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Jet Noise Source Localization Using Linear Phased Array

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Jet Noise Source Localization Using Linear Phased Array

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Abstract

A study was conducted to further clarify the interpretation and application of linear phased array microphone results, for localizing aeroacoustics sources in aircraft exhaust jet. Two model engine nozzles were tested at varying power cycles with the array setup parallel to the jet axis. The array position was varied as well to determine best location for the array. The results showed that it is possible to resolve jet noise sources with bypass and other components separation. The results also showed that a focused near field image provides more realistic noise source localization at low to mid frequencies.

Introduction

Further noise reduction in aircraft engines may be derived through further understanding of the flow physics, and accurate localization of the noise sources at the individual component level. Phased array microphone systems and a robust beamforming algorithm can play an important role in identifying dominant aeroacoustic noise mechanisms. In this study the method of minimum variance, an adaptive constrained optimization technique, was employed to analyze the phased array data. The technique was intended to optimize the output from arrays located in a wind tunnel, but the technique works well in the case of free field measurements such as in jet noise localization. Dongeon and Johnson[1], and Naidu[2] presented the minimum variance technique in their respective books.

One of the earliest applications of phased arrays to jet aeroacoustics was Billingsley and Kinns[3], Soderman and Noble[4] in the mid 1970's. More recently, significant contributions to the use of phased arrays for general aeroacoustics have come from Brooks, Marcolini and Pope[5]; Marcolini and Humphreys[6]; Watts, Mosher and Barnes[7]; Humphreys, Brooks and Hunter[8]; Mosher[9]; Mosher, Watts, Jaeger and Jovic[10]; Dougherty and Stokes[11]. All these authors have demonstrated the potential contributions of the phased array technique by presenting results of detailed acoustic source knowledge made possible by the technique. In our study, most of the jet noise sources were found within the first 10 nozzle diameters of the plume, consistent with many of the previous authors.

The present effort is distinguished from prior work by investigation of the effect of mixing enhancement devices on the jet noise source distribution, by the effect of array location, and by its validation of corrections made for imaging the acoustic source through the freejet shear layer in the simulated forward flight facility. Understanding what source regions are affected by mixing enhancement devices is critical to future development of this technology. As a matter of experimental technique, proper measurement of jet noise requires that the microphones be located in the geometric far-field, while phased array measurements suffer degradations in spatial resolution with increased distance from the source. A direct comparison of results from the phased array placed in the near and in the far field help in the compromise that must be reached in applying phased arrays to jet noise.

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Background

Venkatesh, Polak and Narayanan[12], in their paper, addressed the question of how to better process linear phased array. They also discussed the limitation of the delay-and-sum in resolving multiple source problems, such as the jet noise localization. Their study was necessitated by the fact that the error variance increases with the sources to sensors ratio. In jet noise, there are off axis sources and all sources along the jet axis are distributed continuously. Venkatesh et al.[12] employed the method of minimum variance to reduce the contributions from off-axis sources. The authors also addressed the problems of determining the extent of the off-axis contributions, with respect to the intensity of the focus direction; the resulting grating lobes due to the off-axis contributions; and the need to bound them.

Horne, Hayes, Jaeger and Jovic[13] investigated the effects of distributed source coherence on phased array response. They concluded that the elimination or modification of the diagonal elements of the cross-spectral matrix, when the background noise are predominantly coherent, is not recommended. The background noise sources that are coherent and associated with the radiating sources, such as an array setup in still air for free-jet measurements was considered. Distributed and coherent sources, such as in jet acoustic sources, are expected to produce multiple lobe interference patterns whose levels are dependent on the source frequencies and the array size. In our study, the use of sparse array with limited redundancy serves to reduce the accumulation of spurious coherent side lobes as discussed by Underbrink[14].

