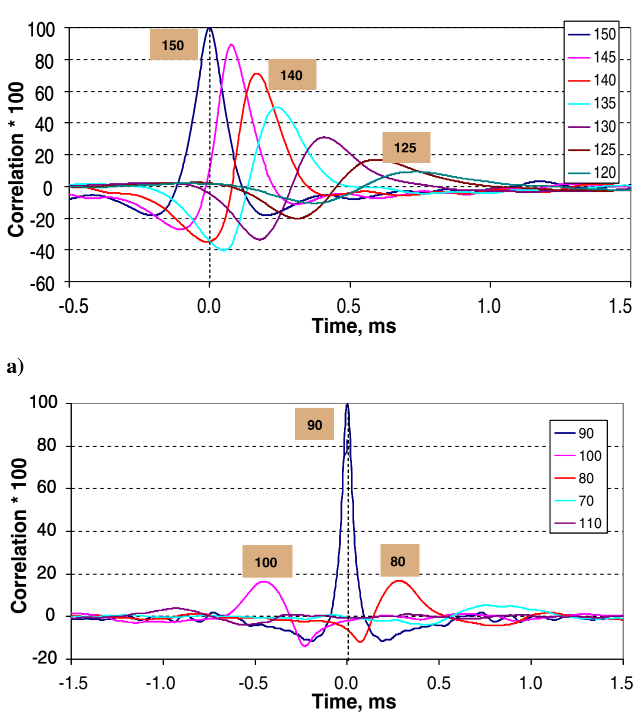
the higher frequencies discussed in Fig. 2. The spectra have been spaced apart vertically for better visualization. The flattening and eventual tail-up at the higher frequencies are, of course, due to noise floor contamination, as explained in Fig. 2. The Mach numbers range from 0.21 to 0.40 in these figures; the spectral shapes at the higher Mach numbers of 0.4–1.0 conform to the LSS shape at 160 deg; see Fig. 19 in [40]. It is seen in Fig. 4 that the spectra for the Mach number range of 0.26–0.4 have the LSS shape at this angle; at 150 deg (Fig. 3) the spectra conformed to the FSS shape. At the lower Mach number of 0.24, the spectrum resembles the FSS shape. At a still higher radiation angle of 165 deg in Fig. 5, the LSS shape is observed for all the Mach numbers, including 0.24. As noted in Fig. 2, the spectrum for $M = 0.21$ is too close to the noise floor and therefore even a qualitative assessment is not possible.

The spectra at 165 deg are collapsed in Fig. 6; data at two higher Mach numbers of 0.6 and 0.7 (denoted by numbers) are also included for the sake of comparison. There is excellent agreement between the spectra and the LSS over the entire frequency range for these higher M. It is clear that the spectra at the lower M (0.24–0.4) also conform to the LSS shape in the frequency range not impacted by the noise floor. The shaded region highlights the higher frequencies that are contaminated; for the $M = 0.4$ jet (dark squares), the demarcating frequency is $\sim$30 kHz, as seen in Fig. 2. At lower Mach numbers, the region of contamination gets wider progressively, as identified by the tail-up and the increasing mismatch with the LSS shape. As expected, the noise from the $M = 0.24$ jet (crosses) is subject to the most contamination. The contamination from the rig internal noise at the lower frequencies is also evident.

A clear trend may be discerned from these figures. Even within the peak radiation sector, typically $\geq \sim 140$ deg, there is a progression in the spectral shape from the FSS to the LSS shape. The jet velocity determines the angle at which the LSS shape is reached: the higher the jet velocity, the lower the polar angle. This trend is true even for extremely low jet velocities. For example, the spectra for $M < 0.4$ conform to the FSS shape at 150 deg (Fig. 3). At 160 deg, the LSS shape is observed for $M \geq 0.26$. At 165 deg, the LSS shape is observed for a still lower Mach number of 0.24; the FSS shape is seen at 160 deg for this Mach number. Further, the peak frequency is independent of jet velocity. It does not seem possible to make meaningful measurements at lower jet velocities. The paramount conclusion from this exercise is that the spectra attain the LSS shape for all jet velocities, at angles close to the jet axis. This is a new finding. Recall that Tam et al. [39] extracted the similarity shapes from highly heated supersonic jets; the convective Mach numbers (M_c, taken to be $\approx 70\%$ of V_j/a) for these high-speed jets are supersonic. In contrast, the convective Mach number for the $M = 0.24$ jet is only ~ 0.17. A discussion of the implications of this finding is deferred to a later section.

2. *Far-Field Correlations*

Both the polar and azimuthal correlations at various jet velocities are examined, especially while keeping in mind the spectral trend observed in the preceding section. The aim of this exercise is to uncover any connection between the noise generation mechanisms between high-speed and low-speed jets. First, we present the correlations for a heated jet: $M = 0.9$, $T_t/T_a = 3.2$, $V_j/a = 1.5$. The convective Mach number is supersonic for this case. Figure 7 shows polar corrections for two different reference microphones at 150 and 90 deg, respectively. As the separation angle between the reference (fixed) and the second microphone is increased, the value of the maximum correlation coefficient decreases progressively. For the 150 deg microphone, there is high correlation for an extended angular range; the coefficient drops to ~ 0.2 (20%) at an angle of 125 deg. The trend is very different for the 90 deg microphone; the correlation drops to ~ 0.2 (20%) when the polar separation angle is only ± 10 deg



a)

b)

Fig. 7 Polar correlations: $M = 0.9$, $Tt/Ta = 3.2$; a) reference microphone at 150 deg; b) reference microphone at 90 deg.

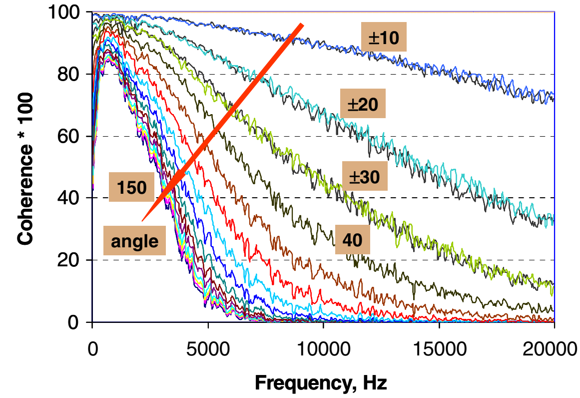
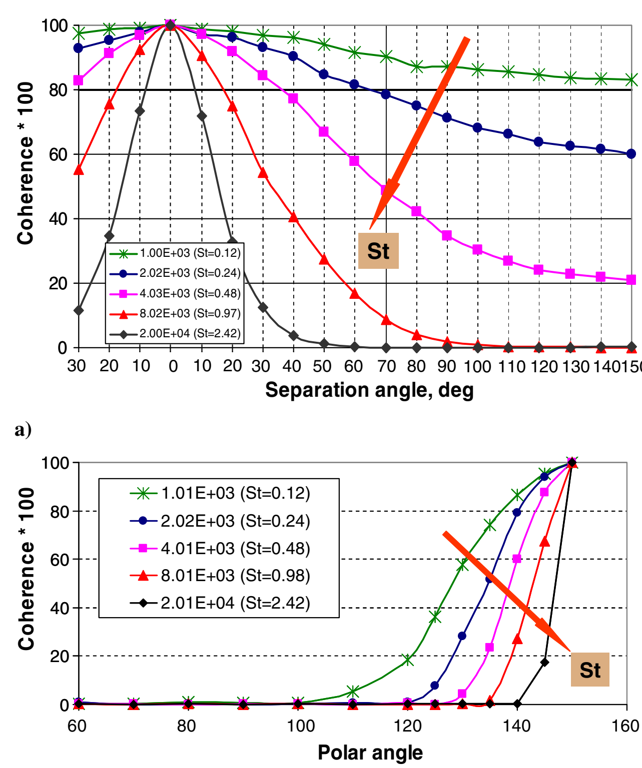


