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Technical Notes

True Farfield for Dual-Stream Jet Noise Measurements

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I. Introduction

THE minimum distance in the far field that corresponds to the true geometric and acoustic far field for jet noise measurements from dual-stream nozzles is established in this study. The practical significance of this minimum limit is the following: for measurements carried out beyond this distance, the assumption of a point source located at the nozzle exit plane to represent the distributed nature of the sources in a jet is valid. In most jet noise tests, the origin of the coordinate system is taken to be on the jet centerline and at the nozzle exit plane; the far-field microphones are set up at radiation angles measured from the origin of the coordinate system. The subsequent processing of the noise spectra over the entire frequency range becomes straightforward, if the assumption of point source is justified. Then, the distance to the source and the radiation angle are simply determined and appropriate corrections for the atmospheric attenuation, etc., may be applied easily. The minimum distance is determined through the examination of a large jet noise database; typical dual-stream exhaust geometries with extended primary nozzles of different diameters, together with several microphone arrays at different distances are used. Jets operating in a static environment as well as in the presence of a flight stream are considered.

Viswanathan [1,2] reported on and discussed numerous issues concerning noise measurements. These include: 1) characteristics of microphones, 2) dynamic range considerations, 3) impact of microphone orientation for distributed sources, 4) impact of microphone distance and atmospheric attenuation on making clean measurements at higher frequencies, 5) scaling methodology and microphone layout for assessing near-field effects, 6) effect of temperature on source distributions, 7) polar response characteristics of microphones, 8) effect of source directivity on minimum distance to far field, etc. The scaling methodology of Viswanathan [3] has been applied to ascertain the distance to the far field, mostly for single jets over a wide Mach number range, in [1,2]. In this paper, the same ideas are extended to dual-stream jets. The measured spectra are corrected to lossless conditions and to a common distance of 20 ft (6.09 m) with the assumption of a point source located on the jet centerline at the nozzle exit plane of the primary nozzle. The values of the atmospheric absorption coefficients are obtained using the method of Shields and Bass [4].

The main results for single-stream jets are first summarized. The true far field for unheated and heated subsonic jets is $\sim 35D$; D is the diameter of the nozzle. The minimum far-field distance for supersonic jets is more nuanced: for unheated jets, a distance of $45D$ represents the far field. For highly heated supersonic jets, $45D$ again represents the far field for the lower polar angles $\leq \sim 100°$ from inlet axis. A distance of $\sim 70D$ for angles $\geq \sim 100°$ might be prudent even though a shorter distance might be adequate for angles $\geq \sim 130°$. Viswanathan [2] showed that the larger distance for highly heated supersonic jets is due to rapid changes in the spectral shapes and overall sound pressure levels (OASPL) in the angular range of ~ 110 to $\sim 130°$. The polar response characteristics of condenser microphones at different frequencies were also reviewed to explain the measured spectral trends at different normalized distances (r/D).

II. Analyses and Discussion

Two different dual-stream nozzle exhaust systems are considered. For the first geometry, the areas of the primary and secondary nozzles are 4.714 and 14.14 sq. in., respectively. An equivalent diameter for this nozzle system is 4.9 in. (0.12 m). The second geometry is much larger, with the areas of the primary and secondary nozzles being 7.01 and 29.19 sq. in., respectively. An equivalent diameter D_e for this nozzle system is 6.79 in. (0.17 m). Two microphone arrays are deployed: one is at a polar radius of 25 ft (7.62 m) and the other one is at a fixed sideline distance of 15 ft (4.57 m). For the fixed sideline array, the distance to the microphone varies as ($15/\sin\theta$), where θ is the radiation angle measured from the nozzle inlet. The origin of the coordinate system is taken to be on the jet centerline and at the nozzle exit plane; the polar angular range covers 50 to 150°.