Facility

The test was conducted in the NASA John H. Glenn Research Center, Aeroacoustic Propulsion Laboratory (AAPL). Figure 1 shows the dual-stream jet exit rig, the freejet (NATR) that simulates flight effect on the nozzle flow, and the microphone array in its nearfield configuration. Two configurations of separate flow nozzles were tested. These nozzles had the basic design characteristics described by Saiyed, Mikkelsen and Bridges[15], namely bypass ratio of 5 with a fan nozzle diameter D of 9.6 inches and an external plug. The core nozzle exit plane was 4.6 inches (~0.5D) downstream of the fan nozzle exit and the plug tip was located 10.3 inches (1.1D) from the fan nozzle exit. The baseline model was designated 3BB, while the second model with 24 core nozzle tabs and 12 fan nozzle chevrons was designated 3T24C. The core tabs mix the core flow with the fan flow and generate streamwise vortices in the core flow. The core tabs had penetrations with the repeating pattern of inward, neutral, outward, neutral penetration, with the penetration created by angling the tabs at a 30^{o} angle with the flow. The fan chevrons had no relative protrusion angles.

The phased array consisted of 16 B&K 4135 microphones spaced across 106" array. The array was mounted on a truss at the height of the jet with the microphones pointed at the jet centerline with the line of microphones parallel to the jet axis. The microphones were spaced unevenly in a pattern designed to have spacings distributed evenly between the minimum and maximum spacing with no redundancy. With each configuration, various power cycle points were tested with and without freestream flow. In addition, the array locations were varied. Results from two array locations and two power settings, given in Table 1 are discussed in this report. NPRC and NPRB are the nozzle pressure ratios of the core and bypass respectively, while TTC and TTB are the total temperatures. The freejet Mach number was set at M=0.28 when it was used with the scale jet to simulate the jet exhaust noise during takeoff.

Table 1.—Definitions of power cycle points tested.

High Power Condition			
NPRB	TTB	NPRC	TTC
1.83	600 (R)	1.68	1500 (R)
Low Power condition			
1.60	600 (R)	1.35	1345 (R)

The phased array data was analyzed using a phased array software package called JENSIR purchased from Planning Systems Inc. of Maclean, VA. In processing the data, spherical or planar waves could be assumed depending upon the relative distance between array and source. Planar wave steering vectors were computed for cases where the array was 56 ft away from the jet and spherical wave vectors were used when the distance was only 6 ft. The software also allowed both conventional and minimum variance beamforming to be used; all results shown here use minimum variance for highest spatial resolution.

Results

Validation of Freejet Correction Using Known Sources

The array and processing software were validated using multiple speakers, with coherent and incoherent white noise and tone sound sources. This was especially critical to validating the effect of the free-jet shear correction on the beamformer. For this a deer whistle such as is usually affixed to an automobile bumper was mounted on the model to provide a point source at a given location with the free-jet flowing.

Figure 2 and 3 show the results of applying the beamforming to data from flow-induced noise sources. The freejet that simulates the flight effects during nozzle testing was turned on with the deer whistle mounted on the fan nozzle with its aft end aligned with the fan nozzle exit. The whistle generated multiple tones including a 3200Hz tone that was detected by the linear phased array. In Figure 2, the whistle was detected at the nozzle exit with the jet running at Ma# 0.1. Figure 3 repeats the results at Ma# of 0.28. Note the identification of a second noise source roughly three diameters upstream of the fan nozzle exit corresponding to the exit of the freejet. This source probably was the flow measuring rakes protruding into the freejet at this location and was found in all data with the freejet running.

Effect of Freejet Flow on Jet Noise Distribution

Having validated the performance of the beamforming for sources within the freejet we now apply the system to jet noise data to show the effect of the freejet on the distribution of jet noise. Figure 4 and 5 show the 3BB baseline nozzle results at Ma# 0.0 and 0.28 respectively, at high engine power setting. At both static and flight conditions the lowest frequencies appeared to peak near $x/D = 6$ with the static case having a slightly broader peak. At mid to high frequencies both static and flight cases have peaks near the plug tip. However, the flight case shows a much more pronounced peak than the static case where the noise generated over the first 6 diameters of the jet is only a few dB below the peak at the plug tip. The source strength at high frequencies is much greater in the static case than in the flight case, intimating that it comes from the fan-ambient shear layer that is weakened with forward flight. That the source at the plug tip are comparable in static and flight cases implies that this source is internal to the jet flow, well insulated from the ambient flow.

