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Instrumentation Considerations for Accurate Jet Noise Measurements

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Accurate measurements of jet noise spectra at model scale over a wide range of frequencies critically depend on the quality of the jet rig as well as the measurement system. The many aspects of the instrumentation system that require careful consideration to ensure the acquisition of good data are discussed. The proper choice of the microphones and their orientation, the dynamic range requirements, and the design of the electronics for minimizing the magnitude of the corrections that must be applied to the raw spectra are among the many issues pertaining to jet noise measurements investigated. The reasons for the upturns in the jet noise spectra at the higher frequencies in recent tests are examined to identify the contributing factors, and some recommendations are provided to avoid this problem. Spectral measurements of simple point sources, simple distributed sources, and model scale jets with normal and grazing incidence microphones on traversing arrays, as well as on fixed poles at different distances from the sources, are used to evaluate these factors. It is also established that a distance of ∼35 nozzle diameters ensures measurement in the true far field for jet noise.

I. Introduction

JET noise data from model-scale dual-stream exhaust systems are commonly used to characterize the noise generation, investigate the effect of cycle conditions, develop noise suppression concepts, and generate large databases for the development and refinement of prediction methodologies. In an engine test, the highest frequency of interest is usually 10 kHz for aircraft certification. In model-scale tests, one needs to obtain accurate spectral measurements over a much wider frequency range to facilitate comparison of scaled model data with engine noise spectra. Therefore, the requirements for a model test are more stringent, necessitating a good understanding of the limitations of the measurement system and the adoption of practices that would ensure good measurements at the higher frequencies. Fundamental issues concerning microphone incidence and its effect on the measured spectra must be considered. Measured jet noise spectra are used here to illustrate the issues because the spectral shapes from simple round jets are well established. However, the discussions are equally pertinent to other sources of noise as well. Some fundamental issues concerning the measurement system, selection, and the orientation of microphones and the distance of the microphones to the noise sources and their consequences on the measured spectra are investigated in this paper.

Linear or polar microphone arrays are usually adequate for simple axisymmetric nozzles. However, for nonaxisymmetric nozzles such as a rectangular mixer/ejector, there is strong azimuthal variation in the radiated noise field. For aircraft application, noise spectra are required over a wide range of polar angles and frequencies to enable the computation of the effective perceived noise level (EPNL). For the computation of the EPNL at the sideline location for certification, one needs to measure the maximum noise level, which could occur at any azimuthal angle that is not known a priori for a complex nozzle. Therefore, it is desirable to quantify the azimuthal content at several angles that span preferably one quadrant in the azimuthal plane. The number of microphones required to accomplish this objective becomes prohibitive, and it is not practical to mount these microphones on poles or booms because such an arrangement would lead to problems with reflections, spacing, interference, etc. An alternative approach is clearly warranted and Boeing built an azimuthal array that could be traversed in the axial direction. The array is mounted on tracks and controlled by a stepping motor that allows for precise positioning at any desired axial location (polar angle). This arrangement introduces additional complexities, as will be discussed.

For industry applications, especially for the simulation of full-scale engines, the scaled frequencies from the model test should cover the frequency range of interest for the engine. This requirement, though not always satisfied, necessitates the measurement of spectra up to very high frequencies in scale-model tests. Viswanathan[1] noted several anomalous trends in the measured spectra at the higher frequencies. Of particular concern was the tail-up at the higher frequencies in recent measurements, contrary to the well-established spectral shapes from simple round jets. The poor quality of data led to a comprehensive investigation of all of the issues related to jet rigs, as well as the data acquisition system, as reported in Ref. 1.

A sample measurement that highlights the problems is first presented. Figure 1 shows typical measured spectra at 150 deg from heated jets, obtained with the microphones set at grazing incidence. The polar angle is measured from the jet inlet axis, with the jet exhaust axis corresponding to 180 deg. Let us ignore the spikes at the lower frequencies because they are caused by rig-generated tones and possible reflections and pay closer attention to the tail-up in the spectra above ∼30 kHz. These spectra were obtained with a simple round nozzle and have not been converted to lossless conditions. Clearly, this is not the expected trend, and there is a problem at the higher frequencies because the spectral levels should keep going down instead of tailing up with increasing frequency. A comprehensive investigation was carried out to identify the underlying problems and to devise suitable solutions. Reflections from the microphone array and microphone holders, incorrect application of microphone corrections, improper choice of gain setting, actual noise level running into the high levels of the electronic noise floor, etc., were all considered as possible reasons for producing the observed trends. A series of diagnostic tests, first with simple sources of noise, helped the assessment of the impact of each of the issues and are described in the following sections.

II. Characteristics of Microphones

Generally, in scale-model tests conducted in an anechoic chamber, the far-field microphones are oriented such that they are either at normal or at grazing incidence. For normal incidence, the microphones

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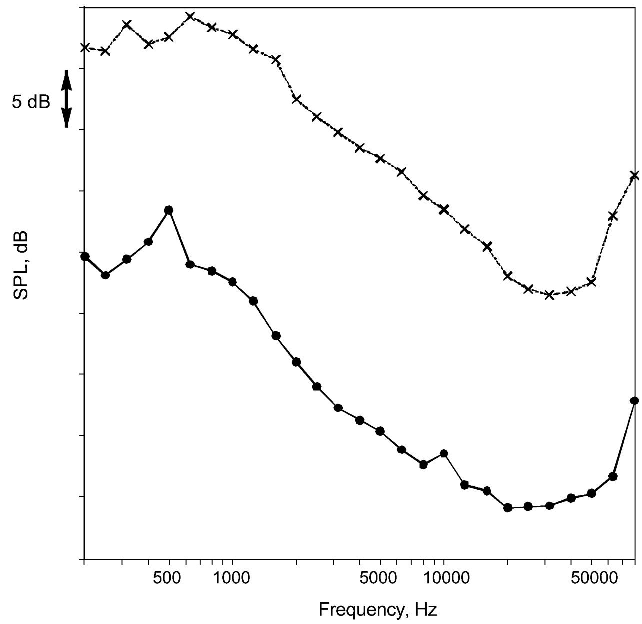


Fig. 1 Typical as-measured spectra at 150 deg (polar angles measured from inlet axis) from heated round model jet; grazing incidence microphones: ●, $M = 0.8$ and ×, $M = 1.0$.

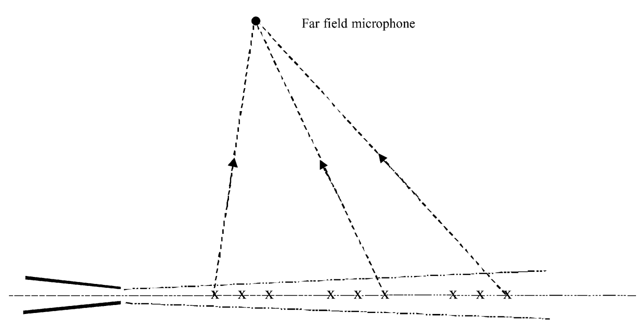


Fig. 2 Plan view of jet sources and microphone at grazing incidence.

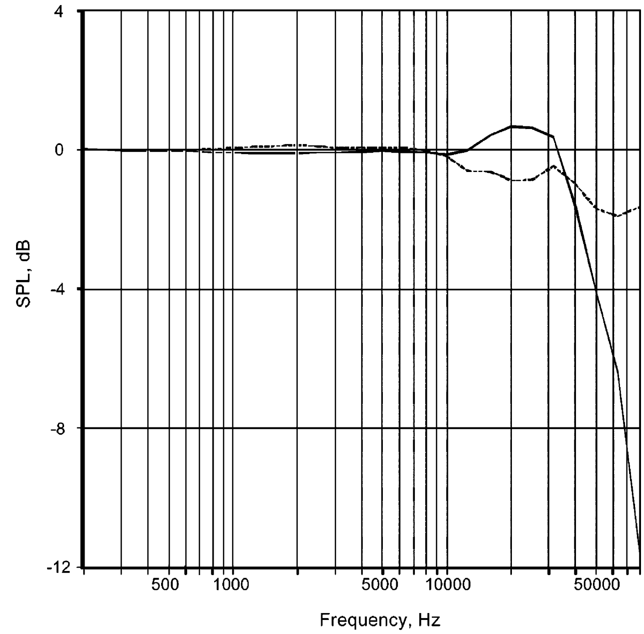


Fig. 3a Variation of average microphone free-field response with frequency: ——, B&K 4136 microphone at grazing incidence and - - -, B&K 4135 microphone at normal incidence.

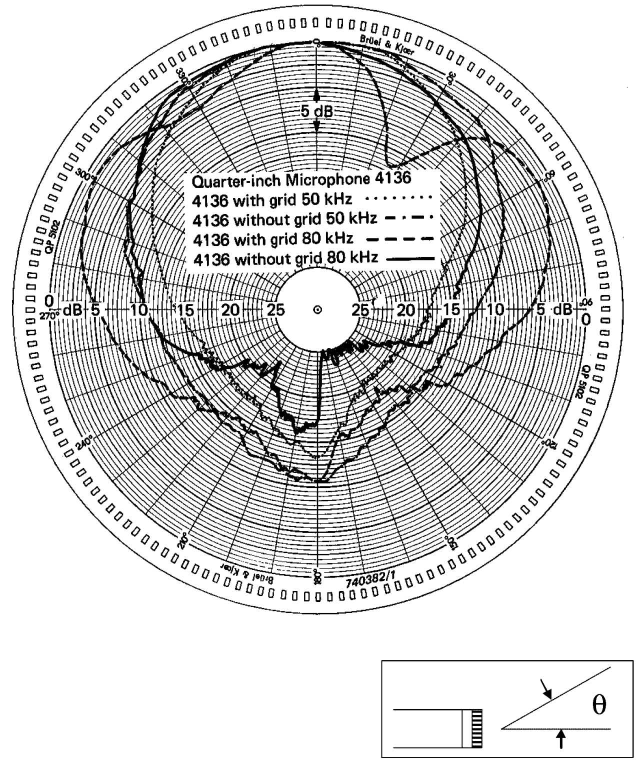


Fig. 3b Directional characteristics of the $\frac{1}{4}$-in. (6.35-mm) B&K 4136 microphone at 50 and 80 kHz (reproduced from Ref. 2).

are usually pointed at the center of the jet at the nozzle exit plane with the implicit assumption that the sources of jet noise can be regarded as a point source concentrated at this location. When the microphones are placed at very large distances, in the true far field of the noise sources, this assumption of a point source is valid and justified. Many anechoic chambers are of limited size, thereby placing constraints on the available distances to the microphones. Provided that the microphones are located in the acoustic and geometric far field, the assumption of a point source is not necessary when the microphones are set at grazing incidence. For grazing incidence, the plane of the diaphragm of the microphones is tangential to and coincides with a plane drawn through the jet centerline. A simple way to achieve grazing incidence is to locate the microphones at the same height as the jet centerline with the microphones pointed vertically up or down. Figure 2 shows a schematic of the plan view of a typical nozzle and the placement of a far-field microphone pointed vertically up. Also shown are hypothetical acoustic rays traveling from the distributed sources to the microphone. For aeroacoustic tests at Boeing, the typical choice has been Bruel and Kjaer (B&K) type 4135 $\frac{1}{4}$-in. (6.35-mm) microphones (or the newer type 4939) for normal incidence and type 4136 for grazing incidence, with the as-measured data fully corrected for bias errors in the frequency response of the measurement chain.

