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Aeroacoustic Characterization of the NASA Ames Experimental Aero-Physics Branch 32- by 48-Inch Subsonic Wind Tunnel with a 24-Element Phased Microphone Array

Bryan T. Costanza[1]
California Polytechnic State University, San Luis Obispo, California 93407

William C. Horne[2] and S.D. Schery[3]
NASA Ames Research Center, Moffett Field, California 94035

and

Alex T. Babb[4]
University of California, Los Angeles, California 90095

The Aero-Physics Branch at NASA Ames Research Center utilizes a 32- by 48-inch subsonic wind tunnel for aerodynamics research. The feasibility of acquiring acoustic measurements with a phased microphone array was recently explored. Acoustic characterization of the wind tunnel was carried out with a floor-mounted 24-element array and two ceiling-mounted speakers. The minimum speaker level for accurate level measurement was evaluated for various tunnel speeds up to a Mach number of 0.15 and multiple streamwise speaker locations. A variety of post-processing procedures, including conventional beamforming and deconvolutional processing such as TIDY, were used. The speaker measurements, with and without flow, were used to compare actual versus simulated in-flow speaker calibrations. Data for wind-off speaker sound and wind-on tunnel background noise were found valuable for predicting sound levels for which the speakers were detectable when the wind was on. Speaker sources were detectable 2 – 10 dB below the peak background noise level with conventional data processing. The effectiveness of background noise cross-spectral matrix subtraction was assessed and found to improve the detectability of test sound sources by approximately 10 dB over a wide frequency range.

I.   Introduction

Aeroacoustic research is ideally carried out in dedicated facilities that have extensive acoustic treatment[1] and minimal facility drive noise. However, advances in acoustic instrumentation and processing with phased microphone arrays[2] are enabling acoustic measurements in facilities with high background noise that are otherwise not well-suited for acoustic studies provided that the source levels of interest are sufficiently strong. The 32- by 48-inch subsonic wind tunnel at NASA Ames Research Center (ARC) is a hardwall indraft facility with very low turbulence[3] that does not have special acoustic treatments and has not been previously used for acoustic research. The goals of this initial aeroacoustic study were as follows:

1) Assess the effectiveness of obtaining acoustic measurements in the ARC 32- by 48-inch wind tunnel with a phased microphone array.
2) Compare results of two different speaker calibration methods.
3) Assess the effectiveness of array processing methods, including deconvolutional processing and cross-spectral matrix subtraction of background noise, in improving the detectability of model noise sources and the accuracy of source level measurements.

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[1] Graduate Student, Aerospace Engineering Department, 1 Grand Ave., Student Member.
[2] Aerospace Engineer, Experimental Aero-Physics Branch, MS260-1, Associate Fellow.
[3] Emeritus Professor, New Mexico Tech.
[4] Graduate Student, Aerospace Engineering Department, 420 Westwood Plaza, Student Member.

II. Apparatus

A. Wind Tunnel

The indraft wind tunnel test section is shown in Fig. 1. The tunnel speed can be set from a Mach number of 0.05 to 0.15 with an adjustable sonic nozzle downstream of the test section. A large inlet contraction ratio and extensive flow conditioning screens were designed for low test section turbulence levels on the order of 0.1%. The wall boundary layer is normally 1- to 2-inches thick in the test section; however, devices for increasing the boundary layer thickness up to 16 inches on the floor of the tunnel were also used for some test conditions. The floor-mounted flush-plate array and ceiling-mounted speakers behind a smooth porous screen (location marked by blue tape) can be seen. The test section speed was measured with the two ceiling-mounted pitot-static probes.

Figure 1. Test setup in the wind tunnel test section with phased array in the bottom, speakers in the top, and two pitot static tubes attached to the ceiling. A hot-wire probe for boundary layer measurements is retracted to the surface of the array plate. The flow moves from left to right.

B. Phased Array

Acoustic measurements for the experiment were acquired with an OptiNav Array-24 system[4] with the accompanying beamforming software. The array was mounted in the floor of the wind tunnel test section in a mount/rotation platform. The array was not moved during this study. The array used Countryman B3 Lavalier 0.22-inch diameter microphones with a flat response of +/- 3 dB over 20-20,000 Hz and maximum level of 150 dB. The microphones were flush-mounted within a 15-inch diameter circle without physical treatment such as recessing behind a porous screen.