Fig. 8 Azimuthal coherence by microphone pair: reference microphone at 270 deg and at a polar angle of 150 deg; $M = 0.9$, $Tt/Ta = 3.2$. The arrow indicates direction of increasing separation angle.

Figure 8 shows the azimuthal coherence spectra for different microphone pairs in the frequency range of 200–20 kHz. The azimuthal array is at a location that corresponds to a polar angle of 150 deg, and the reference microphone is at 270 deg in the azimuthal plane. Two distinct features are exhibited: 1) there is a high level of coherence at the lower frequencies, $\sim 80\%$ for all the azimuthal separations, and 2) the coherence level drops with separation angle as the frequency is increased. For the sake of clarity, the variation of the coherence at selected frequencies (Strouhal numbers) with separation angle is shown in the following plots. Figure 9 shows the azimuthal and polar variations with angle; in the azimuthal plane, the coherence coefficient is very high for the lower Strouhal numbers St almost around the circumference of the jet. Similarly high levels of coherence are seen for the lower St in the polar direction as well. The situation is very different when the coherence functions are examined at a polar angle of 90 deg in Fig. 10. The correlation drops very rapidly in the polar direction. The corresponding correlation



a)

b)

Fig. 9 Variation of coherence coefficient with microphone separation angle: $M = 0.9$, $Tt/Ta = 3.2$; polar angle of 150 deg: a) azimuthal separation angle; b) polar angle.

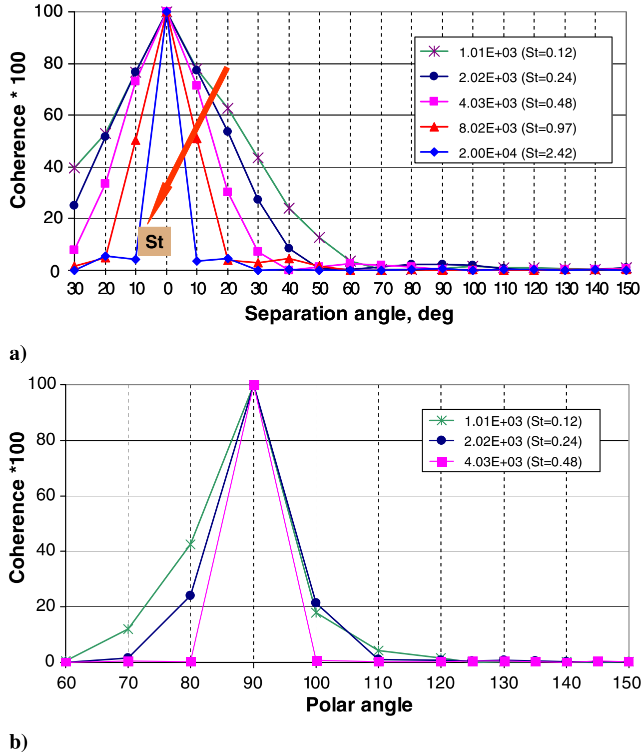


Fig. 10 Variation of coherence coefficient with microphone separation angle: $M = 0.9$, $Tt/Ta = 3.2$; polar angle of 90 deg: a) azimuthal separation angle; b) polar angle.

coefficients in the azimuthal plane for the two polar angles of 150 and 90 deg are shown in Fig. 11. Where a high correlation level of ~0.65 (65%) is maintained for a separation angle of 150 deg in the peak radiation direction, the levels fall below 0.20 for a separation angle of 40 deg at the forward angles.

Thus, there is a drastic difference in the correlation levels between the peak radiation direction of 150 and 90 deg. This is of course related to the different noise sources that are responsible for noise radiation to these directions. It is well known that for a high-speed jet, such as this sample case with $V_j/a = 1.5$, there is strong radiation from the large-scale structures to the aft angles. These structures originate in the unstable initial shear layer, grow exponentially, and eventually decay downstream of the potential core of the jet. Experimental measurements have indicated that the large-scale structures are coherent over a distance of several jet diameters in the streamwise direction. As summarized in Sec. II, these structures are efficient generators of noise and constitute the dominant noise sources, especially in the downstream direction. The observed high azimuthal and polar correlation of the far-field noise at 150 deg is consistent with our understanding that the large coherent structures are responsible for the noise radiation to this angular region.

Detailed spectral analyses have confirmed that the spectral shape at the lower radiation angles is invariant and has a universal shape, regardless of the jet Mach number or the temperature ratio. This component of noise is generated by the random fine-scale turbulence, which is distributed throughout the shear layer. As a result, one would not expect the noise to be correlated. The low levels of azimuthal and polar correlations observed at 90 deg confirm this expectation and lend support to the idea that the random turbulence is indeed the dominant noise source radiating in these directions. There is strong evidence that there are two distinct noise source mechanisms for a high-speed jet.