The high-frequency sensitivity of condenser microphones varies substantially as the angle of the incident acoustic ray on the microphone diaphragm changes from normal to grazing incidence. The directional characteristics of microphone response for various types of microphones and incident angles may be found in Ref. 2. To aid the discussions in the following sections and for the sake of completeness, typical microphone response as a function of frequency for the two types of microphones is shown in Fig. 3a. The directional characteristics of the B&K 4136 microphones at two higher frequencies of 50 and 80 kHz from Ref. 2 are shown in Fig. 3b. The relative response curves in Fig. 3a were obtained by averaging the individual normalized response of several microphones (of the same type) and, hence, are representative of the magnitude of the corrections that must be subtracted from the measured spectral levels. As seen, these corrections are strong functions of frequency: Whereas the magnitudes are small at lower frequencies ($\leq$12,000 Hz), the measured levels could be roughly 8–10 dB higher than the actual sound pressure levels (SPL) at the higher frequencies of interest in scale-model tests if the signal runs into the electronic noise floor for the microphones at grazing incidence. Given these large corrections, care is required in the acquisition of accurate spectra at the higher frequencies because the noise levels at these frequencies are impacted by the microphone orientation as will be shown. It is pointed out that the microphones are set at grazing incidence for engine tests; however, Fig. 3 indicates that the corrections are extremely small for the frequencies of interest. For a discussion on the selection of microphones, see Ahuja,[3] pages 399–405.

A microphone set at normal incidence tends to emphasize the noise source at which it is pointed, that is, along its axis, and sources located within a cone of half-angle ∼10 deg. The microphone is designed to keep the magnitudes of the free-field corrections small. This is especially true for normal incidence. When a microphone is at grazing incidence, however, the contributions from a line of distributed sources (as shown in Fig. 2) are given equal weighting. Therefore, it has been generally believed that, for the measurements of jet noise, it is preferable to set the microphones at grazing incidence to get a truer value of the spectral levels. The pros and cons of the choice of microphones and their orientation are described in the following sections. Sample experimental results are provided to highlight the main points.

III. Test Details

The experiments were carried out at the Boeing Low Speed Aeroacoustic Facility (LSAF). Detailed descriptions of the test facility, the jet simulator, the data acquisition and reduction process, etc., may be found in Viswanathan.[1,4] Hence, only an overview is provided here. Three different sources were used: a point source, a line of distributed sources, and a model jet. Aeroacoustic measurements from single-stream nozzles of various diameters, two compound-flow nozzles of different exit diameters, and a dual-stream nozzle were made. Different microphone arrangements were adopted, depending on the issue that was investigated. For example, to verify the accuracy of the microphone corrections, noise from a point source, generated using an "air ball" (a spinning metallic sphere with multiple holes of different diameters) was measured with two microphones set at normal and grazing incidence, respectively, and at the same distance of 5 ft from the noise source. Two other pairs of microphones were located at larger distances of 10 and 25 ft, respectively. The same exercise was then repeated with a line of distributed sources obtained by blowing high-pressure air into a tube with fine holes along the length of the tube and capped at the opposite end.

For a standard jet noise test, the microphones are usually located at a constant sideline distance of 15 ft (4.572 m) from the jet axis. Several linear arrays of microphones are used at different azimuthal angles, usually with a polar angular range of 50–155 deg. Additional microphones at a sideline distance of 9.17 ft (2.79 m) were also located at large polar angles to minimize interference with the exhaust collector; these microphones were at a different azimuthal angle. In the measurements reported in Refs. 1 and 4, all of the microphones were mounted on fixed poles and set at normal incidence. This arrangement is adequate for simple axisymmetric nozzles, the radiated noise field from these being nearly axisymmetric. As noted in the Introduction, a traversing array has also been used. Figure 4 shows a plan view of the anechoic facility, and Fig. 5 an end view of the wind tunnel, the jet rig, and the traversing array. In past tests with non-axisymmetric nozzles, eight microphones were typically used on the array to map the sound field in one quadrant in the azimuthal plane. Now, because the same microphones are traversed to obtain data over a large range of polar angles, they necessarily have to be set at grazing incidence. Otherwise, the incident angle from an acoustic ray keeps varying as the polar angle is changed.

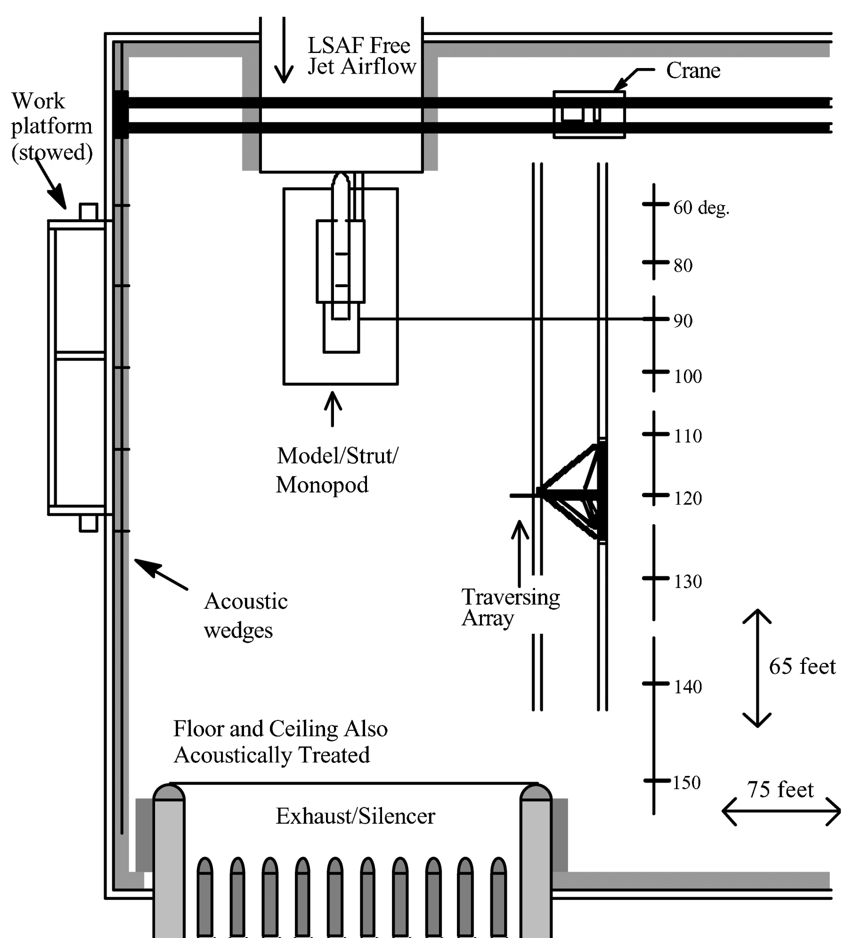


Fig. 4 Plan view of anechoic chamber, jet rig, wind tunnel, and traversing array.

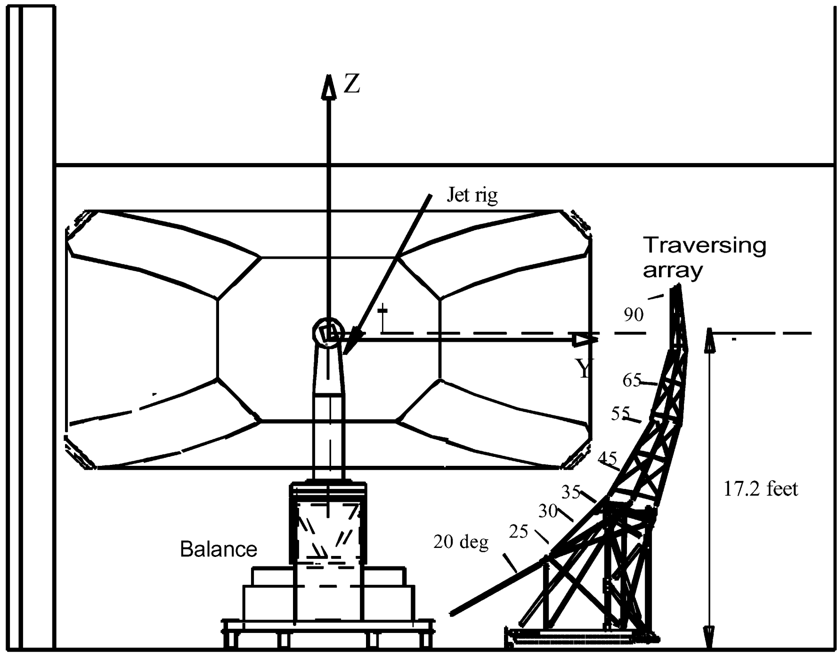


Fig. 5 End view of jet rig, wind tunnel, and traversing array.

This requirement of grazing incidence places additional demands on the data acquisition system as discussed later.

IV. Results and Discussion

A. Microphone Incidence Corrections and Gain Setting

Measurements from the simple point source and the simple distributed source clarified these two issues. Both of these sources produce high-frequency noise and moderately flat spectra, which enabled the gain setting of the microphones to be set to a large value of 60 dB. It was first verified that, with the proper application of microphone corrections, the corrected spectra from the two microphones at a distance of 5 ft were identical for the point source. Good collapse of the corrected spectra was obtained for the distributed sources as well, with the pair of microphones at a distance of 5 ft. The same agreements were observed for the pair of microphones at a distance of 10 ft as well. Furthermore, different schemes for mounting the microphones were evaluated. It was observed that the reflections from the microphone holder, wrapped with foam inside and on the outside, and the sting mounting produced negligible wiggles in the narrowband spectra, indicating the absence of standing waves and strong reflections. These simple tests ruled out errors in the application of the incidence corrections being responsible for the turn-ups at the higher frequencies.