The measured one-third octave spectra are converted to lossless form and to an arbitrary distance of 20 ft (6.09 m), with the distributed sources taken to be represented by a point source located at the origin of the coordinate system. The normalized distances are quoted in terms of the equivalent diameter in the figures. The measurement error is typically within ± 0.5 dB in well controlled experiments. However, the error band increases to ± 1 dB in more realistic outdoor tests and is even higher in flight tests. In addition, random variations of ~ 0.5 dB appear from angle to angle. Note that there are some blips of ~ 1 dB magnitude at certain frequencies and nearly perfect agreement at other frequencies. One needs to be aware of these issues when examining spectra. First, results are presented for nozzle system one ($D_e = 4.9$ in.). Spectra at three different cycle conditions are included. The nozzle pressure ratios and stagnation temperature ratios in the primary stream (subscript p) and secondary stream (subscript s), are: 1) $NPRp = 1.38$, $Tp/Ta = 2.15$, $NPRs = 1.6$, $Ts/Ta = 1.0$; 2) $NPRp = 1.57$, $Tp/Ta = 2.27$, $NPRs = 1.6$, $Ts/Ta = 1.0$; and 3) $NPRp = 1.57$, $Tp/Ta = 2.27$, $NPRs = 3.0$, $Ts/Ta = 1.0$. Spectra obtained at static conditions ($M_t = 0.0$) with the two microphone arrays at three different angles of 90, 110, and 145° are shown in Fig. 1. At 90°, there is good agreement between the two sets of spectra. The corresponding normalized distances (r/D_e) are 61.2 and 36.7. The low-frequency sources are located farther downstream from the nozzle exit and have axial extents of many diameters; the high-frequency sources are located much closer to the nozzle exit plane. The good spectral agreements over the entire frequency range indicate that there are no near-field effects, even at the lower frequencies, which have longer acoustic wavelengths. As we move to aft angles, the microphone distance for the sideline array increases progressively and reach $39.1D_e$ at 110° and $64D_e$ at 145°. The spectral agreements are uniformly good at all the angles and over the entire frequency range. The distance of $\sim 36D_e$ then represents the true far field for the range of jet conditions analyzed.

Next, the spectra from the same nozzle system with forward flight are presented in Fig. 2. For the jet with a coflow, the propagation distance to the microphone needs to account for the convection and refraction effects. The changes in the spectral amplitude and the

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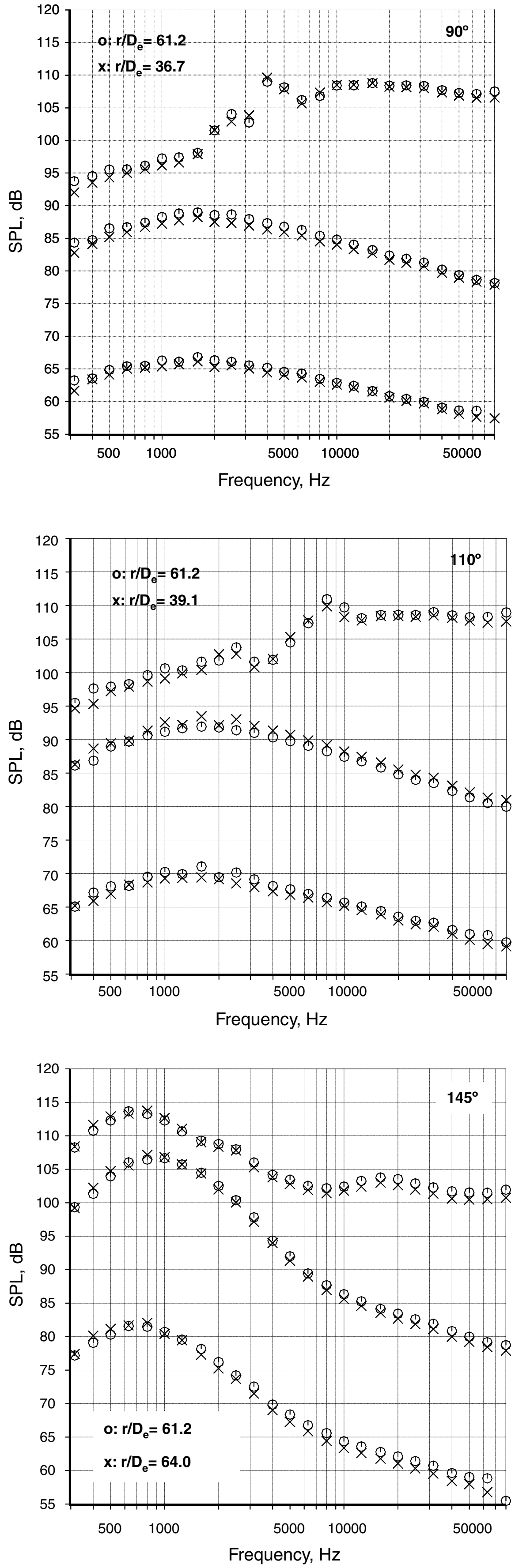