We now turn our attention to a low-velocity jet: $M = 0.4$, $T_t/T_a = 1.0$, $V_j/a = 0.4$. The convective Mach number is ~0.28 for this case. Figures 12a–12e show the azimuthal correlations at five polar angles of 90, 130, 150, 155, and 160 deg, respectively. At the two lower polar angles, the maximum correlations drop to ~0.2 (20%) for a separation angle of 50 deg. At a polar angle of 150 deg, maximum correlation levels ≥ 0.2 (20%) are maintained for an azimuthal separation of 120 ; at 155 deg, there is increased peak correlation ≥ 0.36 (36%) for a larger azimuthal separation angle of 150 deg. At 160 deg, the peak correlations increase to ≥ 0.54 (54%) for all separation angles. The correlations at 160 deg for the low-velocity jet are comparable to those for the convectively supersonic jet shown in Fig. 11 in the peak radiation angle. Figure 13 provides the far-field spectra at four of the polar angles and comparisons with the similarity spectra. The data at the two lower polar angles of 90 and 130 deg conform to the FSS shape; the spectrum at 160 deg has the LSS shape. The spectrum at 150 deg is in transition from the FSS to the LSS shape, and can be represented only by a combination of both shapes (notionally shown in figure). When the correlations are examined together with the far-field spectra, the following picture emerges: when the spectral shape conforms to the FSS shape, there is low correlation; when the spectral shape conforms to the LSS shape, there is very high correlation. In the transition region, the level of correlation is much higher than that seen for the FSS shape. The trends seen for the low-velocity jet ($V_j/a = 0.4$) are remarkably similar to those for the high-speed jet ($V_j/a = 1.5$). However, the high correlation values, as well as the LSS shape, are confined to a narrow angular sector, close to the jet downstream axis. Strong evidence has been presented here that indicates that the large-scale structures are important noise generators for low-velocity jets as well.

The main results for a round jet are reiterated. The spectra from very low-velocity jets ($V_j/a \geq 0.24$) attain the LSS shape at angles close to the jet axis; this feature seems to be a fundamental characteristic of jet noise at all jet velocities. The far-field spectra, at polar angles where the spectra conform to the LSS shape, exhibit very high correlations. In contrast, the spectra from jets of any velocity with the FSS shape (at lower radiation angles) have low correlations. In the transition region, where the contributions from both components are important, the correlation values are in between those seen for the FSS and LSS shapes. These trends reinforce the idea that there are two distinct components of turbulent mixing noise: the coherent large structures radiating to the aft angles and the random turbulence radiating to the lower angles. With increasing polar angle, the contributions from the large-scale structures increase progressively and eventually dominate the total radiation at aft

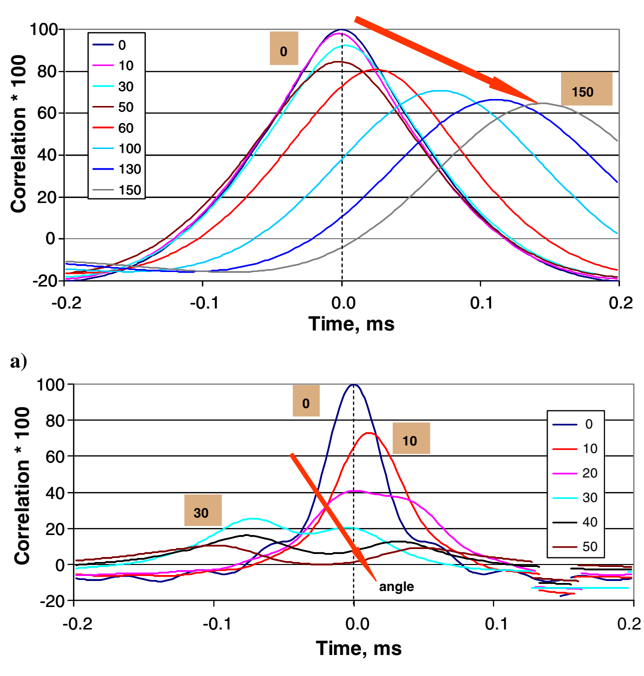


Fig. 11 Azimuthal correlations; $M = 0.9$, $Tt/Ta = 3.2$: a) azimuthal array positioned at polar angle of 150 deg; b) azimuthal array positioned at polar angle of 90 deg.

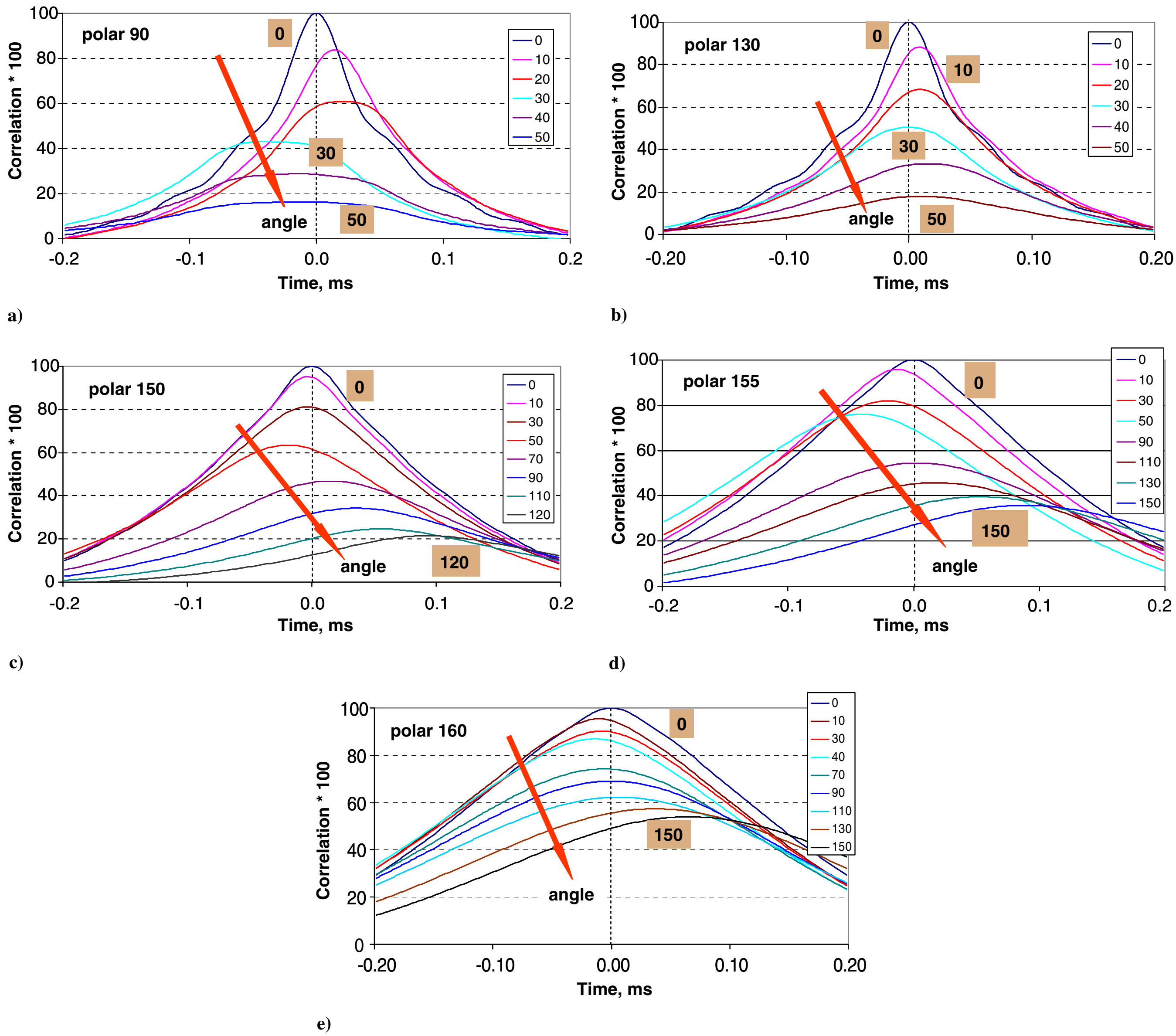


Fig. 12 Azimuthal correlations at various polar angles; $M = 0.4$, $Tt/Ta = 1.0$: polar angle of a) 90, b) 130, c) 150, d) 155, e) 160 deg.

angles. The jet velocity controls the polar angle beyond which the noise from the coherent structures becomes fully dominant.