B. Dynamic Range Requirements

Throughout these tests with the simple sources as well as with a round nozzle, two other microphones were positioned at a much larger distance of 25 ft, again at normal and grazing incidence, respectively, as noted. When the corrected spectra from this pair of microphones were compared, it was noticed that spectra from the microphone with the grazing incidence exhibited the turn-up at the higher frequencies, indicating that the measured signal was running into the electronic noise floor at the higher frequencies. Typically, the electronic noise floor keeps rising with increasing frequency, reaching high levels at the higher frequencies of interest in model-scale tests. An examination of the directional characteristics curves (Fig. 3b here and Figs. 6.26 and 6.27 in Ref. 2) indicates that there is a ∼12-dB difference between the signals detected by the normal and grazing incidence microphones at 50 kHz. This difference keeps increasing with frequency, and at 80 kHz, the difference is ∼16 dB. Therefore, the dynamic range of the measurement system has to be much higher when the microphones are set at grazing incidence. Otherwise, the application of the corrections to the signal from the grazing incidence microphone results in the addition of these terms to the electronic noise floor and not the actual signal, thereby resulting in the turn-up at the higher frequencies. Another critical consideration for microphones set at grazing incidence pertains to the possible presence of other unsuspected sources in the chamber, such as due to hydraulic systems, air seals, etc. Although the microphones may be at grazing incidence for the jet sources, they could be pointed directly at the other sources; given the increased free-field gain for normal incidence (seen in Fig. 3b, for example), these other sources could overwhelm the actual jet noise.

The spectra from a dual-stream nozzle at large aft angles have a steep rolloff at the higher frequencies. The magnitude of the difference between the spectral peak (at ∼1000 Hz) and the spectral level at 80 kHz is ∼50 dB for one-third octave spectra. It is well known that one-third octave spectra tend to emphasize the high-frequency part of the spectrum because the band width that corresponds to a particular center frequency keeps increasing with increasing frequency. For narrowband spectra, the dynamic range is considerably larger, and the difference between the peak and lowest levels could be as high as ∼65 dB. The dynamic range of the measurement system should be adequate to span the range of the overall SPL and the lowest level of interest. When narrowband spectrum analyzers are used, the issue of adequate dynamic range becomes more critical. The primary issue here is to keep the signal sensed by the microphone above the electronic noise floor. It is important to understand the requirements for any given test and ensure that proper measurements are possible (also see Sec. IV.D). Given the sign of the response corrections, there is a fundamental problem associated with using grazing incidence as the dynamic range requirement is further increased. Based on the preceding exercise, improvements to the data acquisition system were implemented that resulted in a significant increase in the useful dynamic range and the elimination of the tail-up at the higher frequencies. A new and upgraded data acquisition system with Hewlett–Packard E1433B analyzers was installed. This system provides the capability for the acquisition of narrowband data of desired bin spacing and frequency range, as well as simultaneous data acquisition from 40 channels. In the current tests, very fine narrowband data with a bin spacing of 24 Hz up to a maximum frequency of 88,320 Hz were acquired and synthesized to produce one-third octave spectra, up to a centerband frequency of 80,000 Hz. Given the complexities with the traversing array and the longer time required per measurement to acquire data over a wide range of polar angles (wherein the array has to be moved and positioned at each angle), fixed pole-mounted microphones are now preferred for most standard tests.

C. Effect of Microphone Incidence for Distributed Noise Sources

It is evident that microphones at normal incidence are more sensitive and, hence, preferable for the acquisition of good data at higher frequencies. The potential errors introduced by distributed sources, such as in a high-speed jet, with this arrangement are now evaluated as follows. To address this issue, two linear microphone arrays were set up at azimuthal angles ϕ of 25 and 90 deg. These microphones were mounted on poles, with all of the microphones set initially at normal incidence and pointed at the center of the nozzle exit plane. Data were acquired at several test points on a selected engine cycle line, set 1. Then, all of the microphones in the array at the azimuthal angle of 25 deg were set at grazing incidence and data were acquired at the same cycle points, set 2. The microphones on the other array ($\phi = 90$ deg) were untouched and remained at normal incidence. These served as reference or control microphones for tracking any changes in the spectra due to minor changes in the jet operating conditions and variability in test day conditions. Finally, the two sets of data were corrected to standard day conditions using the method of Shields and Bass[5] to eliminate the differences due to atmospheric conditions.

First, we establish the repeatability of data by examining the spectra from the reference microphone array ($\phi = 90$ deg) acquired in sets 1 and 2. Spectral comparisons at polar angles of 95 and 130 deg and at three power settings are shown in Figs. 6 and 7, respectively. There is excellent agreement between the two sets of spectra except for a small difference in the range from ~3000 to ~4000 Hz at 130 deg. Above a frequency of 10 kHz, the two sets of curves are virtually identical at both angles. Equally good agreement is seen at other polar angles as well. Figures 6 and 7 indicate that it is possible to acquire consistent and repeatable data when proper care is taken.

Next, we present data from the other array ($\phi = 25$ deg) to assess the effect of microphone incidence for distributed sources. Figures 8 and 9 show comparisons at the same polar angles from the other array, where the incidence of the microphones was changed from normal (set 1) to grazing (set 2). There are noticeable differences with frequency, which are consistent for the three jet conditions and the two angles. The biggest discrepancy is seen at ~50 kHz. Surprisingly, the same trends are observed at nearly all polar angles. To obtain a quantitative measure of the effect due to distributed sources in the jet, the difference in the SPLs Δ as a function of model-scale frequency was calculated at each microphone in the two azimuthal arrays. Furthermore, to eliminate the variations due to slightly different power setting, the Δ at four cycle conditions were averaged. The magnitudes of the averaged Δ as functions of frequency and polar angle are displayed as contour plots, in Figs. 10 and 11.

In Fig. 10, the Δ from the 90-deg azimuthal microphones (control microphones) are shown. At all angles and all frequencies, the measured levels are within ±0.25 dB, attesting to the impressive repeatability of data. Figure 11 shows the effect of the distributed sources, as captured by the two different microphone orientations on the array at an azimuthal angle of 25 deg. Figure 11 shows that there are systematic differences, with a strong dependence on frequency and a weaker dependence on polar angle. For some frequency bands, the normal incidence microphone records a higher level than the grazing incidence microphones, whereas at other frequencies, the

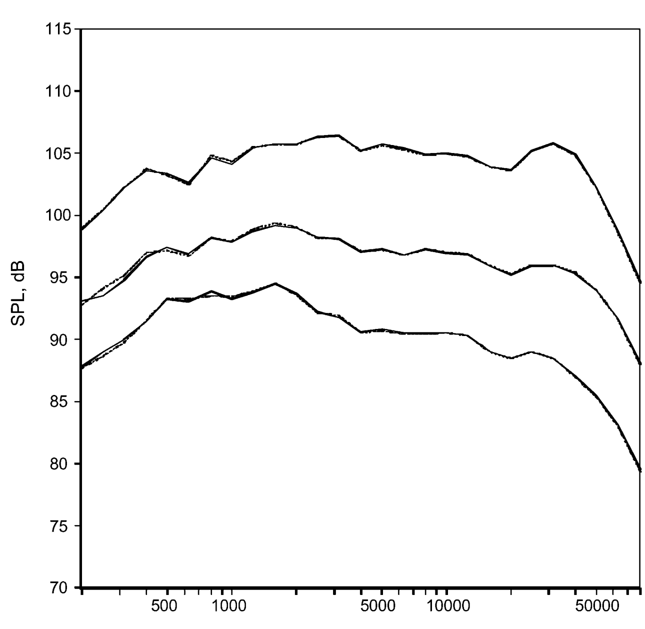


Fig. 6 Spectra at 95 deg at three power settings from the control microphones: - - -, set 1 (normal incidence) and ——, set 2 (normal incidence); azimuthal angle $\phi = 90$ deg.

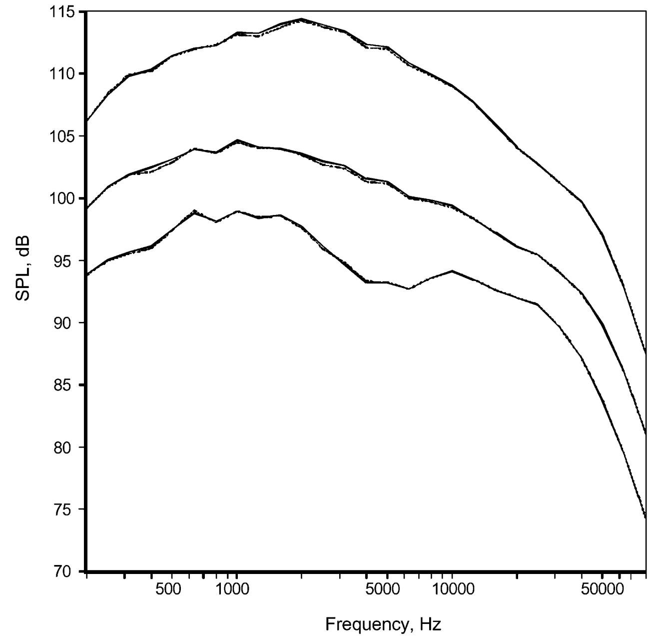


Fig. 7 Spectra at 130 deg at three power settings from control microphones: - - -, set 1 (normal incidence) and ——, set 2 (normal incidence); azimuthal angle $\phi = 90$ deg.

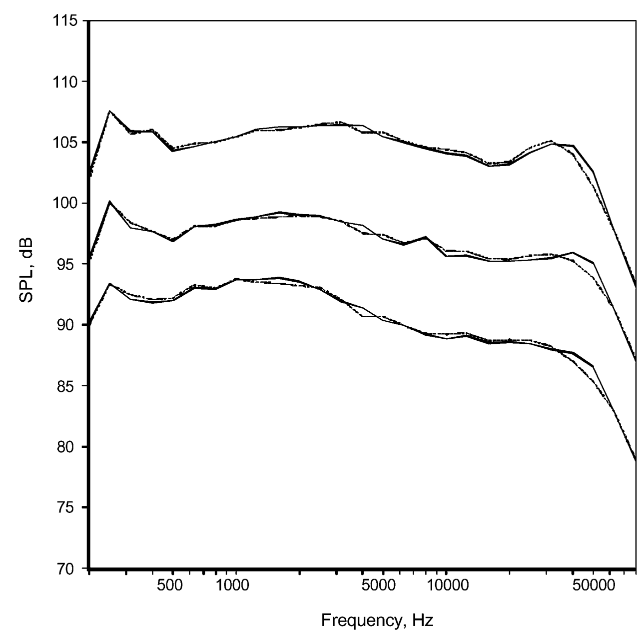


Fig. 8 Spectra at 95 deg at three power settings: - - -, set 1 (normal incidence) and ——, set 2 (grazing incidence); azimuthal angle $\phi = 25$ deg.

reverse is true. When we examine the spectra in Figs. 8 and 9, there is crisscrossing of the spectra at specific frequencies, and these frequencies are the same for different cycle conditions as denoted by the bands of the same color for all of the polar angles in Fig. 11. These results suggest that the observed differences could be due to small systematic errors in the applied free-field corrections (Fig. 3a) rather than due to any fundamental physics of the noise-generation and radiation process. This point is further discussed later. A principal conclusion can be drawn from the preceding comparisons: Regardless of the microphone orientation, the measured spectra, with appropriate free-field corrections, are similar even for distributed sources, provided the microphones are located in the far field.