Fig. 1 Spectral comparison at three cycle conditions, $M_t = 0.0$. o: polar array; x: sideline array.

radiation angle due to the coflow have been calculated using the procedure developed by Amiet [5,6], with the proper geometry of the jet and the wind-tunnel. An interpolation of the resulting spectra at the true radiation angles to the radiation angles for the static case (fixed microphone angles) allows the direct comparison of the spectra obtained at various tunnel Mach numbers. For the wind-on case, the proper values of the atmospheric attenuations inside and outside the tunnel flow are used. The jet conditions in Fig. 2 are: $NPRp = 1.8$, $Tp/Ta = 2.38$, $NPRs = 1.8$, $Ts/Ta = 1.0$, and the tunnel Mach number is 0.20. Spectral comparisons at three radiation angles of 90, 110, and 130° are shown. For the angles close to 90°, the microphone distances (r/D_e) for the fixed-distance sideline array have the lowest values; therefore, two angles in this angular sector have been selected. There is good agreement between the two sets of spectra at all the angles and over the entire frequency range. Equally good agreement is observed at all other angles as well (not shown); this is not unexpected because the r/D_e at oblique angles has higher values. The distance of $\sim 36D_e$ is then sufficient for making true far-field measurements (so far) for dual-stream jets, both in a static environment and in the presence of a forward flight stream.

The spectra from the larger exhaust geometry, with equivalent diameter of 6.79 in., are now examined. Again, three cycle conditions are included: 1) $NPRp = 1.25$, $Tp/Ta = 2.52$, $NPRs = 1.65$ $Ts/Ta = 1.16$; 2) $NPRp = 1.53$, $Tp/Ta = 2.87$, $NPRs = 1.74$, $Ts/Ta = 1.21$; and 3) $NPRp = 2.0$, $Tp/Ta = 2.35$, $NPRs = 2.58$, $Ts/Ta = 1.09$. These three correspond to typical cutback, maximum takeoff and cruise conditions, respectively. Because of the shorter r/D_e, the spectra at 135, 110, and 90° are presented in the order of decreasing r/D_e for the fixed sideline array in Fig. 3. At 135°, there is acceptable agreement from both sets of spectra. This good agreement is perhaps not unexpected because the r/D_e for the sideline array is

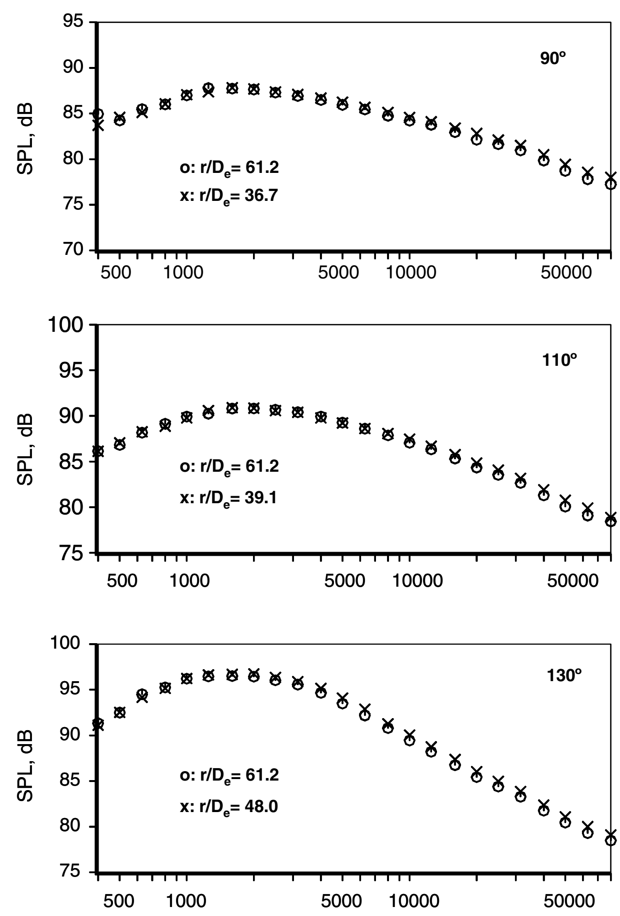

Fig. 2 Spectral comparison, $M_t = 0.2$. $NPRp = 1.8$, $Tp/Ta = 2.38$, $NPRs = 1.8$, $Ts/Ta = 1.0$. o: polar array; x: sideline array.