Similarly, Figure 6 and 7 show the 3BB baseline nozzle results at Ma# 0.0 and 0.28 respectively, at relatively lower engine power setting. The interpretation is similar to the high power case. Interestingly, the noise source located at 3 diameters upstream of the nozzle exit, identified in verification tests as the freejet exit, is relatively strong compared with the sources downstream. This upstream source is actually roughly the same level as in the high power cycle case. From this we conclude that the noise of the freejet is uncomfortably close to that of the test article for good far-field acoustic measurements, a caution to interpretation of simple far-field acoustic data. Also of interest is that the noise source located at the plug tip, while being lower than in the high power cycle case, is relatively stronger than the sources downstream. This points to the possibility that this source may actually be separation from the plug tip, which will scale as core velocity U as U^6 rather than U^8 as the freespace jet plume sources do.

Effect of Mixing Enhancement Devices on Source Distributions

Figure 8, when compared against Figure 4 shows the effects of changes in nozzle design, e.g. the addition of tab and chevron mixing enhancement features. There is a reduction in amplitude of the downstream sources over all frequencies in the 3T24C nozzle. At low frequencies there is minimal change in peak location. At frequencies above 1000Hz, however, the reduction in downstream source strength leaves the plug tip source dominant, giving the impression of a very different source distribution. Note that the data shows no strong sources upstream of the plug tip, .e.g. at the core or fan nozzle exits. If the plug tip source is due to separation from the plug, it must overshadow the sound produced by the tabs and chevrons themselves.

Effect of Phased Array Distance

Figure 9, 10, 4, and 11 show the effects of the array to source range on measured source distribution. In Figure 9 and 10 an acoustic source (loudspeaker) was imaged using phased array data acquired from a 6 ft and a 56 ft sideline distance respectively. As expected for a simple point source, the spatial resolution is degraded as the array to source distance is increased. At 6 ft the peak width (arbitrarily defined by the peak-6dB level) is only a fraction of the jet diameter at all frequencies, while at 56 ft, the width is much broader. The resolution is perhaps 4 diameters at the lowest frequencies, in line with the 10x change in resolution expected from a similar change in distance.

Recall that Figure 2 was obtained with the array located 6ft (7D) from the 3BB nozzle at high power cycle condition (static). In Figure 11 the array was located in the far-field, 56 ft (70D) from the same jet. The near field results clearly showed that above 3000Hz there was a strong source at the plug tip which dominated the distributions. At 70 nozzle diameters the peak location at low frequencies agrees with the 7 diameter result, assuring that there is little bias in the latter from being too close to the jet. However, at higher frequencies the far-field array cannot resolve the source near the plug tip. Not until 12kHz does the peak become noticeable. Comparison with the peak widths of the point source in Figure 9 shows that this is the frequency where the far-field array finally has resolution under 1 jet diameter as is required to resolve the plug tip source.

Summary

Experiments described in this paper show that high-resolution phased array beamforming produces physically meaningful source distribution measurements, even for jet rigs with forward flight simulation. Known sources can be accurately located within the freejet and jet noise distributions are self-consistent. When applied to jet flows the phased array is a very helpful diagnostic tool, indicating that in the present rig a significant source is located at the plug tip and that the freejet seems to have excessive noise relative to the jet for low power cycle conditions, It shows that the reduction of the jet noise with mixing enhancement comes from a reduction of source strength along the entire jet plume and does not find substantial increase in source strength near the tabs and chevrons themselves. Finally, the near- and far-field measurements showed no bias from measuring too near the jet, but clearly showed the benefit of placing the array in the near-field.