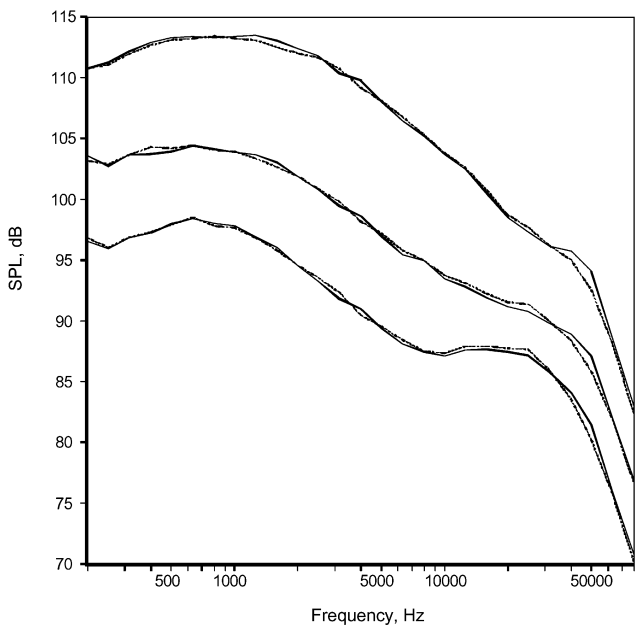


Fig. 9 Spectra at 130 deg at three power settings: - - -, set 1 (normal incidence) ——, set 2 (grazing incidence); azimuthal angle $\phi = 25$ deg.

The effect of the distributed sources on the EPNL was also computed for all of the cycle points. A detailed discussion of the model scale nozzle size requirement for resolving the range of engine-scale frequencies is given in Ref. 1 (Sec. IV). This issue is further elaborated by Viswanathan.[6] A scale factor of eight is used in the computation of the EPNL here, to avoid extrapolated data at the higher full-scale frequencies. Typically, the difference in EPNL is between 0.1 and 0.16 effective perceived noise decibels (EPNdB) due to the change in microphone incidence, whereas it is ~0.07 EPNdB for the control microphones. That is, the magnitude of the change is of the same order as data repeatability. (A variation of ±0.1 EPNdB in repeat measurements is considered excellent.) In summary, there is a systematic spectral difference due to the microphone orientation. However, the effect on EPNL is very small. Therefore, the assumption of a point source and the resultant aiming of the microphones at the nozzle exit are acceptable, as demonstrated here. An inspection of Figs. 6–9 and the results reported in Refs. 1 and 4 indicate the elimination of the tail-up at the higher frequencies noted initially in Fig. 1. Note that the tail-up at the higher frequencies has also been observed in the spectra obtained at other facilities; see Figs. 31 and 32 in Ref. 1.

D. Impact of Microphone Distance to the Noise Sources

Two other factors that lead to this problem of the tail-up at the higher frequencies are now discussed. In some facilities, the microphones are positioned at fairly long distances from the nozzle to ensure far-field measurements. The effect of atmospheric attenuation impacts the measured spectra as follows. Because the atmospheric attenuation is a strong function of frequency, it is important to factor in this effect while planning a test. The value of the atmospheric attenuation, as given in Ref. 5, could be as high as ~1 dB/ft

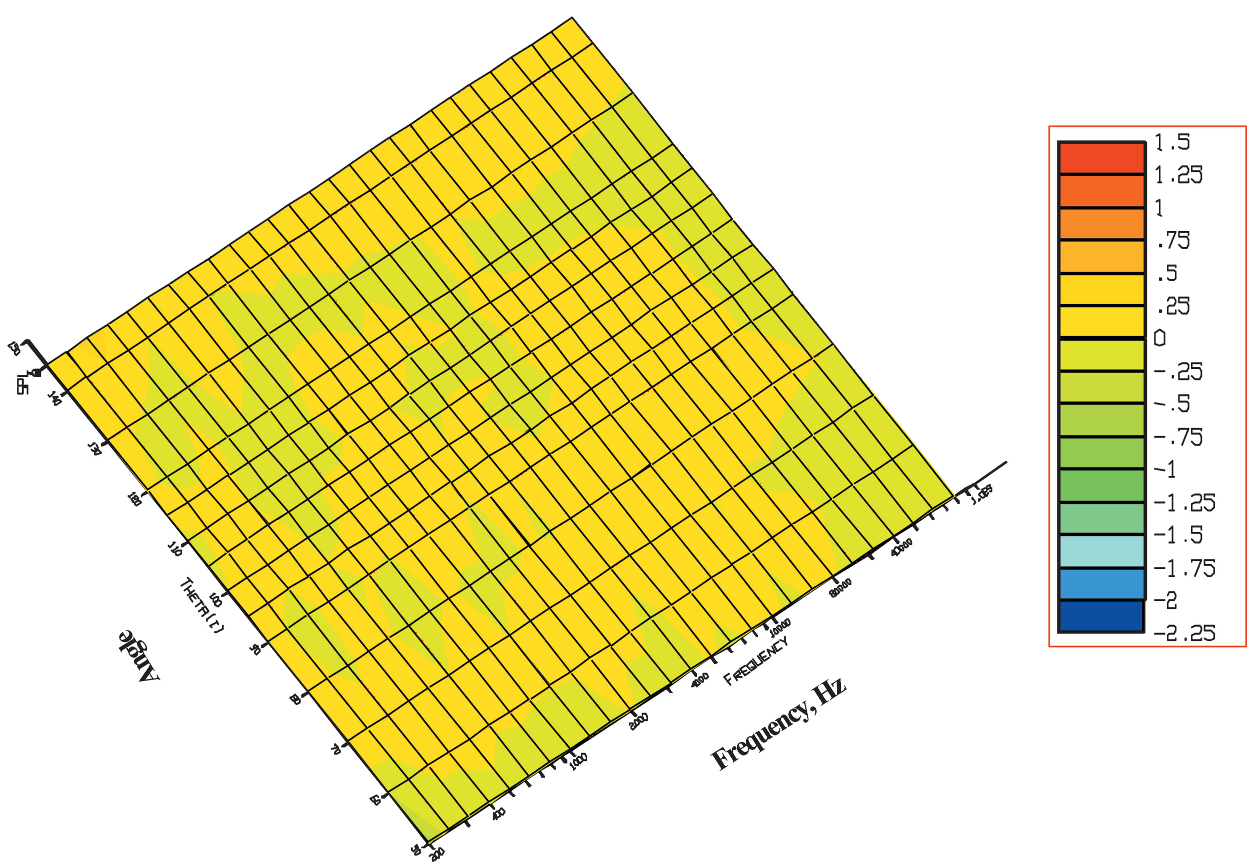


Fig. 10 Contour plot of spectral difference at the control microphones: set 1 (normal incidence) and set 2 (normal incidence); azimuthal angle $\phi = 90$ deg.

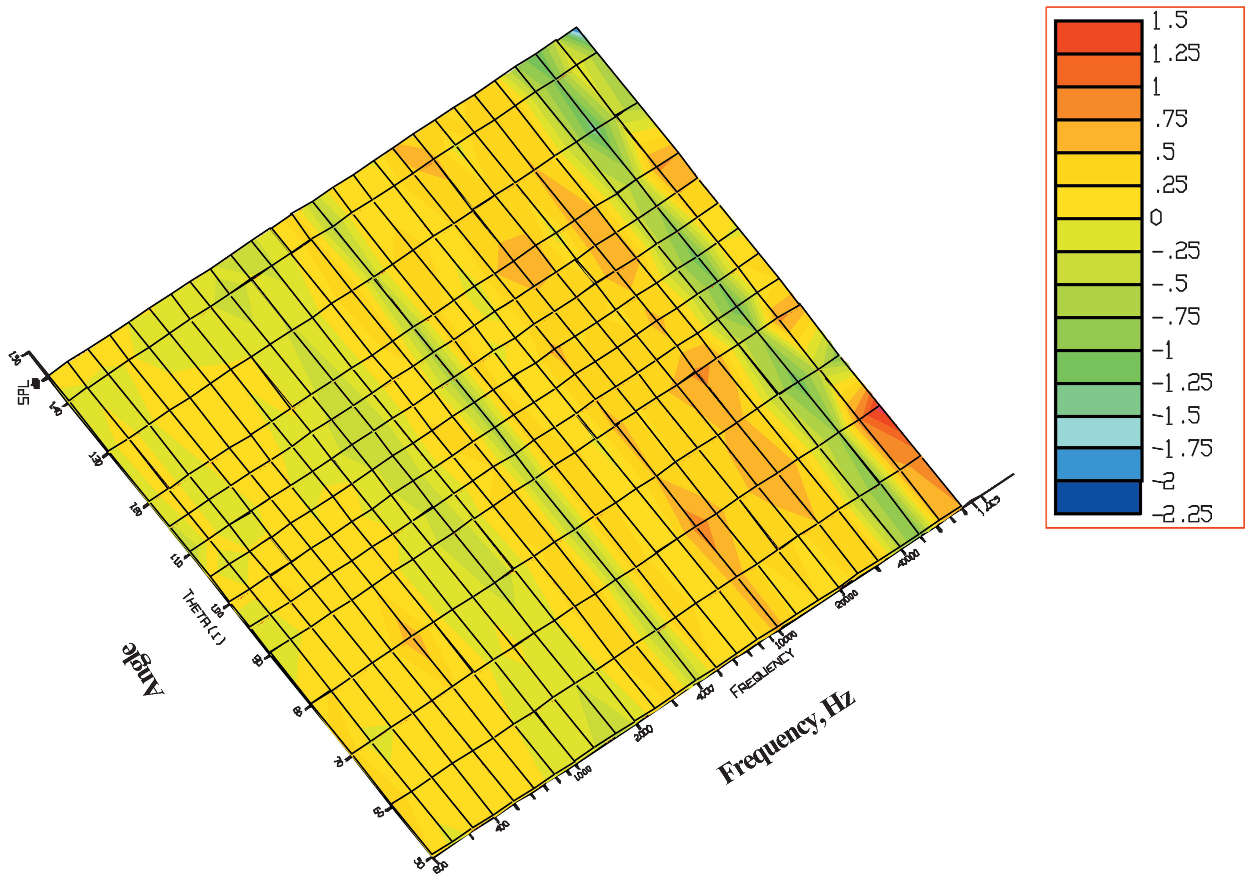


Fig. 11 Contour plot of spectral difference: set 1 (normal incidence) and set 2 (grazing incidence); azimuthal angle $\phi = 25$ deg.