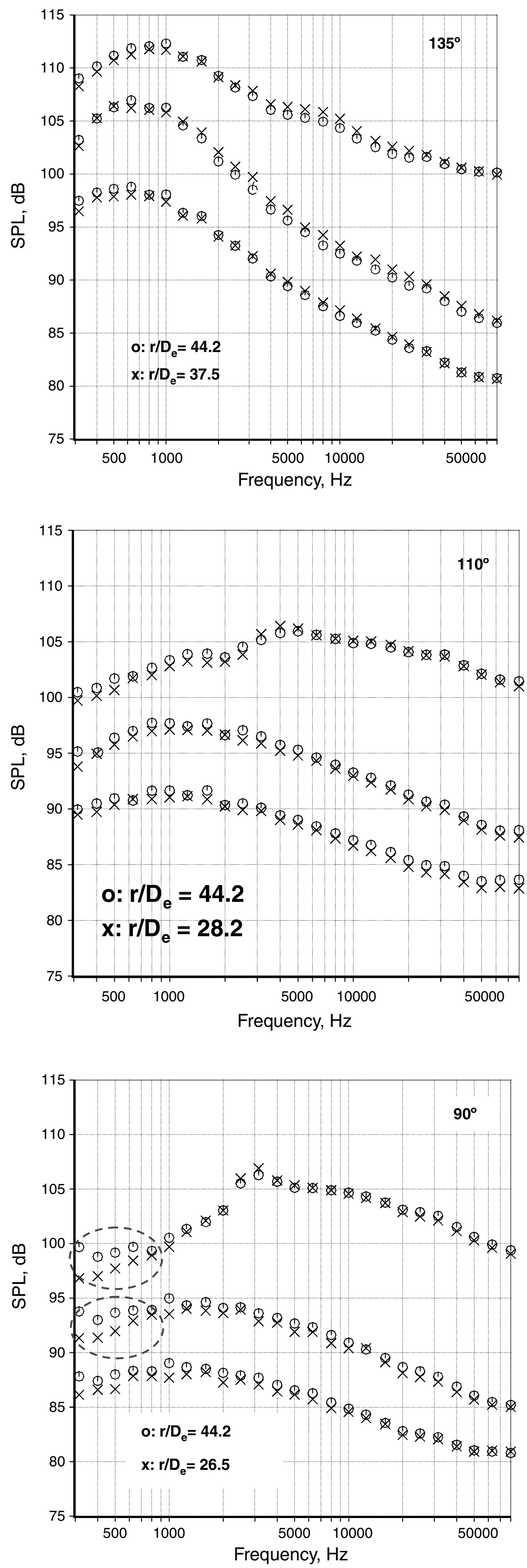

Fig. 3 Spectral comparison at three cycle conditions, $M_t = 0.0$. o: polar array; x: sideline array.

37.5; as seen in Fig. 1, this distance represents the true far field. There is also good agreement at 110°, with a minimum r/D_e of only 28.2! Finally, near-field effects are observed at the very low frequencies $\leq \sim 800$ Hz at 90°, with minimum r/D_e of 26.5. However, very good agreement is observed at the higher frequencies. The distance of $26.5D_e$ represents the edge of the near field for the very low frequencies; the source region stretches for several diameters for these low frequencies. Note that there is acceptable agreement for these same frequencies at 110°, with $r/D_e = 28.2$. These results seem to suggest that a distance of only $\sim 28D_e$ marks the boundary between far field and near field for dual-stream jets for all practical cycle conditions.

The reason for the good agreement at these surprisingly low values of r/D_e is investigated. The directivities of the OASPL for the larger nozzle system for the same three cycle conditions are shown in Fig. 4. Measurements from both the microphone arrays are plotted. First of all, there is good agreement between the two sets of data at all the angles. Secondly, there is a gradual variation in the aft quadrant, with a gentle increase in levels with angle. A similar comparison for the smaller nozzle system ($D_e = 4.9$ in) is shown in Fig. 5. For cycle point 3 with supersonic secondary jet ($NPRp = 1.57$, $Tp/Ta = 2.27$, $NPRs = 3.0$, $Ts/Ta = 1.0$), the directivity curve is almost flat. Once again, there is good agreement over the entire polar angular range. The main conclusion is the following: there is no rapid change in OASPL in the aft quadrant; rather, there is a gradual variation for dual-stream jets.