The metal array plate was modified to accommodate a hot-wire traverse system as well as three additional microphones placed in a line directly upstream of the traverse location. The hot-wire probe measured boundary layer properties that will be reported later.

All data including microphone data, hot-wire fluctuating signals, and speaker input signals were acquired with 48 channels of MOTU I/O 24 A/D converter with 96 ksamp/sec, 24-bit simultaneous sampling.

C. Speakers

Two speakers were mounted in an acrylic plate that fit flush with the top of the test section. An Electrovoice EV-DH3 20-Watt high frequency driver with 8-Ω impedance and a horn radiator provided output from 2 to 20 kHz. An Altec-Lansing M65 5-inch diameter bass/midrange driver with 8-Ω impedance capable of receiving up to 25

Watts from 100 to 8000 Hz provided low-frequency sound. Power between the speakers was distributed with a cross-over network with a cross-over frequency of 4000 Hz. The speakers were driven with an amplified GenRad 1382 pink-noise source. The total crossover input was varied from 0 to 3 Volts rms (V_{rms}), which corresponded to a power level of 0 to 1.1 Watts. The speaker center could be placed 42.5 inches upstream, 6.5 inches upstream, or 26.5 inches downstream of the array plate center. A metal porous screen covered the speakers that were mounted in the ceiling 32 inches above the array. Blue masking tape seen in Fig. 1 marks the speaker locations (the square outline marks the higher-frequency speaker; the octagon outline marks the lower-frequency speaker).

III. Methodology

A. Array Processing

Acoustic propagation through the test section with flow results in phase shifts that differ from no-flow cases. This can be accounted for by using convected steering vectors during array processing[2]. For low Mach numbers and propagation from a broadside source the primary effect of convection is an apparent shift of the source downstream as a function of Mach number by the angle $\sin^{-1}(M)$. Convection effects in this study were accounted for by applying the angular shift consistent with a uniform Mach number in the test section.

All beamforming processing presented in this report was accomplished with the TIDY algorithm.[5] Other beamforming and noise-reduction methods, such as conventional beamforming, CLEAN-SC, and DAMAS2, were evaluated with limited data sets, but TIDY showed the best sidelobe suppression and source visibility for this application.

B. Noise Reduction with Background Noise CSM Subtraction

Blacodon[6] recently reported effective reduction of background noise sources by subtracting the cross-spectral matrix (CSM) of the empty tunnel background noise from the CSM of model test data at the same flow condition. In general, empty test-section background noise is available only at the beginning and/or end of a wind tunnel study with the test model removed. In this study the effectiveness of CSM subtraction of empty section background noise was also assessed with real and virtual speaker calibration data. For the virtual speaker calibration, the wind-off speaker signal was added to the speaker-off background noise signal before processing, as described in detail below. The CSM subtraction benefit can be seen in Fig. 2, which depicts hemispheric source location maps for the 1/3 octave band centered at 1550 Hz. Flow is from right to left at M = 0.15. The fixed background sources at this frequency are primarily downstream associated with turbulent wall flow being ingested by the valve controlling the sonic throat. Noise from the two pitot static probes was also observed in Fig. 2a (also refer to Fig. 1) but this noise was eliminated with CSM subtraction as seen in Fig. 2b. With CSM subtraction applied in Fig. 2b the peak background noise levels were reduced from 97 to 89 dB in the same band.

C. Wind-on Speaker Calibrations

The speaker response was recorded for most permutations of wind speed (Mach 0.05, 0.10, 0.15), speaker position (42.5 inches upstream, 6.5 inches upstream, and 26.5 inches downstream), speaker input ($0V_{rms}$, $1V_{rms}$,