(1 dB/30.5 cm) at a frequency of 80 kHz, whereas it is <0.03 dB/ft (0.03 dB/30.5 cm) for frequencies less than 8 kHz. Whereas the correction due to spherical divergence affects the spectral levels at all frequencies by an equal amount, the effect of atmospheric attenuation reduces the spectral level at the higher frequencies significantly although with only a modest effect at the lower frequencies. In typical scale-model tests, the spectral peak occurs at a frequency of <5000 Hz. Therefore, moving the microphone 20 ft farther from the nozzle, for example, could increase the requirement for the dynamic range of the measurement system by ~19 dB, if we assume the earlier given typical values for the atmospheric attenuation. Again, the dynamic range requirement for the spectra at aft angles from a dual-stream nozzle is ~80 dB (narrowband analyzer), for a microphone at a distance of 30 ft from the nozzle exit. This extra requirement due to the microphone being moved 20 ft farther, for example, could potentially lead to the actual noise signal running into the electronic noise floor of the measurement system. In addition, orienting the microphones at grazing incidence further exacerbates this problem. This phenomenon was the reason for the observed tail-up at the higher frequencies, when the results from the simple tests were described earlier.

As discussed in Ref. 1, it is important to measure good-quality data at high frequencies in scale-model tests, to permit the extrapolation of data to engine scale. This requirement is of even greater significance in the evaluation of concepts for noise reduction because a thorough knowledge of the interplay of the changes in spectral content and directivity is required. Viswanathan[1] provided concrete examples to emphasize this point. Therefore, it is recommended that microphones be oriented at normal incidence to ensure acquisition of good data at the higher frequencies. Based on the results shown here, this arrangement would be justified because the effect of the distributed sources on a metric such as the EPNL is minimal. Another factor pertains to the use of the grid cap on the microphone. The range of useful frequencies is considerably reduced by the presence of the grid caps, with unreliable measurements above a frequency of ~50 kHz for $\frac{1}{4}$-in. (6.35-mm) microphones. Therefore, the use of grid caps is not recommended if spectra are needed above a frequency of ~40 kHz.

Although it is straightforward to incorporate the preceding recommendation of normal incidence with microphones mounted on poles or booms, it is more challenging if a traversing array is essential for a particular test. A novel microphone arrangement was conceived and implemented for this application. Based on the directional characteristics of the microphones as given in Ref. 2, one could mitigate the problems at the higher frequencies associated with grazing incidence as follows. The objective is to maintain the ray incidence angle as close to normal as possible to enhance the signal strength as sensed by the microphone. An examination of the free-field polar response curves in Ref. 2 indicates that for incidence angles ≤30 deg the deviations are small (~2 dB) up to 100 kHz. Hence, it is desirable to maintain the ray incidence angle within this limit. To accomplish this goal, two microphones were positioned at each azimuthal angle on the array. One of them was set at normal incidence for a polar angle of 90 deg; the other one was pitched forward by 30 deg. When the array is located in the forward quadrant, measurements are made with the first microphone for a polar angular range of 60–90 deg. For larger polar angles of 120–150 deg, measurements are made with the second microphone. In the intermediate range, either microphone can be used. Thus, the incident angle of the ray is restricted to within the limit for a polar angular range of 60–150 deg. For several jet velocities, measurements were made with both sets of microphones at several polar angles and appropriate free-field corrections applied. It was verified that there was good collapse of the spectra from the two sets. As an additional check, the data from the array microphones were compared with those obtained using independent pole-mounted microphones set at normal incidence at a few selected polar angles. Again, there was excellent agreement (not shown here) between the spectra from the microphones on poles and on the traversing array. Thus, a practical method for dealing with the issue of noise floor was developed and demonstrated.

E. Where Is the True Far Field for Jet Noise Measurements?

We now address a fundamental question that pertains to jet noise measurements: How far away (in terms of nozzle diameters) should the microphone be located to ensure that it is in the true acoustic and geometric far field? A definitive answer would provide guidelines as to the minimum distance that is acceptable and that would avoid the problems discussed in Sec. IV.D. Several distances have been suggested in the literature; however, no one has provided conclusive experimental evidence to date that answers this basic issue. Therefore, a careful study has been carried out and the results are presented now.

1. Method Adopted and Implications

In the past (Ref. 7, for example), the microphone is typically moved away from (or toward) the source and the radial decay of the overall SPL and the spectral level at individual frequencies are examined for spherical divergence (6 dB decrease for a doubling of the distance). The measured reduction in spectral level with distance is compared with the theoretical decay rate, and the distance at which the two trends begin to deviate is designated as the limit of the near field. However, there is some subjectivity in how the comparison with the ideal decay rate is carried out. A different approach is adopted here. Spectra are measured from nozzles of increasing diameters with the same linear array of microphones, thereby, progressively decreasing the nondimensional distance (r/D) to the microphones. The normalized spectra at the same jet conditions are compared to detect any near-field effects. Some pitfalls associated with this approach are first discussed.

A clear understanding of rig internal noise, its magnitude, and the affected frequencies for nozzles of different diameters is crucial. Of course, rig internal noise is specific to each jet rig and is a function of the rig design and layout of the various components and plumbing. Viswanathan[1] provided a comprehensive treatment of this issue (see Sec. IV in Ref. 1). The increasing influence of rig noise on the quality of the spectra for nozzles of increasing diameters was illustrated, and it was pointed out that it would not be possible to acquire good quality spectra with large nozzles, with a given jet rig. This problem is more serious at lower jet velocities, especially for unheated jets. Viswanathan[8] further expanded on this topic and presented comparisons of his spectra with other published data and noted that most of the noise data obtained at various facilities were severely contaminated. A rigorous analysis was carried out, and good collapse of noise data acquired with nozzles of different diameters was demonstrated. We start with a sample plot to explain the different concerns because this discussion is germane to the issue at hand.

We restrict our attention to measurements at a polar angle of 90 deg; these spectra have been obtained with a linear sideline array at a constant distance of 15 ft. With this arrangement, the microphone at this angle is closest to the nozzle and the slant distance keeps increasing with increasing oblique angles. Spectra from unheated jets at three Mach numbers, 0.6, 0.8, and 1.0, and from three nozzles of diameters 1.5, 2.45, and 3.46 in. (3.81, 6.22, and 8.79 cm) are presented in Fig. 12. Heated jets are avoided because the consequences of low Reynolds number (for small nozzles) were shown to lead to a change in spectral shape in Ref. 8. A nominal minimum value of $\sim 4 \times 10^5$ for the Reynolds number was recommended in Ref. 8 if the effects associated with low Reynolds number are to be avoided. It is imperative here to not confuse any near-field effects with changes in spectral shape due to lower Reynolds numbers. The spectra are normalized as follows: The effect of nozzle diameter on spectral levels is scaled out and the parameter [$\mathrm{SPL} - 10 \times \log_{10}(A)$] (where A is the nozzle exit area) is plotted against the Strouhal number. The one-third octave spectral range spans the centerband frequencies of 200–80 kHz. The normalized distances (r/D) to the microphones are 120.0, 73.5, and 52.0, respectively, for the three nozzles. At the lowest Mach number of 0.6, there is good collapse of the data to the left of the spectral peak; however, at the higher Strouhal numbers, the spectral levels for the largest nozzle ($D = 3.46$ in.) are seen to be higher. At the highest Mach number of 1.0, there is excellent collapse of the data up to a Strouhal number of ~ 10, well above the spectral peak. At the highest three one-third octave center frequencies, there is some discrepancy for the largest nozzle. The magnitude of the contamination (~ 1 dB) is much less than at the lowest Mach number and is confined to a narrow range of higher frequencies. Similar comparisons at intermediate Mach numbers of 0.7 and 0.9 reveals that both the magnitude and the range of affected frequencies are progressively smaller with increasing Mach number, indicating the obvious presence and impact of rig noise. Spectra at $M = 0.7$ and 0.9 are not shown for the sake of clarity.

The experiments were carried out over a period of several months; the ambient conditions, of course, change during this time and the jet velocity for the same nozzle pressure ratio (Mach number) is slightly different. The difference in velocity is typically from ~ 3 to ~ 8 ft/s; we could eliminate the slight difference in noise due to the velocity difference through incorporation of a suitable normalization term such as [$80 \times \log_{10}(Vj/a)$], where a is the ambient speed of sound, for example, to the spectra at 90 deg. However, the change in noise level is ~ 0.2 dB in most instances. Similarly, one could correct for the effect of ambient conditions on noise; several expressions have been developed in the past. These correction terms are typically expressed in terms of the mismatch between the ambient pressures and temperatures with standard day pressures and temperatures. More elaborate forms of this term have also been developed by several researchers. The magnitude of these corrections again tends to be small. Therefore, these two correction terms are not used in the normalization of the spectra. A comprehensive treatment of the weather corrections and the suitability of the different proposed methods are examined in detail in Ref. 6. However, it is pointed out that the inclusion of these terms would minimize the scatter (which is small as is) seen in Fig. 12 still further.

Figure 12 clearly frames the issue of rig noise in a quantitative fashion and also pinpoints the affected frequencies. Two important implications are evident: The rig noise is significant only at the higher frequencies, and there is excellent agreement at the lower frequencies. The effects of the microphone being in the geometric near field are more pronounced at the lower frequencies. The wavelength λ that corresponds to the lowest frequency of 200 Hz is 5.64 ft (1.72 m). Given the excellent collapse (especially at $M = 0.8$ and 1.0) at the lower frequencies, it is obvious that there are no near-field effects and that the microphone is in the true far field for the largest nozzle ($D = 3.46$ in.), which is at a normalized distance of 52.