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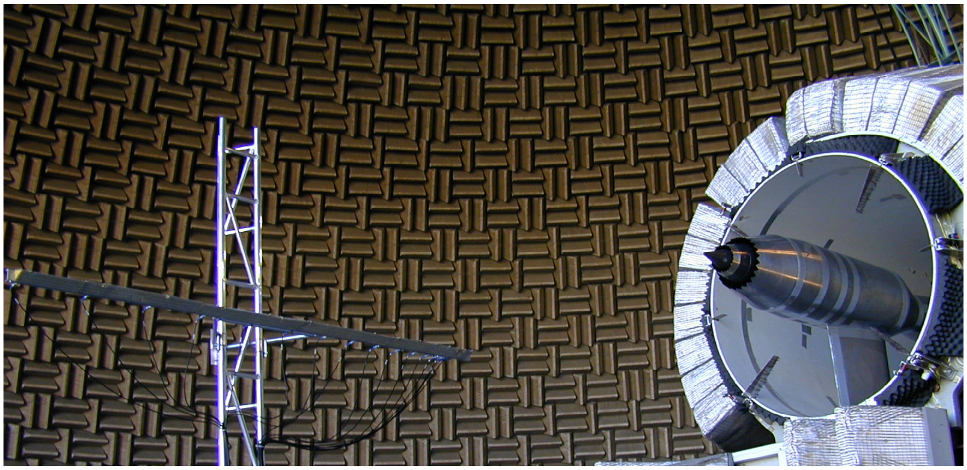

Figure 1.—Test rig and microphone in facility.

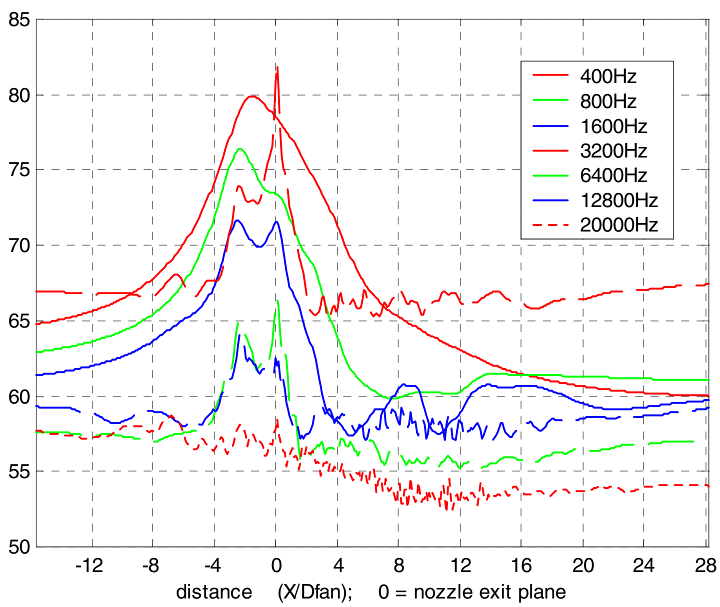

Figure 2.—Acoustic source distribution. Deer whistle in freejet; Ma# = 0.1; r/D = 7.