If indeed the noise from large coherent structures is important for all jet velocities, what can be done about it? We can alter it with a beveled nozzle, as shown in the next section.

B. Alteration of the Noise Radiated by Large Coherent Structures

Based on the premise that the noise from large coherent structures could be important at low jet velocities, Viswanathan [44,45] proposed the beveled nozzle for altering the basic noise radiation characteristics of round jets. Figure 14 shows a schematic sketch of the beveled nozzle and the measurement conventions for the bevel as well as the azimuthal angles. He carried out detailed aeroacoustic measurements from two beveled nozzles, with bevel angles of 24 and 45 deg (bevel45), and illustrated that the noise radiation patterns are drastically different in the azimuthal plane. Specifically, the noise radiated toward the short lip of the beveled nozzle attains the LSS shape at a much lower polar angle, relative to a round nozzle, for the same jet conditions. To aid the discussion and provide a connection with the new correlation results to be presented here, the spectra from heated jets with $T_t/T_a = 3.2$ and at several Mach numbers are first shown. Figure 15 is a reproduction of Figs. 21 and 22 from [42]. The plume deflection angle due to the beveling is ~10 deg for bevel45; therefore, the microphone at a polar angle of 110 deg to the x axis of the coordinate system corresponds to a polar angle of 120 deg with respect to the plume axis for bevel45. Figure 15 shows spectra at the equivalent angle of 120 deg with respect to the plume axis for both the round and bevel geometries. The spectra for the round nozzle conform to the FSS shape for all Mach numbers; however, the spectra for the bevel45 toward the short lip have the LSS shape at this polar angle.

Correlation results for the round and beveled nozzles are presented next. Figure 16 shows polar correlations for the $M = 0.9$, $T_t/T_a = 3.2$, with the reference microphone at a polar angle of 120 deg. The correlation functions are very similar for the round and bevel45 nozzles toward the long lip: there is high correlation in the aft directions and the maximum values remain above ~0.2 (20%) until a polar angle of 140 deg; however, the maximum correlation drops rapidly in the direction of the lower polar angles. The correlation functions are very different in the direction of the short lip of bevel45. First of all, high correlation levels persist until a polar angle of 150 deg in the aft direction. An unusual feature is that the maximum correlation coefficients (>0.4) for the microphones at 140 and 150 deg are seen for the negative correlations. Perhaps the more interesting trend is observed toward the lower polar angles, where higher correlation levels are seen over an extended angular range.

Figure 17 shows polar correlations with the reference microphone at 150 deg for the long and short lip directions (see Fig. 7a for a

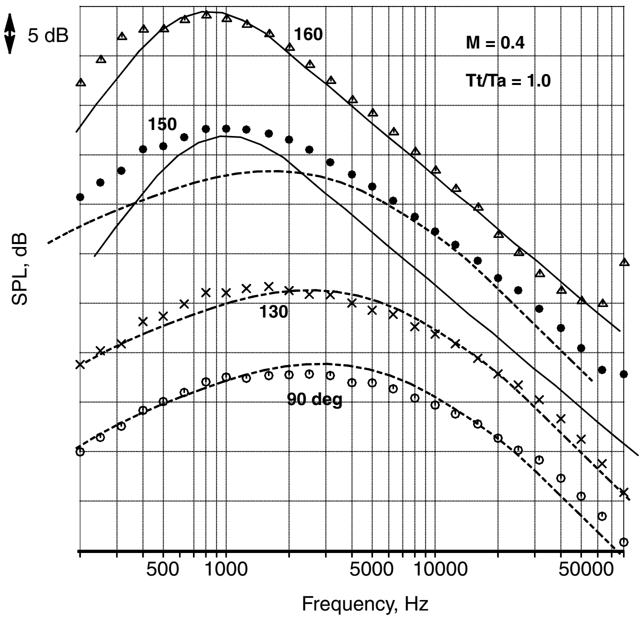


Fig. 13 Comparison of one-third-octave data with similarity spectra; $M = 0.4$, $Tt/Ta = 1.0$. Symbols: data; solid line: LSS spectrum; dashed: FSS spectrum.

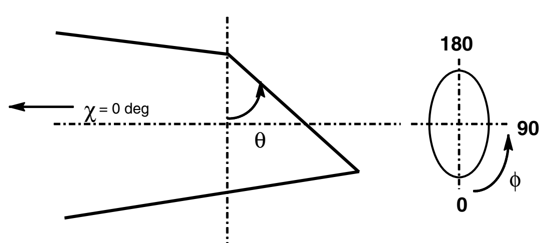
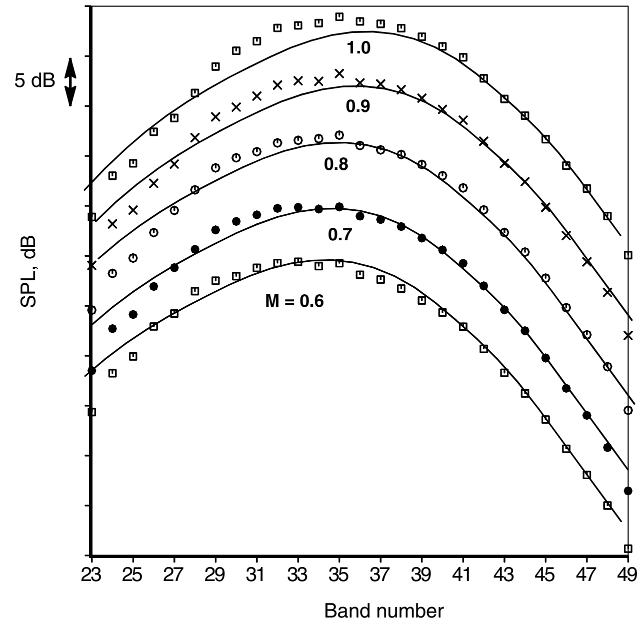