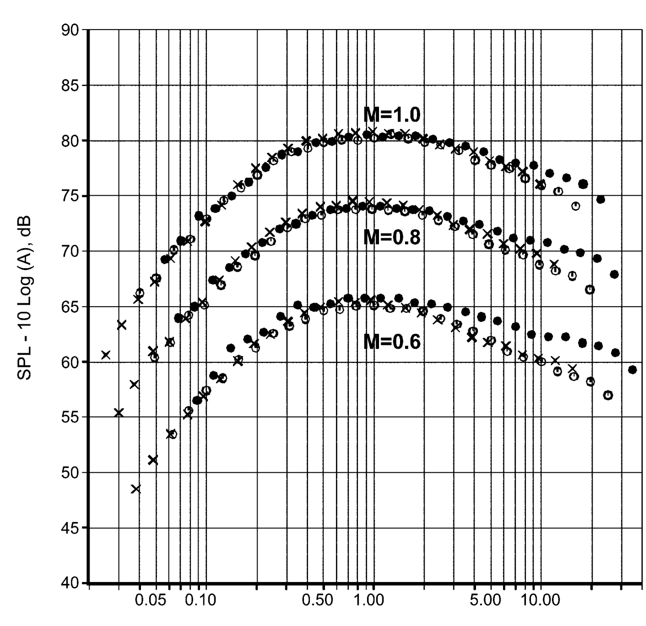
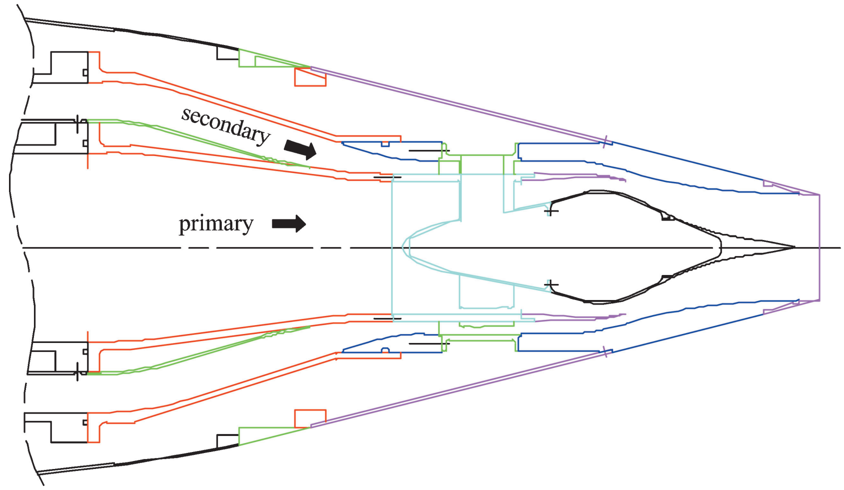
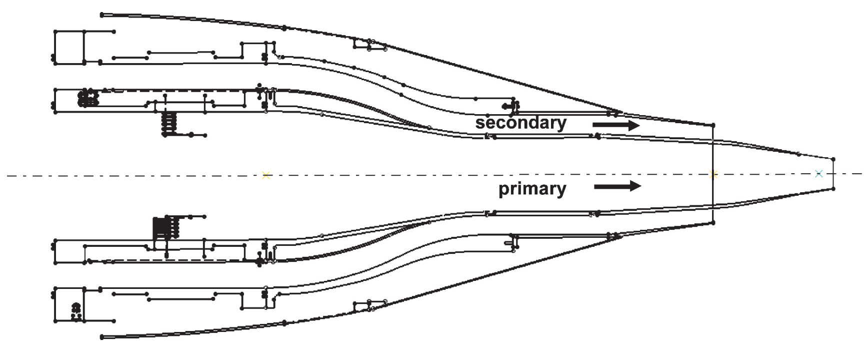


Fig. 12 Normalized spectra at 90 deg from unheated jets at Mach numbers 0.6, 0.8, and 1.0; microphone distance = 15 ft, ×, D = 1.5 in., r/D = 120; ○, D = 2.45 in., r/D = 73.5; and ●, D = 3.46 in., r/D = 52.



a)



b)

Fig. 13 Schematics of a) compound flow nozzle and b) dual-stream nozzle.

2. Minimum Distance to the Far Field

Next we address the following question: What is the minimum distance that would represent a true far field? The method adopted here, in which the spectra from nozzles of different diameters are collapsed, brings the issue of rig noise to the forefront; Fig. 12 and the results presented by Viswanathan[1,8] make it clear that we cannot keep increasing the size of the nozzle without compromising the quality of the data. Great care was required, and taken, to acquire clean data; however, the contraction ratio of the upstream plenum to the nozzle area sets a threshold on the maximum diameter that can be tested and still not be affected by rig noise. The jet rig used here has two streams to simulate the exhaust systems of turbofan engines. One could increase the cross-sectional area of the supply pipes by using both streams to feed a common nozzle, thereby, increasing the contraction ratio. Larger nozzles may then be tested because the upstream velocity in the supply pipes is reduced with the increased cross-sectional area. Figure 13a shows a schematic of a compound flow nozzle; two nozzles with exit diameters of 4.21 and 4.71 in. (10.69 and 11.96 cm) were used. The normalized distances (r/D) to the microphone at 90 deg are 42.8 and 38.3, respectively. An additional configuration, a dual-stream nozzle reported in Ref. 4, was also tested to further increase the nozzle size as follows. The two streams were operated unheated and pressure balanced, to yield a single large jet. With the primary nozzle extended downstream of the fan nozzle, a boundary layer forms on both the inside and outside of the primary nozzle (Fig. 13b). However, the effect of the boundary layers and the wake on the radiated noise is negligible, as will be seen. This nozzle yields an effective diameter of 4.9 in. (12.45 cm), with $(r/D) = 36.7$.

We inspect the normalized spectra at a high Mach number of 1.0 with these larger nozzles in Fig. 14; the spectra obtained with a smaller nozzle ($D = 2.45$ in., denoted by the filled circles) is also included. There is very good collapse of the data from the different nozzles throughout the frequency range. We observe the closest agreement at the lowest frequencies ($Sr \leq 0.4$); however, the magnitude of the scatter is only ~1 dB even at the higher frequencies. The main conclusion is that there are no near-field effects at the lowest frequencies even for the larger nozzles. Figure 14 also indicates that the dual-stream nozzle, with both the streams operated at the same jet velocity, indeed operates as an equivalent single jet.

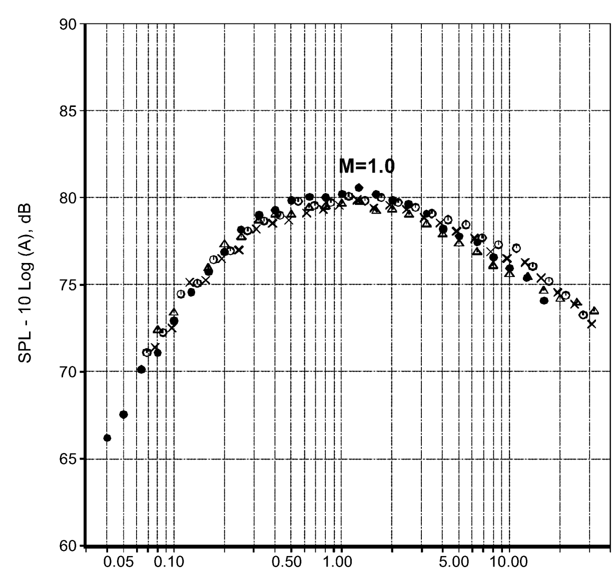


Fig. 14 Normalized spectra at 90 deg from unheated jet; $M = 1.0$. microphone distance = 15 ft (4.57 m): ●, $D = 2.45$ in. (6.22 cm), $r/D = 73.5$; ○, $D = 4.21$ in. (10.69 cm), $r/D = 42.8$; ×, $D = 4.71$ in. (11.96 cm), $r/D = 38.3$; and Δ, $D = 4.9$ in. (12.45 cm), $r/D = 36.7$.

As a further check, we look at the axial distribution of the source strength at different Strouhal numbers. These measurements were

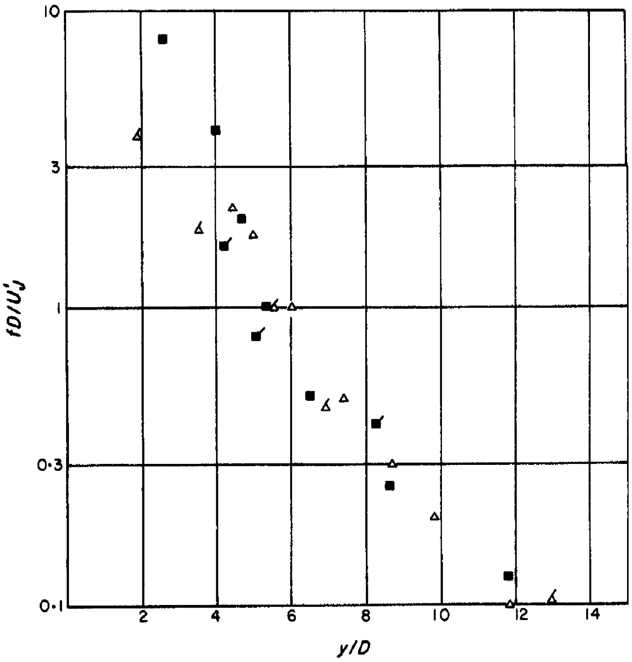


Fig. 15 Axial variation of centroids of source distribution: filled symbols, $M = 1.0$, acoustic mirror and open symbols, $M = 0.86$, polar correlation technique (Fig. 9 from Fisher et al.[11]).

carried out by Chu et al.[9] and Grosche[10] using acoustic mirrors and by Fisher et al.[11] using the polar correlation technique. A comparison of the results from these studies, compiled by Fisher et al.[11] and shown as Fig. 9 in Ref. 11 is reproduced here as Fig. 15. Figure 15 shows the axial variation of the centroids of the source strengths at different Strouhal numbers, which have been calculated from the distributions of individual frequencies. The mirror measurements were for a jet with a Mach number of 1.0, whereas the polar correlation measurements were for a jet with a Mach number of 0.86. Note that the collapse shown in Figs. 12 and 14 are at a Mach number of unity. The main observation from this figure is that the low frequency sources ($Sr \leq 0.3$) are concentrated at an axial distance from $\sim$8 to $\sim$12 nozzle diameters from the nozzle exit plane. Furthermore, an examination of Fig. 8 in Ref. 11 indicates that there is a considerable axial distance over which the amplitude at a particular frequency has significant levels. That is, the source distribution could extend to several nozzle diameters even at the higher frequencies.

Let us reexamine Figs. 6–9. These data were acquired with a large nozzle of diameter 5.34 in. (13.56 cm), with a corresponding $(r/D) = 33.7$ for the microphone at 90 deg. The spectral difference due to the distributed sources at the lower frequencies ($\leq$1000 Hz) in Fig. 8 (from the grazing incidence microphone) is comparable in magnitude to that seen in Fig. 6 (from the normal incidence microphone). This trend indicates there is no discernible effect due to the distributed nature of the low-frequency sources on the spectra for this microphone distance. This observation, taken in conjunction with the excellent collapse of spectra demonstrated in Figs. 12 and 14, implies that a normalized distance of $\sim 35D$ represents the true far field for jet noise measurements. We can further infer from the data presented so far that the discrepancy seen at $\sim$50 kHz in Figs. 8, 9, and 11 is caused by minor errors in the magnitude of the applied free-field corrections: At this high frequency, the source should be compact and the magnitude of the discrepancy (still less than 1 dB) is independent of the radiation angle (and, thus, distance to the microphone). Also remember that the response of a microphone is omnidirectional at low frequencies.[2] That is, a microphone set at normal incidence and pointed at the nozzle exit is not subjected to errors due to the increasing ray incidence from sources located far downstream. This characteristic feature of the microphone is beneficial for jet noise measurements because the low-frequency sources are located at greater distances from the nozzle exit plane.

F. Reflections from Surfaces

We now address a final issue, reflections of acoustic waves from various surfaces. Reflections from the microphone sting mounting system, exposed poles, exhaust collector, etc., could produce standing waves and introduce oscillations or wiggles in the spectra. It is not possible to predict or calculate the affected frequencies because the reflections are geometry dependent. It is recognized that it would be impossible to eliminate completely any reflection from the microphone mounting fixture, for example. However, the goal is to minimize the reflections through proper techniques. It is well established that jet noise spectra are smooth; therefore, it is easy to identify the wiggles caused by reflections. It was noted in Sec. IV.A that the sting mounting system refined and adopted here does not produce strong reflections.