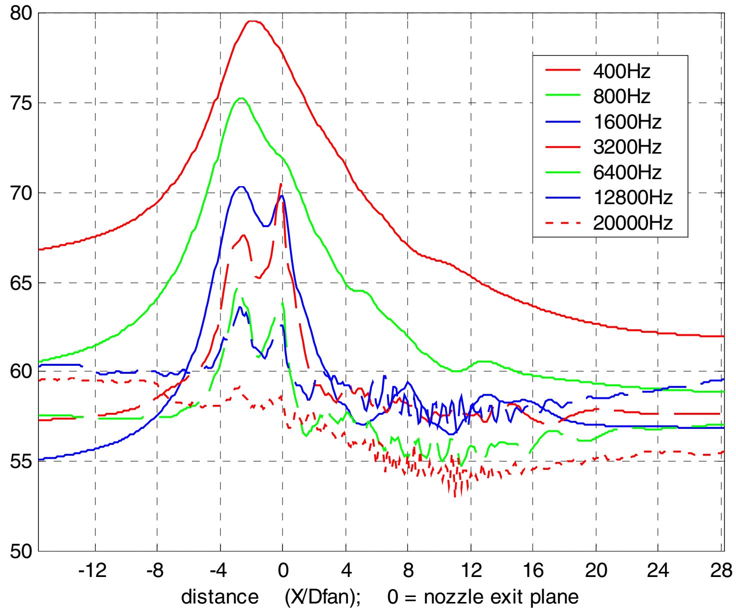

Figure 3.—Acoustic source distribution. Deer whistle in freejet; Ma# = 0.28; r/D = 7.

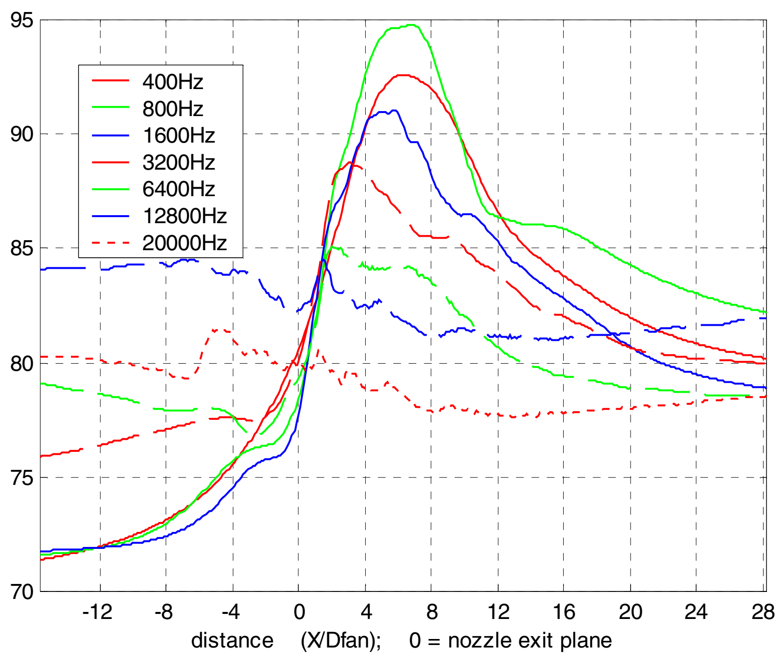

Figure 4.—Acoustic source distribution. 3BB baseline nozzle at high power cycle; Ma# = 0; r/D = 7.