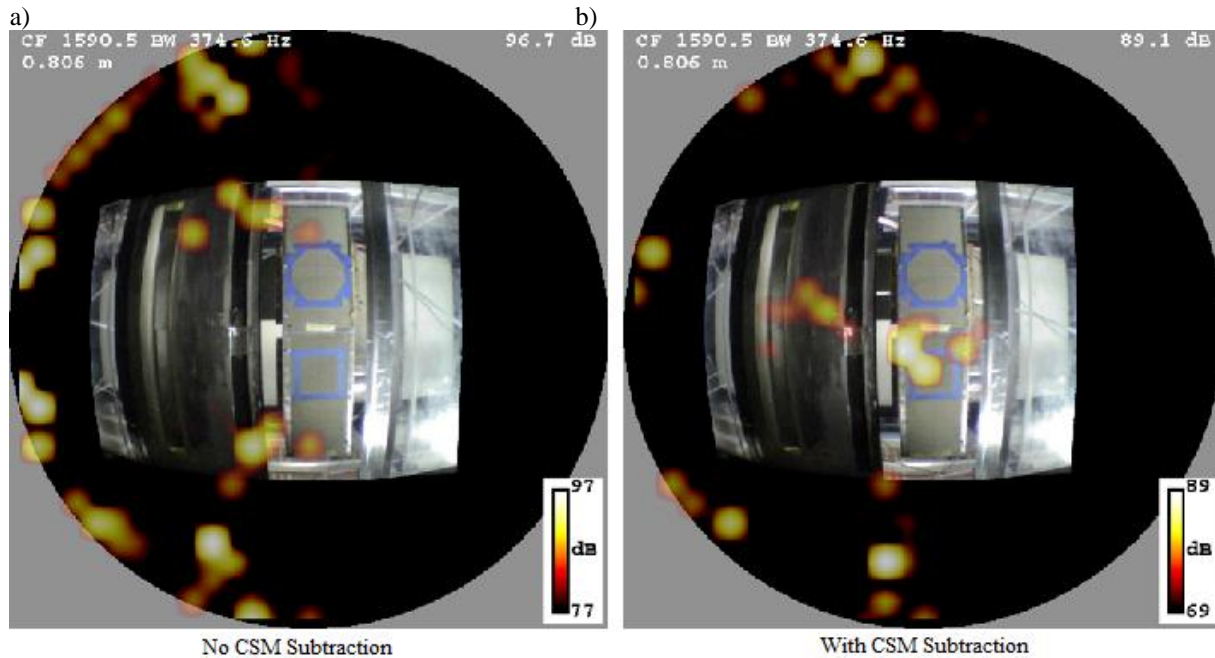a)   b)

Figure 2. Comparison beamform result with (right) and without (left) CSM subtraction for background noise at M = 0.15 and f = 1550 Hz. Note the different sound level scales: 77 - 97 dB for (a) versus 69 - 89 dB for (b). Flow is from right to left.

$3V_{rms}$), and nominal boundary layer thickness (2-inch and 16-inch). Repeat sampling of selected conditions was obtained. Acoustic recordings were approximately 80 seconds but all analysis was done with 79-second samples to ensure that all samples were of equal length.

D. Virtual Speaker Calibration

In-flow speaker calibration is useful to directly determine array response to a known source, but requires the fabrication of a streamlined fairing housing for the speakers, and positioning the fairing at all of the source locations of interest. For this study (and a similar effort in the 80x120 ft wind tunnel[7]), an estimate of the minimum level of sources that could be accurately measured was obtained by simulating in-flow speaker sources by combining signals from empty section background noise with wind-off speaker sources, and then processing the resulting composite sources.

IV. Analysis and Results

A. Comparison of Measured Peak Levels from Real and Virtual Speaker Calibration

Virtual calibration levels corresponded with real calibration levels to within 6dB over all frequencies and much less at most frequencies, as shown in Fig. 3. Differences can be attributed to a variety of causes, including directional variations in speaker output as well as changes in speaker loading due to different flow conditions. Visual beamforming maps of the real and virtual calibration are practically identical as seen in Fig. 4.