The exhaust collector, though, presents an unavoidable problem. It is evident from Fig. 4 that the microphones at large aft angles would be close to the lip of the exhaust collector. It is desirable to locate the microphones upstream of the lip and avoid placing them in the shadow zone of the collector. For a linear array at a lateral distance of 15 ft (4.57 m) or a polar microphone array, the microphones at angles of 150 deg and higher are necessarily close to the collector lip. To keep the microphones upstream of the lip, the microphones are moved to a smaller lateral distance, for example, 12.75 ft (3.89 m) instead of 15 ft (4.57 m), at the higher angles. This practice further exacerbates the problem of reflections from the collector lip as will be shown.

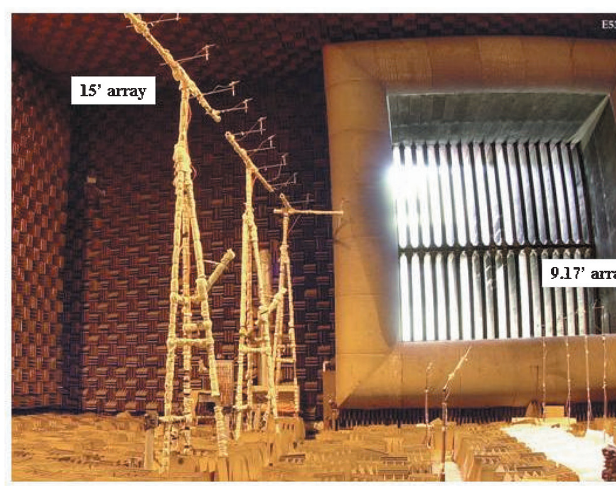


Fig. 16a Photograph of exhaust collector and microphone arrays.

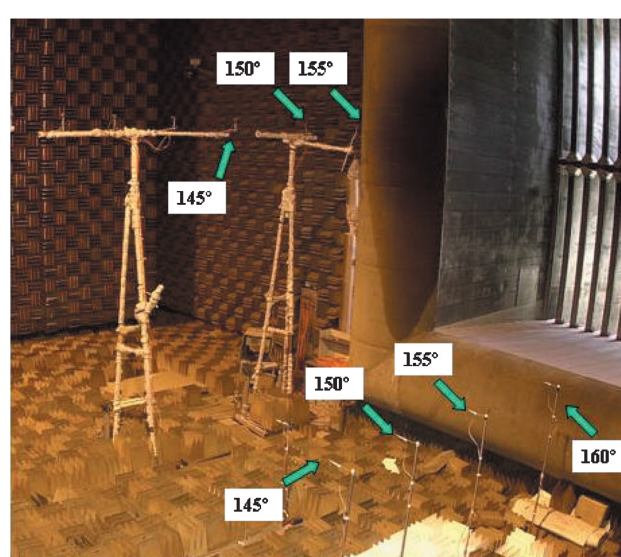


Fig. 16b Closeup of microphones at large aft angles and exhaust collector.

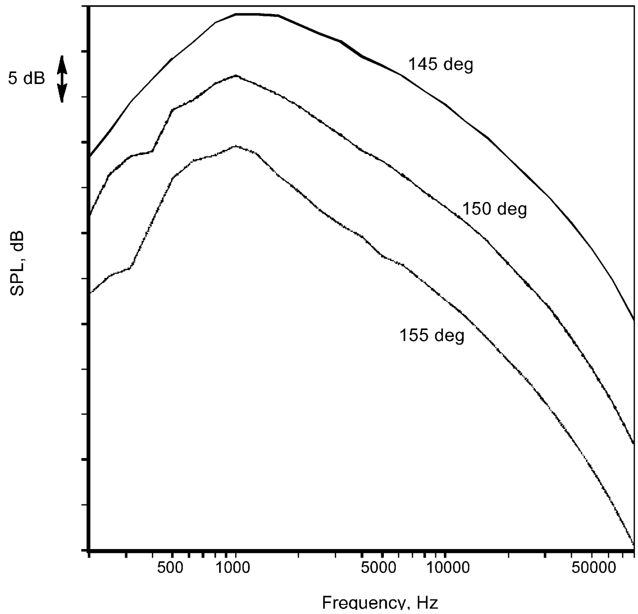


Fig. 17a Measured spectra from 15-ft (4.57-m) sideline array microphones at different polar angles; $M = 1.0$, with unheated jet.

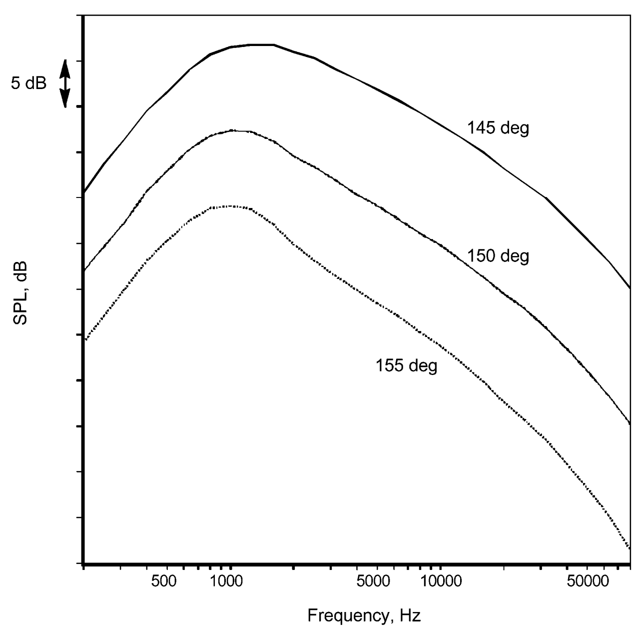


Fig. 17b Measured spectra from 9.17-ft (2.8-m) sideline array microphones at same polar angles as Fig. 17a, $M = 1.0$, with unheated jet.

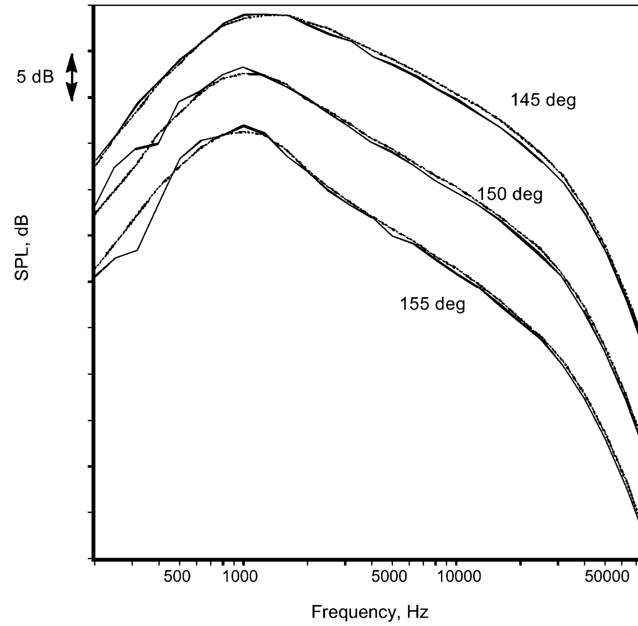


Fig. 18 Normalized spectra from two sideline arrays. $M = 1.0$, and unheated jet. Data corrected to standard day conditions and to polar distance of 20 ft (6.1 m): ——, 15-ft (4.57-m) array and - - -, 9.17-ft (2.8-m) array.

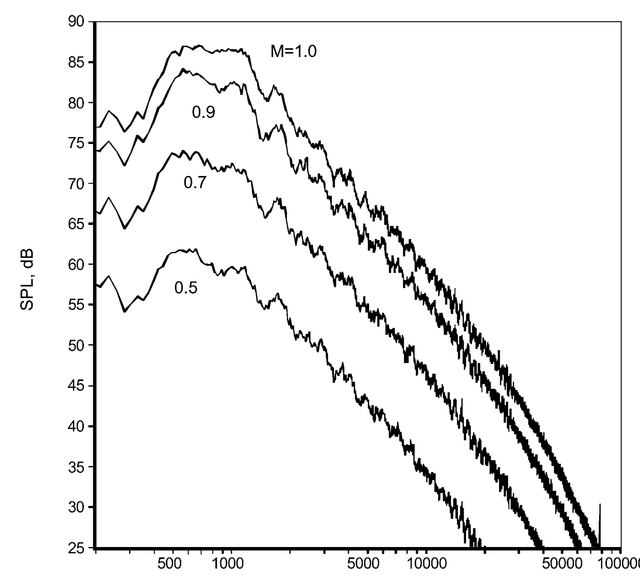


Fig. 19a Measured narrowband spectra from 15-ft (4.57-m) sideline array microphone at 155 deg, unheated jets at $M = 0.5$, 0.7, 0.9, and 1.0.

In the one-third octave spectra presented by Viswanathan,[1,8] some wiggles are noted at the lower frequencies at large aft angles. It was surmised that these wiggles were due to reflections from the collector. To investigate this issue and quantify the magnitude of the reflections, a set of microphones were located at a lateral distance of 9.17 ft (2.8 m) at large angles of 145, 150, 155 and 160 deg (at a different azimuthal angle). Figure 16a shows a photograph of the exhaust collector and the two microphone arrays. Note that there are no other reflecting surfaces, given the large size of the anechoic chamber. Figure 16b shows a closeup of the microphones at the aft angles, with the microphone angles labeled. Figures 16 orient the reader to the microphone layout and should clarify the following discussion. Sample comparisons at large aft angles from the two sideline arrays of 15 ft (4.57 m) and 9.17 ft (2.8 m) are now presented. Figures 17a and 17b show spectra at three polar angles of 145, 150, and 155 deg from the two arrays, respectively, from an unheated jet at a Mach number of unity. The spectra have been arbitrarily spaced apart to enhance visual observation, and attention is drawn only to spectral shapes. In Fig. 17a, some oscillations are seen at 150 and 155 deg at frequencies <2000 Hz, whereas the spectra are smooth at all of the angles in Fig. 17b. Figure 18 shows a comparison of the two sets of spectra corrected to standard day conditions and to a common distance of 20 ft (6.096 m). There is good collapse of the two sets of data, except for the wiggles at the lower frequencies. Evidently, the proximity of the microphones to the collector contaminates the data at lower frequencies. Note that the effect of the interference/reinforcement is a function of the distance from the collector lip. At 155 deg, the spectral levels from the 15 ft (4.57-m) array are ~3 dB lower at 300 Hz, whereas the levels at 150 deg are higher by ~2 dB. The position of the microphone relative to the standing wave pattern caused by the reflection causes either reinforcement or reduction in amplitude.