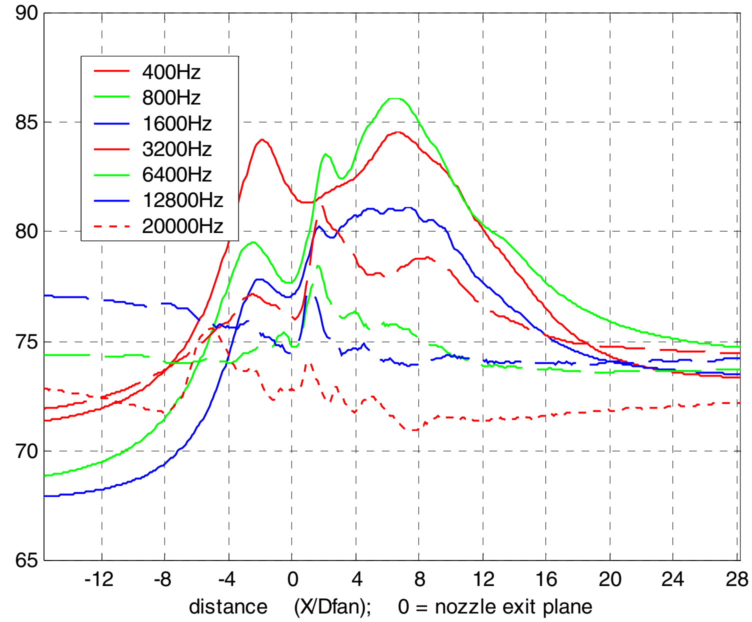

Figure 5.—Acoustic source distribution. 3BB baseline nozzle at high power cycle; Ma# = 0.28; r/D = 7.

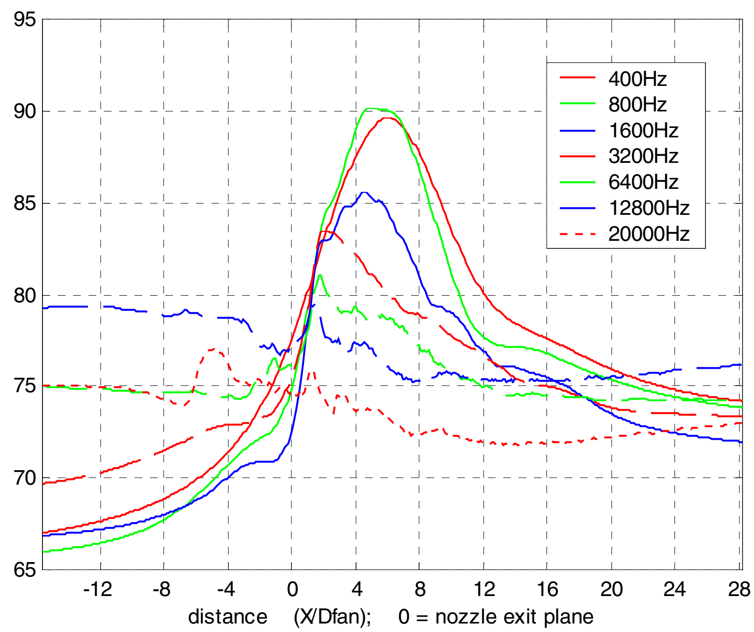

Figure 6.—Acoustic source distribution. 3BB baseline nozzle at low power cycle; Ma# = 0; r/D= 7.

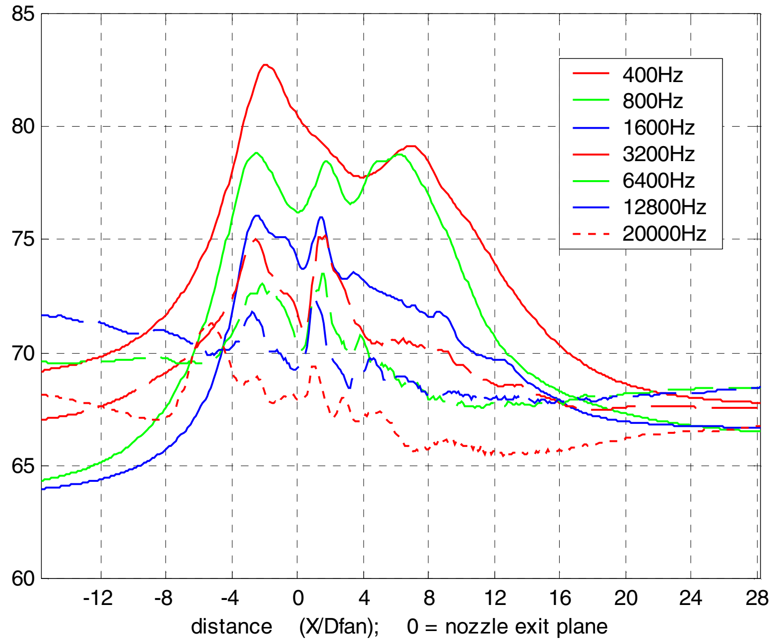

Figure 7.—Acoustic source distribution. 3BB baseline nozzle at low power cycle; Ma# = 0.28; r/D = 7.