B. Source Visibility

Figure 5 presents spectra of both the empty section background noise (heavy solid line) and wind-off speaker spectra with four relative gain levels in 10 dB increments (dashed lines). The tunnel flow conditions presented are for a 2-inch boundary layer at M = 0.10 and 0.15, and for a 16 inch boundary layer at M = 0.05, 0.1, and 0.15. The background noise spectra exhibit similar overall shape with some differences depending on Mach number and boundary layer thickness. In each case, the 1/3 spectra are indicative of the peak beamform level observed over the
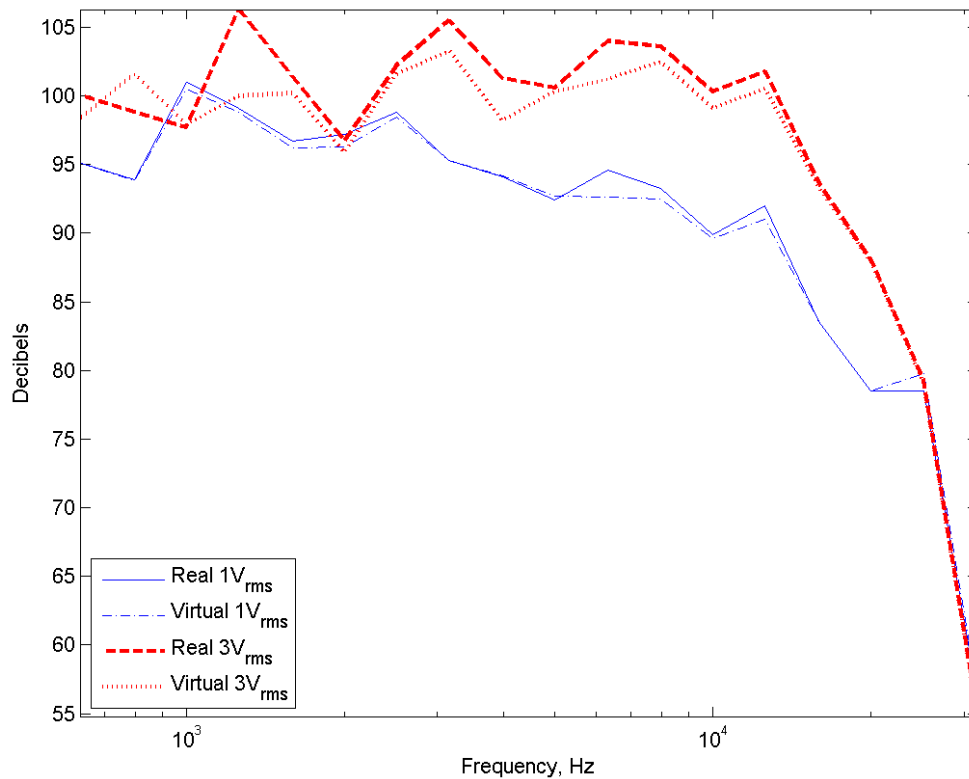

Figure 3. Comparison of decibel level predicted by virtual calibration to the actual calibration.

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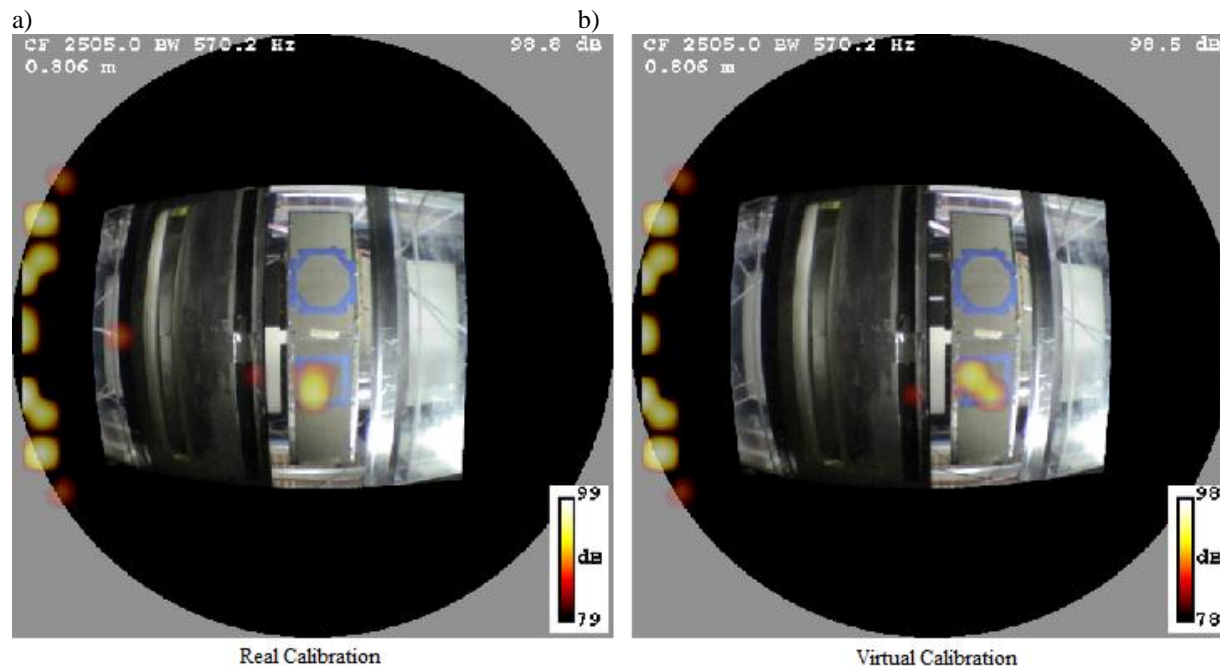a)   b)