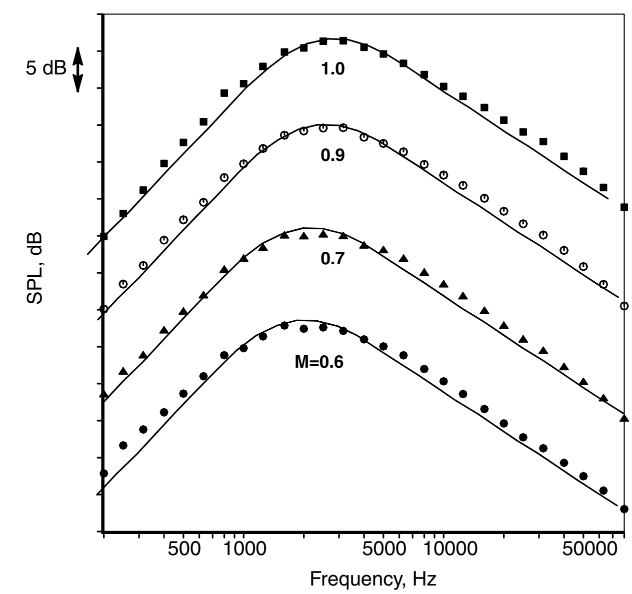
Fig. 14 Conceptual sketch of the beveled nozzle and the measurement convention for the bevel angle and the azimuthal angle.

comparable plot for the round nozzle). The correlation curves for the long lip direction are not too dissimilar from those for the round nozzle; peak correlation values $> \sim 0.2$ (20%) are observed until an angle of 125 deg. The trends for the short lip are again quite different: very high negative correlations of $\sim$0.49 (49%) and $\sim$0.43 (43%) are seen for 125 and 120 deg, respectively. Further, the positive peak for 120 deg is $\sim$0.22 (22%), roughly half the value of the negative peak. Only for the short lip is the peak value seen at negative correlations. The significance of this feature is not clear.

Figure 18 shows azimuthal correlations for the round and the bevel45 short lip; the reference polar angle is again 120 deg. The azimuthal correlations for the round nozzle drop off rapidly with separation angle, similar to the trends seen in Fig. 11 for a polar angle of 90 deg; similar trends are observed for the bevel45 long lip (not shown). However, toward the short lip of bevel45, the maximum correlation remains above $\sim$0.7 (70%) for a separation angle of 30 deg and then drops off rapidly. The reason for this behavior becomes clear when the spectral shapes at different azimuthal angles are examined in Fig. 19. First of all, the sound field is axisymmetric for the round nozzle, with identical spectral shapes for all the azimuthal angles. For the bevel45 with the short lip at 270 deg, there is a small angular sector of $\sim \pm 30$ deg where the spectra have the LSS shape; outside this sector, the shapes revert to the FSS shape. It is precisely in this angular sector that high correlation levels are seen in Fig. 18b. Once again, high correlation levels are associated with LSS-shaped spectra. The correlation measurements provide direct evidence of the hypothesis proposed by Viswanathan [44] that the noise reduction of the beveled nozzle is achieved through the manipulation of the noise generated by the coherent large-scale structures. For comprehensive information on the noise characteristics of single beveled nozzles, see Sec. IV in [44].



a)



b)

Fig. 15 Comparison of one-third-octave data with similarity spectra, $Tt/Ta = 3.2$; polar angle = 120 deg: a) symbols: data for round nozzle; lines: FSS; b) symbols: data for bevel45 short lip; lines: LSS.

The spectra at various Mach numbers (with $T_t/T_a = 3.2$) have been collapsed using the scaling laws developed by Viswanathan [46] at two angles of 110 and 120 deg. Figure 20 shows the collapsed spectra for the round nozzle and bevel45 toward the short lip. With the appropriate velocity exponent, there is good spectral collapse for both nozzles at both of the angles. Note that the plain Strouhal number is used on the x axis; there is no Doppler shift for frequency. Again, the spectral shape is not controlled by the jet velocity (V_j/a) but by the fixed temperature ratio. In the classical approaches to jet noise, the underlying belief is that the spectral shape at 90 deg is modified in the aft directions by source convection and flow/acoustic interactions. From a simple modification to the geometry through beveling, the spectral shape has been radically altered, as seen in Figs. 15 and 20. No application of Doppler factors or any kind of adjustment to the spectra based on moving sources and flow/acoustic

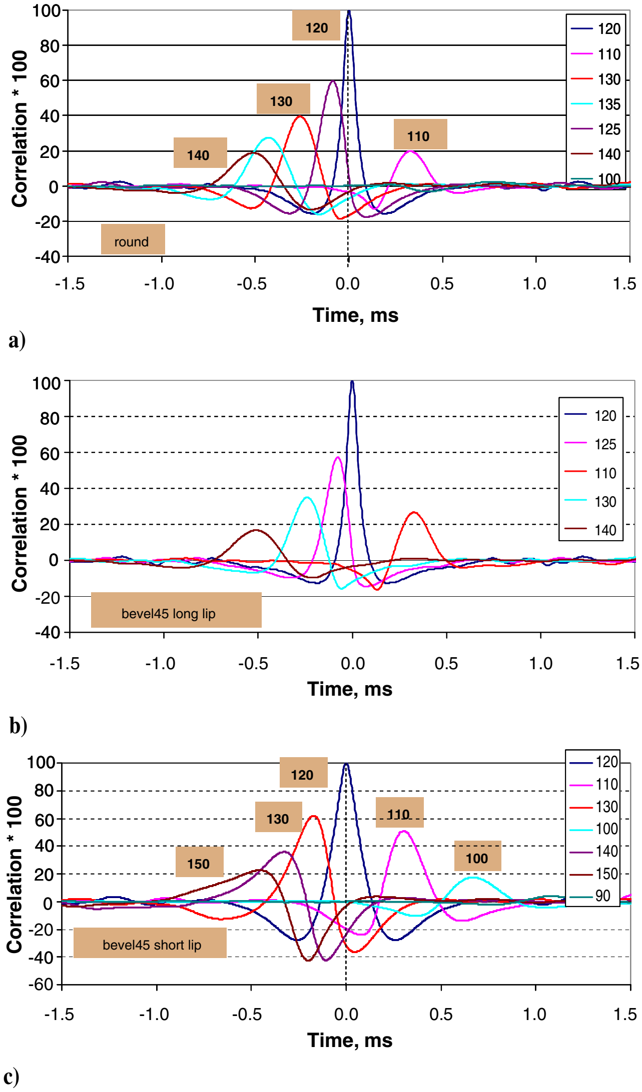


Fig. 16 Polar correlation, with reference microphone at polar angle of 120 deg; $M = 0.9$, $Tt/Ta = 3.2$: a) round nozzle, b) bevel45 long lip, c) bevel45 short lip.