It is instructive to contrast the directivity of OASPL for dual-stream jets with that of a highly heated supersonic single-stream jet. Figure 25 in [2] shows such a comparison of the OASPL from the two arrays for a supersonic jet with $M_j = 1.84$ and at two stagnation temperature ratios of 1.0 and 3.2. There is good agreement for the unheated jet. However, the levels measured by the nearer microphone are lower for the heated jet in the polar angular range of $\sim 100°$ to $\sim 125°$. Examination of the spectra in this angular range (figure 27 in [2]) indicated that the variations for the unheated jet are minor. There is a drastic change in the spectral levels in this angular range for the highly heated supersonic jet. There is an increase of ~ 10 dB in the low-frequency regime and up to the spectral peak at ~ 3 kHz. At the higher frequencies there is a ~ 5 dB increase in the levels. For this heated jet at high velocity jet with $V_j = 3040$ ft/s, the spectral shape changes from a broad peak to a narrower peak in this angular region, resulting in the observed increase of ~ 10 dB at the lower frequencies. As shown in Viswanathan [2], the peak source for the highly heated supersonic jet is at $\sim 15D$ from the nozzle exit plane. If the spectra measured by the two microphone arrays are reprocessed

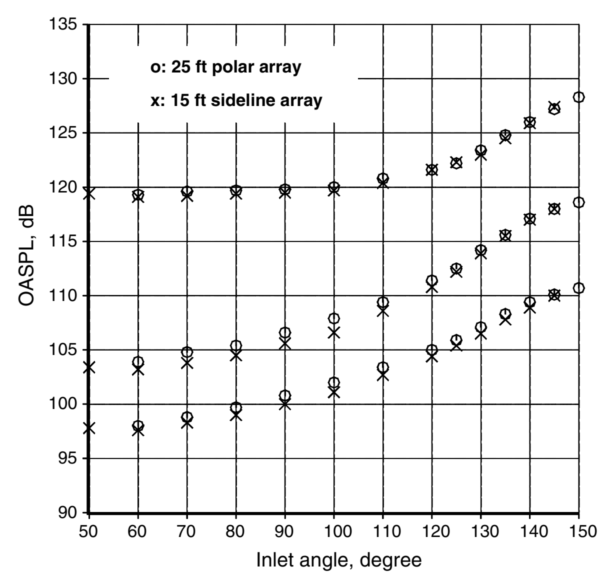

Fig. 4 Directivity of OASPL for three cycle conditions. Larger nozzle system, $D_e = 6.79$ in.

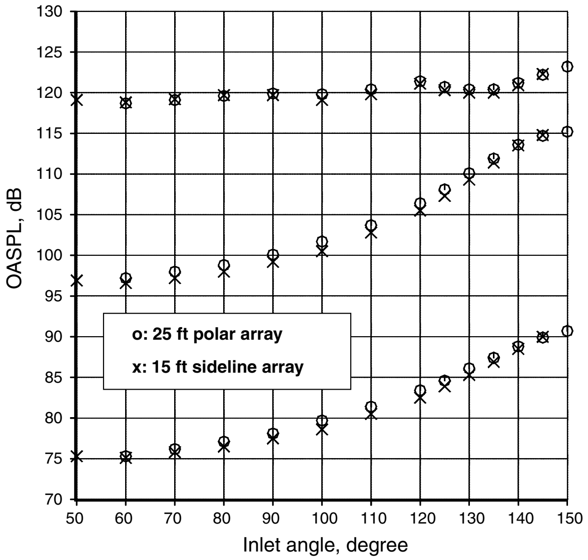

Fig. 5 Directivity of OASPL for three cycle conditions. Smaller nozzle system, $D_e = 4.9$ in.

with the source located at $15D$ instead of at the nozzle exit plane, the discrepancies in the OASPL and in the spectral comparisons in the polar angular range of ~110 to ~125° are eliminated. See section IV.E in [2] for complete details.

Let us examine the variation in spectra in the same angular range of ~110 to ~125° for the dual-stream jet at typical takeoff power ($NPRp = 1.53$, $Tp/Ta = 2.87$, $NPRs = 1.74$, $Ts/Ta = 1.21$) in Fig. 6. There is no drastic change in spectral shape; furthermore, the increase in peak spectral level at ~1000 Hz is only 5 dB. The increase in OASPL in this angular range is also ~5 dB in Fig. 4. Thus, there is neither drastic change in the spectra or in OASPL for typical maximum takeoff power for dual-stream jets. The peak source for the aft angles is located at $\sim 5D$ for dual-stream jets. As explained in Viswanathan [2], condenser microphones have the following polar response characteristics: 1) at low frequencies up to 20 kHz, the sensitivity due to incident ray angle in the range of ±30° is close to 0 dB; 2) even at a very high frequency of 80 kHz, the sensitivity due to incident ray angle in the range of ±15° is close to