Figure 4. Comparison of beamforming results for real and virtual calibration. Flow Mach number is 0.15, processed at Mach number of 0.00.

hemisphere visible to the array. The boundary layer variations were primarily of interest in a different phase of the study that examined the effect of boundary layer turbulence on array microphone coherence. In the present study, the two boundary layer conditions were considered to assess order-of-magnitude effects of varying experimental conditions.

The two signals (wind-off speaker at various output levels and empty-section background noise) were added sample-by-sample in MATLAB prior to array processing of the composite signal. The beamformed results were then examined for reliable visibility of the speaker sources for each 1/3 octave band frequency with a 20 dB plot range.

Small filled circles in Fig. 5 indicate that the speaker source was unambiguously visible with only array processing, while open circles indicate conditions for which the speaker source was visible after subtracting the CSM of the empty test section noise prior to array processing of data. As can be seen in Fig. 5, array processing without background noise CSM subtraction allowed detection of the source with levels a few dB below the background noise. Background noise CSM subtraction allowed detection of the speaker source at levels often 10 dB lower or more, depending on frequency. These results are consistent with similar assessments of source visibility in the Air Force NFAC 80- by 120-foot wind tunnel at NASA Ames.[7] Although these facilities are vastly different in size, the speed range is similar and the background noise in both are dominated by strong downstream sources associated with either the tunnel fan drive or sonic flow valve.