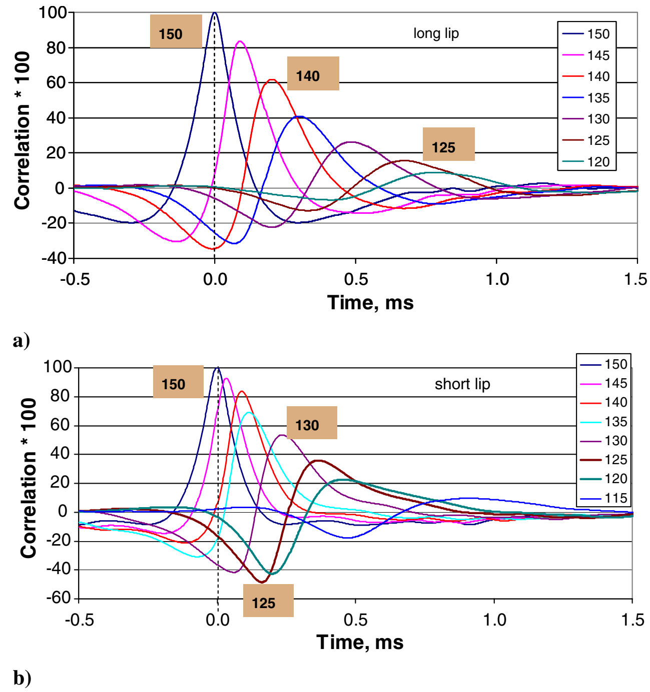


Fig. 17 Polar correlation, with reference microphone at polar angle of 150 deg; $M = 0.9$, $Tt/Ta = 3.2$: a) bevel45 long lip, b) bevel45 short lip.

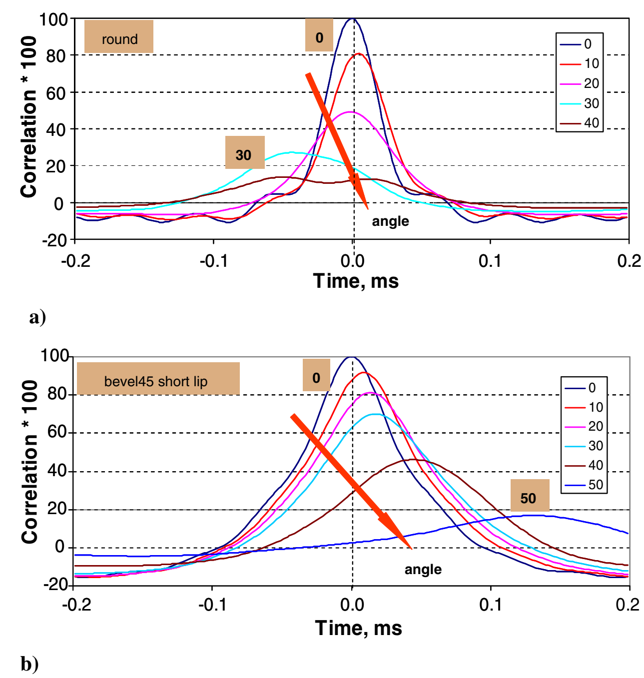


Fig. 18 Azimuthal correlation with microphone array at polar angle of 120 deg; $M = 0.9$, $Tt/Ta = 3.2$: a) round nozzle, b) bevel45 short lip.

interaction can possibly explain the distinctly different (FSS and LSS) spectral shapes seen at the same radiation angle in the preceding figures; the shortcomings with the classical approaches vis-á-vis the experimentally observed change in spectral shape with increasing angle have been discussed in detail in [43,46]. It is obvious that without accounting for the role of large coherent structures, it would be impossible to predict the correct spectral shapes in the aft quadrant; see Sec. IV.C.

C. Role of Large-Eddy Simulation

It is apropos to discuss briefly the role of large-eddy simulation (LES) for the prediction of jet noise; though this paper deals mainly with experimental measurements, the findings warrant its inclusion. The dynamics of the large coherent structures, their inception, their evolution, their development by pairing, and their eventual collapse in the jet plume, are intrinsically captured by LES. (On the other hand, there is no explicit accounting of the large structures in steady-state Reynolds-averaged Navier–Stokes computational fluid dynamics, which is used as input to traditional models for jet noise.) Therefore, predictions based on LES should be able to capture the correct spectral shapes in the aft quadrant. Recently, a rigorous assessment of the LES has been carried out (see [47,48]). Four main issues were addressed:

1) Can LES predict the measured LSS shape for an unheated $M = 0.4$ jet at angles $\geq \sim 150$ deg?

2) Can LES predict the gradual progression from the FSS to the LSS shape with radiation angle for a high-speed jet?

3) Can LES predict the observed azimuthal variations in the spectral shapes for a beveled nozzle?

4) Can LES predict the peak source locations for jets of different V_j/a?

It was demonstrated clearly in these two studies that the LES predictions address these issues satisfactorily. For the sake of completeness, a single figure from [48] is reproduced here as Fig. 21; for comprehensive details of the LES methodology see [49,50]. The predictions are shown for the bevel45 nozzle, with $M = 1.0$ and $T_t/T_a = 3.2$. The predicted spectra radiated toward the short and