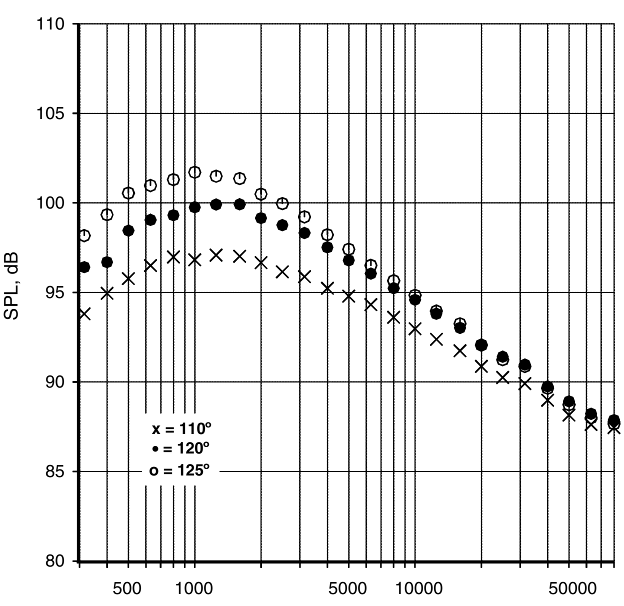

Fig. 6 Spectral variations with radiation angle for typical takeoff power. x: 110°; •: 120°; o: 125°.

0 dB. The error in angle is less than ~5° for the measurement locations in this paper. Therefore, the microphone at a distance of only $\sim 30D_e$ can not distinguish if the source is assumed to be at the nozzle exit plane as opposed to the true location of $\sim 5D_e$. This is the reason for the good spectral agreement at all frequencies observed in Figs. 1–3 and the good agreement in the OASPL seen in Figs. 4 and 5. The assumption of a point source located at the nozzle exit plane is therefore justified even for microphone distances of $\sim 30D_e$ for dual-stream jets. It is also clear that the minimum distance requirement is more stringent for a highly heated supersonic single-stream jet.

In theory, it is possible to establish a dual-stream jet with a highly heated supersonic jet and surround it with a low speed secondary stream with a velocity of ~500 ft/ sec. The noise characteristics of such a dual-stream jet would be close to that of the single supersonic jet, because the contributions from the secondary jet to the far-field noise would be minimal. It is conceivable then that the issues discussed with respect to supersonic jets become pertinent for this dual jet. However, such a dual-stream jet has no practical relevance as the cycle conditions are completely unrealistic and do not correspond to any turbofan engine.

III. Conclusions

The minimum distance in the far field that corresponds to the true geometric and acoustic far field for jet noise measurements from dual-stream nozzles is established in this study. For measurements carried out in the true far field, the distributed nature of sources can be taken to be represented by a point source located on the jet centerline at the nozzle exit. If this condition is satisfied, the subsequent processing of the measured data becomes greatly simplified as detailed knowledge of the source distributions for different frequencies is not required. Therefore, this issue has practical importance in the acquisition and processing of spectra. Spectral measurements from two different representative exhaust geometries, with microphone arrays at different normalized distances (r/D_e), have been analyzed to determine the minimum distance to the far field. In addition, typical jet conditions are considered, both in a static environment and in the presence of a forward flight stream.

Normalized lossless spectral comparisons at various conditions are examined. From the data, it is established that a distance of $\sim 30D_e$ represents the true far field for dual-stream jets. The reason for this surprisingly low value has been investigated through the examinations of the variation of the spectra with angle and the directivity of the OASPL. Additional insights are gained through a joint examination of the far-field noise characteristics of highly heated supersonic single-stream jets along with those for the dual-stream jets. The gradual variation of the spectra and OASPL with angle for the dual-stream jet, in contrast to those of the highly heated supersonic single jets, allows the far field to be reached at a lower value of r/D_e for dual-stream jets. In this regard, the requirement for minimum distance for the dual-stream jet is less demanding than it is for the supersonic heated single jet. The value of the low minimum distance determined here is the following: no corrections or source distributions need to be included in the processing of experimental data obtained at microphone distances larger than the minimum distance. This simplification, justified by the results of this study, is extremely useful from a practical standpoint.

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