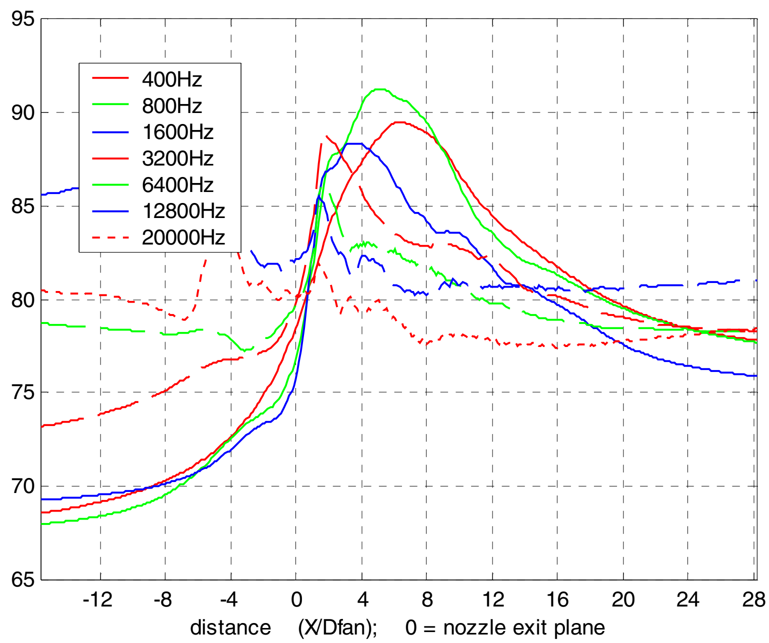

Figure 8.—Acoustic source distribution. 3T24C baseline nozzle at high power cycle; Ma# = 0; r/D = 7.

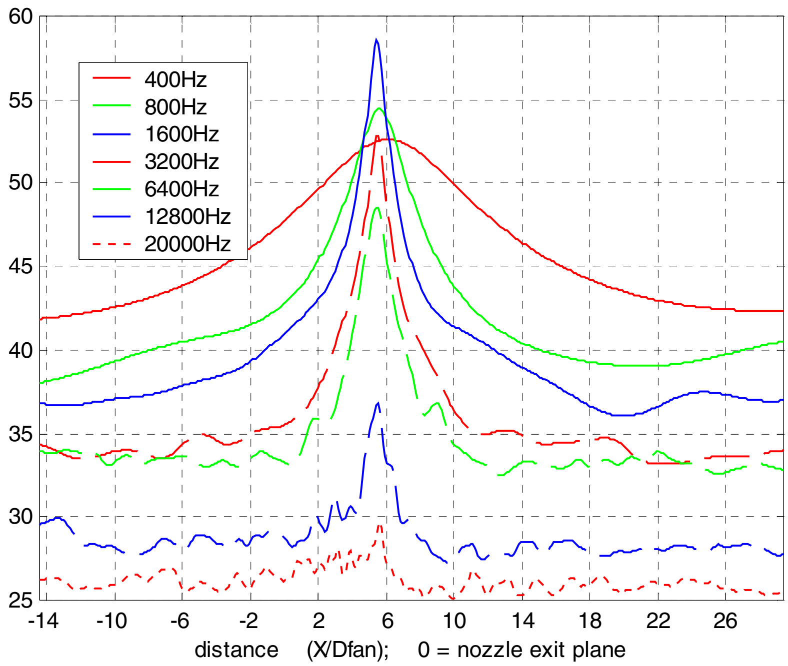

Figure 9.—Acoustic source distribution. White noise acoustic source; Ma# = 0; r/D = 70.