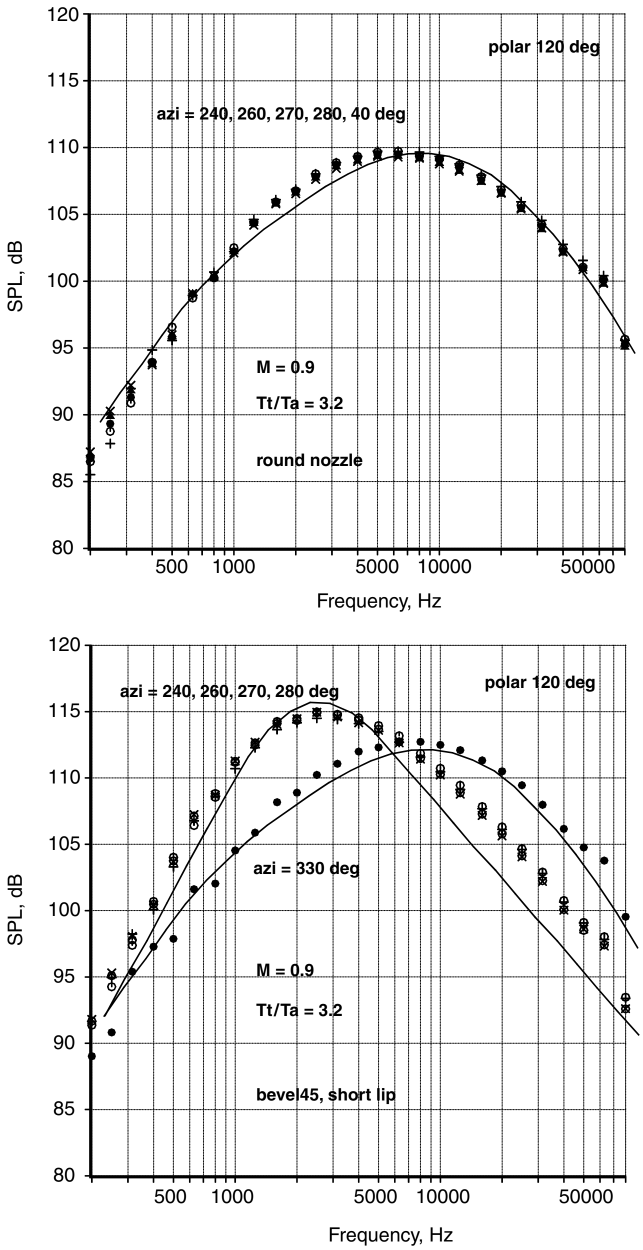


Fig. 19 Measured one-third octave data and comparison with similarity spectra at different azimuthal angles; $M = 0.9$, $Tt/Ta = 3.2$, bevel short lip at azimuthal angle of 270 deg.

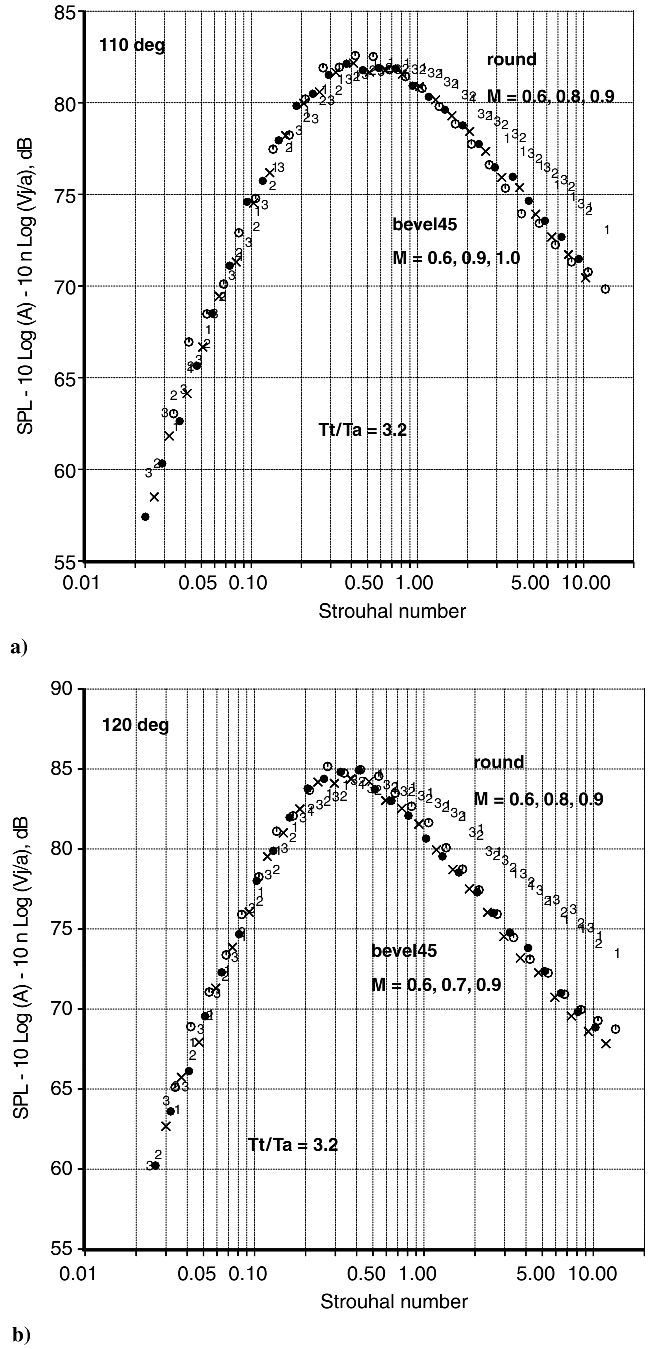


Fig. 20 Collapsed one-third-octave spectra from round and bevel45 toward short lip: a) 110, b) 120 deg.

long lips at four polar angles, where the spectral shapes begin to change, are compared against the data. First of all, there is excellent agreement between the predictions and the data in the absolute levels; perhaps more significant is the fact that the LES predicts the difference in the noise signature in the two azimuthal directions for the beveled nozzle. Attention is drawn to the spectral shapes toward the short lip at two of the polar angles of 90 and 120 deg; clearly, the predictions capture the broad peak at 90 deg and a sharper peak at 120 deg. Thus, the subtle features in the spectra are reproduced by LES, thereby establishing the importance of the dynamics of the large-scale structures in jet noise. The salient conclusion, in support of the experimental measurements presented here, is that LES provides unambiguous evidence for the importance of large coherent structures in noise radiation even at low jet velocities.

It has also been verified that the spectra from the beveled nozzle could be collapsed using the scaling laws of [46]. At the same polar angle, the spectra at different (V_j/a) but constant T_t/T_a have the FSS and LSS shapes for the round and beveled nozzles, respectively. The flowfields computed by LES in [48] do not show drastic differences between the two geometries. Approaches based on classical theories of jet noise, with moving sources and flow/acoustic interaction effects, would be unable to explain/predict the observed spectral trends.

The mechanism responsible for the generation of noise by the large coherent structures at low (V_j/a) needs to be established. The hypothesis in Viswanathan [40,44] of a rapid amplitude modification of the instability waves downstream of the end of the potential core seems plausible; this idea should be investigated. Based on the experimental evidence presented here, Morris[†] [51] posed the following question: If indeed the catastrophic collapse of the coherent structures is the mechanism responsible for noise radiation to the peak direction at low velocities, why would the same phenomenon not prevail at higher jet velocities? He pointed out that the rapid decay process, at both low and high jet velocities, would

[†]Morris, P. J., personal communication, 21 May 2007.