Narrowband spectra at 155 deg from the 15-ft (4.57-m) array and from unheated jets at four Mach numbers of 0.5, 0.7, 0.9, and 1.0, shown in Figs. 19a, highlight this problem. As seen, the affected

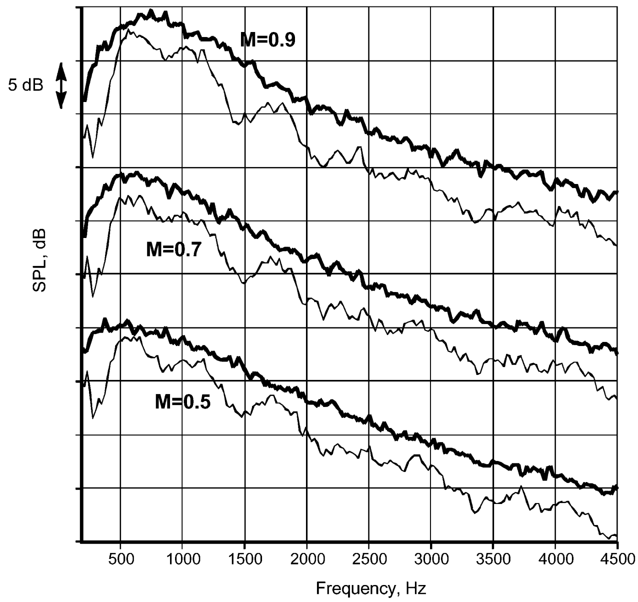


Fig. 19b Narrowband spectra (not normalized) from 15- and 9.17-ft (4.57- and 2.8-m) sideline array microphones at 155 deg, unheated jets at $M = 0.5$, 0.7, and 0.9: ▬▬, 9.17-ft array and ——, 15-ft array.

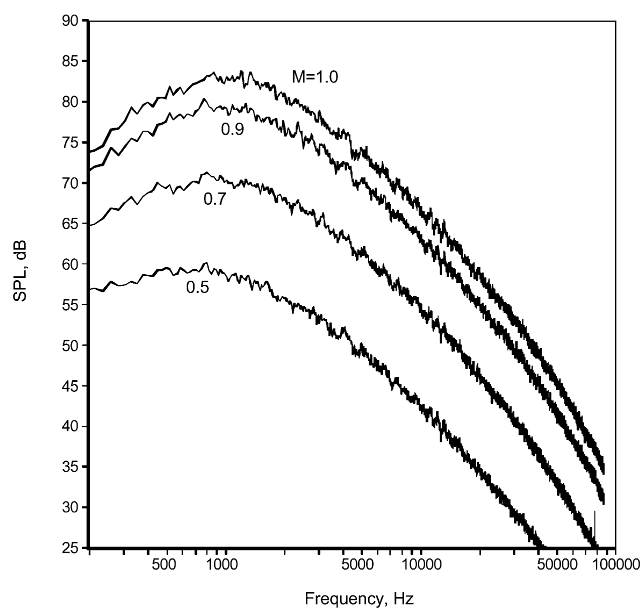


Fig. 20 Measured narrowband spectra from 15-ft (4.57-m) sideline array microphone at 140 deg, unheated jets at $M = 0.5$, 0.7, 0.9, and 1.0.

frequencies are mostly independent of jet velocity and are only functions of the geometric layout of the microphones. All of the spectra exhibit similar shapes at the lower frequencies, with the reflections occurring at the same frequencies. Attention is also drawn to the range of the SPL for the $M = 1.0$ jet in this Fig. 19; the overall sound pressure level is 101.6 dB and the lowest level is ~20 dB. Therefore, the dynamic range requirement for the measurement system must be greater than ~80 dB, as noted in an earlier section.

A comparison of raw spectra at an angle of 155 deg from the two arrays (different microphone distances) at the lower frequencies is shown in Fig. 19b. The use of a linear scale for frequency serves to enhance the visual observation of the effect of the reflection from the collector. Contrast the spectra at 155 deg (Fig. 19a) with the spectra shown in Fig. 20 at a lower angle of 140 deg, which are smooth. Evidently, the reflections do not affect the spectra from microphones that are beyond a distance of ~6 ft (Figs. 16a and 16b) from the exhaust collector lip. The exhaust collector lip at LSAF has a 5-in.-thick layer of acoustic foam to minimize reflections. However, as seen here, reflections are not completely eliminated. Therefore, care must be exercised in the placement of the microphones.

Finally, a comparison of the spectral shapes shown in Fig. 17b with those in Fig. 1 illustrates the marked improvement in spectral shapes. The enhancements made to the instrumentation system have clearly eliminated the many problems that had plagued earlier measurements.

V. Summary

Some fundamental issues concerning acoustic measurement systems and their consequences on the measured spectra are examined in this study. The underlying reasons for the observed tail-up at the higher frequencies in jet noise spectra from several test facilities have been investigated, and steps to eliminate this problem have been proposed. It has been shown that it is inherently better to orient the microphones at normal incidence to the primary source. The great benefit of setting the microphones at grazing incidence is due to the fact that the acoustic rays from a line of distributed sources are always at grazing incidence no matter where the source is located. That is, no a priori knowledge of the distribution of the jet sources is required with this microphone arrangement. However, given the poor sensitivity at the higher frequencies of the microphones at grazing incidence, a fixed usable dynamic range of the measurement system, and the dynamic range requirement for the jet spectra in the peak radiation direction, this arrangement could result in the contamination of the spectra at the higher frequencies.

The effect of distributed sources in a jet on the measured spectra has been quantified at several cycle points, through the use of normal incidence and grazing incidence microphone arrays. A large nozzle, with a diameter of 5.34 in. (13.56 cm) and a microphone distance of $33.7D$, was used to enhance this effect, if any. Systematic differences, which exhibit a strong dependence on frequency and a weaker dependence on polar angle, are observed. At most frequencies, the difference in spectral levels due to the distributed sources is within ± 0.25 dB. Though the spectral difference could be ± 1 dB at certain frequencies, the effect on EPNL is negligible. These discrepancies could be associated with small systematic errors in the applied free-field corrections, rather than due to any inherent physics of the noise generation and radiation. Therefore, it has been established that by orienting the microphones at normal incidence and pointing them at the nozzle exit, with the implicit assumption of a concentrated point source, we do not incur a substantial error in the measurements. Given this finding, it is preferable to adopt this arrangement wherever possible to ensure good spectral measurement at the higher frequencies. Also note that the magnitude of the corrections applied to the raw spectral measurements is small with this arrangement. However, if a specific test requires microphones to be set at grazing incidence, care must be taken to ensure that they are not accidentally pointed at other extraneous sources.

It has also been shown that the distances to the microphones must be chosen carefully, to avoid placing needless burdens on the requirement of dynamic range for the measurement system. In this context, the issue of the minimum distance that must be maintained to ensure true far-field measurements for the distributed sources of jet noise has been evaluated. Excellent collapse of the spectra obtained with nozzles of six different diameters at the same jet velocities and at the same microphone location was demonstrated. The nozzle diameters spanned a range of 1.5–4.9 in. (3.81–12.45 cm) with corresponding microphone distances of $120D$–$36.7D$ at a polar angle of 90 deg. At the lower frequencies, where the near-field effects would be pronounced, the tightest collapse of the data with a scatter less than 1 dB in magnitude was observed. This result, together with the trends noted for the distributed sources with the normal and grazing incidence microphones, indicates that a minimum distance of $\sim 35D$ would be adequate to ensure true far-field measurements. However, larger distances may be employed (and certainly desirable) provided clean measurements at the highest frequencies is possible. Conclusive experimental evidence has been presented for the first time to establish the normalized distance that represents the acoustic and geometric far field for a jet.

This investigation, which has concentrated on the issues with the measurement system, complements the research carried out by the author on the improvements to the jet rig that was reported elsewhere. Several recommendations that would lead to better noise measurements have been made. These are 1) choosing the microphones and the instrumentation system properly; 2) orienting the microphones at normal incidence and without the grid caps; 3) designing of proper microphone mounting scheme to minimize reflections; 4) ensuring adequate dynamic response for the entire measurement system; 5) ensuring that the microphones are in the geometric and acoustic far field of the sources, but not too much farther if the dynamic range of the system is limited; 6) avoiding the placement of microphones too close to reflecting surfaces such as walls, floors, ceilings, exhaust collectors, etc.; and 7) above all, understanding clearly the limitations of the measurement system.

These prudent steps ensure that accurate measurements of the spectra at the higher frequencies are not compromised with a given data acquisition system. Excellent repeatability of data has also been demonstrated. Though not explicitly discussed here, the subject of scaling jet noise spectra has played an important role in establishing the many results here. Specific issues on scaling, implications for engine tests, and methodology that would allow comparison of model-scale data with engine data are addressed in an upcoming paper.

Acknowledgments

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References

[1]Viswanathan, K., "Jet Aeroacoustic Testing: Issues and Implications," *AIAA Journal*, Vol. 41, No. 9, 2003, pp. 1674–1689.

[2]"Condenser Microphones and Microphone Preamplifiers for Acoustic Measurements," *Brüel and Kjaer Handbook*, Naerum, Denmark, Rev. 1982.

[3]Ahuja, K. K., "Designing Clean Jet-Noise Facilities and Making Accurate Jet-Noise Measurements," *International Journal of Aeroacoustics*, Vol. 2, No. 3–4, 2003, pp. 371–412.

[4]Viswanathan, K., "Parametric Study of Noise from Dual-Stream Nozzles," *Journal of Fluid Mechanics*, Vol. 521, Dec. 2004, pp. 35–68.

[5]Shields, F. D., and Bass, H. E., "Atmospheric Absorption of High Frequency Noise and Application to Fractional-Octave Band," NASA CR 2760, June 1977.

[6]Viswanathan, K., "Does a Model Scale Nozzle Emit the Same Jet Noise as a Jet Engine?" AIAA Paper 2005-2936, May 2005; also *AIAA Journal* (submitted for publication).

[7]Plumblee, H. E., "Effects of Forward Velocity on Turbulent Jet Mixing Noise," NASA CR-2702, July 1976.

[8]Viswanathan, K., "Aeroacoustics of Hot Jets," *Journal of Fluid Mechanics*, Vol. 516, Oct. 2004, pp. 39–82.

[9]Chu, W. T., Laufer, J., and Kao, K., "Noise Source Distribution in Subsonic Jets," *Inter-Noise 72 Proceedings*, International Conf. on Noise Control, Washington, DC, 1972, pp. 472–476.

[10]Grosche, F. R., "Distribution of Sound Source Intensities in Subsonic Jets," *Noise Mechanism*, AGARD Conf. CP-131, 1973.

[11]Fisher, M. J., Harper-Bourne, M., and Glegg, S. A. L., "Jet Engine Noise Source Location: The Polar Correlation Technique," *Journal of Sound and Vibration*, Vol. 51, No. 1, 1977, pp. 23–54.

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