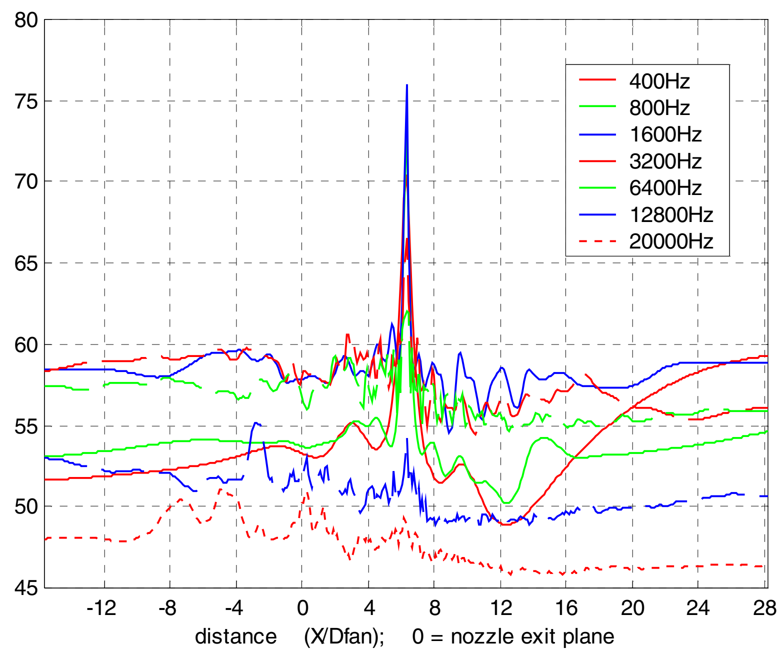

Figure 10.—Acoustic source distribution. White noise acoustic source; Ma# = 0; r/D = 7.

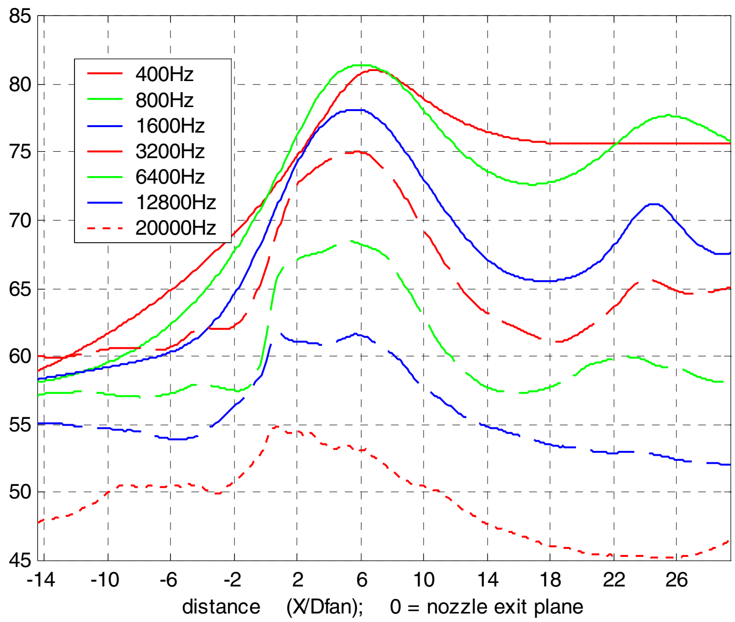

Figure 11.—Acoustic source distribution. 3BB baseline nozzle at high power cycle; Ma# = 0; r/D = 70.

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13. ABSTRACT *(Maximum 200 words)*

A study was conducted to further clarify the interpretation and application of linear phased array microphone results, for localizing aeroacoustics sources in aircraft exhaust jet. Two model engine nozzles were tested at varying power cycles with the array setup parallel to the jet axis. The array position was varied as well to determine best location for the array. The results showed that it is possible to resolve jet noise sources with bypass and other components separation. The results also showed that a focused near field image provides more realistic noise source localization at low to mid frequencies.

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