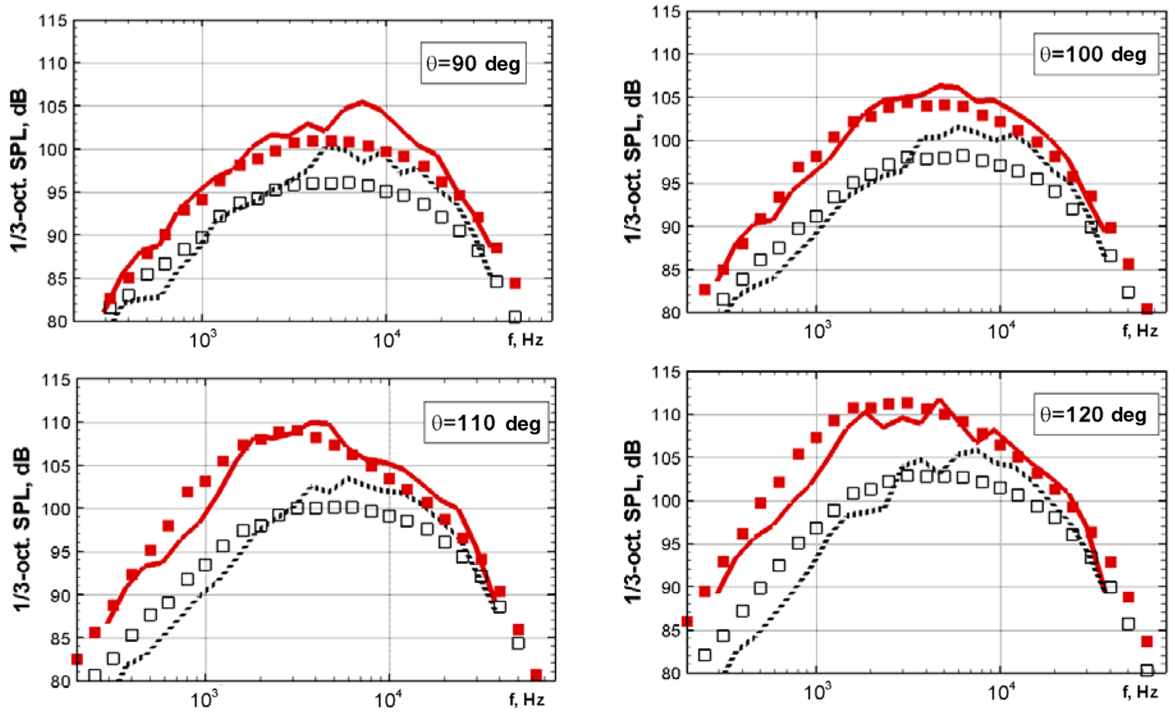


Fig. 21 Comparison of predicted one-third-octave spectra with data; Bevel45, $M = 1.0$, $Tt/Ta = 3.2$. Symbols: data; lines: predictions; solid/filled: short lip; dashed/open: long lip.

have to occur in such a way that the radiating part of the source wave-number-frequency spectrum remains essentially unchanged to produce the same spectral shape in the far-field noise. This observation raises intriguing questions; numerical simulations and novel experimental measurements of the dynamics and the collapse of large coherent structures is clearly warranted.

V. Summary

Noise source mechanisms in subsonic jets, over a wide range of (V_j/a), are characterized with far-field spectral and correlation data. Several issues, including the importance of the role of large coherent structures in noise generation at extremely low (V_j/a), are addressed. To this end, the far-field spectra from unheated round jets have been acquired at extremely low Mach numbers of 0.12–0.45; these data complement existing data in the Mach number range of 0.4–1.0. It is already established that the spectra at the lower polar angles conform to the fine-scale similarity shape regardless of the jet Mach number and temperature ratio. The new measurements indicate that the same trend of the large-scale similarity shape, observed at 160 deg from unheated jets with $M = 0.4$–1.0, prevails down to a Mach number of 0.26. At a still higher aft angle of 165 deg, the LSS shape is observed for all the Mach numbers for which meaningful measurements are possible. At all jet velocities, there is a gradual progression from the FSS to the LSS shape; in the transition region, the spectra may be characterized by a combination of the two shapes. However, at angles close to the jet axis, the LSS shape is attained by jets of all (V_j/a). This seems to be a fundamental characteristic of jet noise and is a new finding.

Far-field correlations reveal several key features of jet noise: there is very little correlation for all V_j/a at the lower polar angles, where the FSS shape is observed. At a polar angle of 90 deg, the peak correlation coefficient drops to <0.2 (20%) within a small angular sector of ± 10 deg in the polar direction and $\pm\sim 50$ deg in the azimuthal direction. In contrast, for a high-speed jet $(V_j/a = 1.5)$ at a polar angle of 150 deg, the peak polar correlation coefficient remains higher than ~ 0.2 (20%) over an extended polar angular range of 25 deg; in the azimuthal direction, the values of the peak coefficient are >0.65 (65%) for all separation angles from 10 to 150 deg.

Remarkably similar trends are seen at low (V_j/a) as well: there is very little correlation at the lower polar angles. At 150 deg, the peak correlation remains above ~ 0.35 (35%) for an azimuthal separation of 90 deg; at 160 deg, the peak values remain above ~ 0.55 (55%) for all separation angles from 10 to 150 deg! The FSS shape prevails at the lower polar angles; at 150 deg, the spectrum consists of contributions from both the fine-scale and large-scale turbulence, and at 160 deg the spectrum attains the LSS shape. There is a corresponding trend in the azimuthal correlations: high correlations for the LSS-shaped spectra and low correlations for the FSS-shaped spectra. It is fair to conclude that the noise from the large coherent structures is indeed important at low speeds.

The drastic difference in the nature of the dominant source responsible for noise radiation, i.e., a random incoherent source at 90 deg (and lower polar angles) and a highly-correlated coherent source at 150 deg (and large aft angles), indicates strong evidence for the existence of two independent sources in both high-speed and low-speed jets, with the coherent large structures radiating to the aft angles and the random turbulence radiating to the lower angles. With increasing polar angle, the contributions from the large-scale structures increase progressively and eventually dominate the total radiation at aft angles. The jet velocity controls the polar angle beyond which the noise from the coherent structures becomes fully dominant.

For beveled nozzles, conceived specifically to alter the noise radiated by the large-scale structures, correlation measurements have been obtained to augment previous spectral data. In contrast to the spectra from a round nozzle, which conform to the FSS shape at a polar angle of 120 deg for all Mach numbers and stagnation temperature ratios, the spectra from a beveled nozzle conform to the LSS shape for Mach numbers in the range of 0.6–1.0 at a temperature ratio of 3.2. There is a corresponding higher polar correlation for the bevel45 toward the short lip. Also, the angular range with higher correlations extends to the lower polar angles. A curious and unexplained feature is that much higher negative peaks are seen only in the direction of the short lip. In the azimuthal plane, peak correlations of ~ 0.7 (70%) are observed for an angular range of ± 30 deg for the short lip; the spectra within this angular range conform to the LSS shape. In contrast, the levels of correlation are much lower for the round nozzle. The correlation data confirm earlier observations that the noise from the large structures is beamed to lower polar angles toward the short lip and that the noise reduction of the beveled nozzle is due to the manipulation of the noise mechanism associated with the coherent structures.

Acknowledgments

It is a pleasure to thank several colleagues who ensured the success of this study. The crew at the Low-Speed Aeroacoustic Facility at Boeing did a commendable job in setting up and operating the azimuthal array. Many fruitful discussions on the instrumentation and the processing of the data with Don Boston were invaluable; the software support provided by Guy Neubert for the processing of the array data was indispensable.

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