Similar assessments of minimum detectable source level were made for other flow conditions and speaker locations, as reported in Table 1. These results are based on in-flow speaker response at $1V_{rms}$ amplifier output and utilizing CSM subtraction with TIDY processing. The background noise data used for CSM subtraction were taken a short time before or after the primary measurement. For selected conditions, comparisons of the results of background noise CSM subtraction showed negligible difference between background noise files that were acquired either on the same or different day as the in-flow speaker measurement.
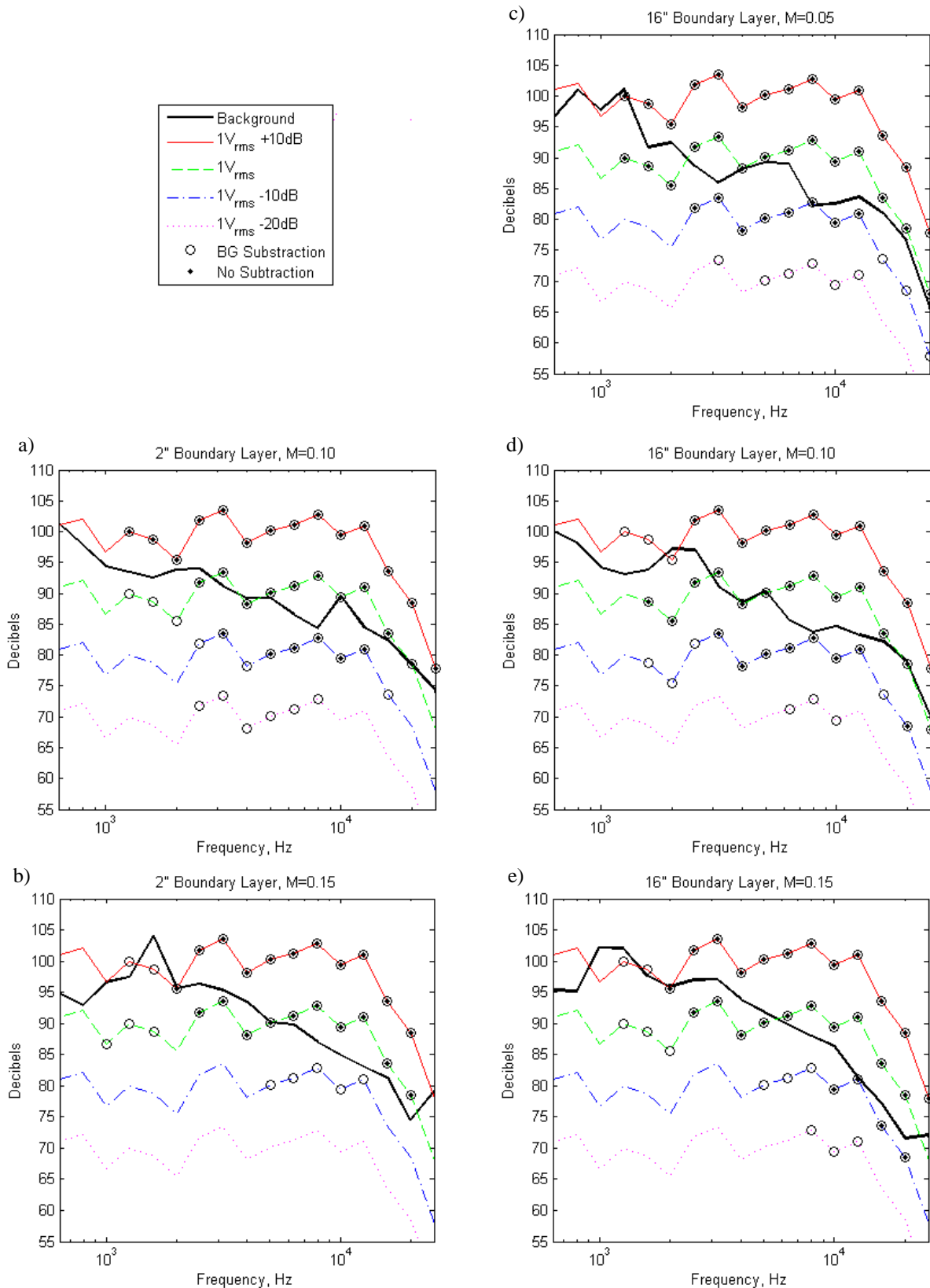
Figure 5. Virtual Calibration noise 1/3 octave spectra and source visibility. Speakers in the 6.5-inch upstream position. Insufficient data exists for 2-inch boundary layer at Mach=0.05. "No Subtraction" means CSM subtraction is not necessary to visually resolve the source. Data points with an open circle but no dot are the test points visible only when using CSM subtraction.

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Table 1. Tabulated results to summarize the visibility of the speaker source at different configurations and tunnel conditions. "Yes" means that the speaker source can be visually resolved in the beamform map and "No" means that it is not visible. Speaker input is 1V$_{rms}$.

Center Frequency, Hz	2" Bound. Layer		16" Bound. Layer	
	For 6.5"	Aft 26.5"	For 6.5"	Aft 26.5"
631.2	No	No	No	No
796.9	No	No	No	No
1000.0	No	No	No	No
1257.4	Yes	No	Yes	No
1590.5	Yes	No	Yes	No
2000.0	Yes	No	Yes	No
2505.0	Yes	No	Yes	No
3156.1	Yes	No	Yes	No
3984.3	Yes	Yes	Yes	No
5010.0	Yes	Yes	Yes	No
6312.3	Yes	Yes	Yes	No
7968.6	Yes	No	Yes	No
10000.0	Yes	No	Yes	No
12574.3	Yes	No	Yes	No
15905.4	Yes	No	Yes	No
20000.0	Yes	No	Yes	No
25148.7	No	No	No	No
31810.8	No	No	No	No
40000.0	No	No	No	No

Constant: Mach 0.15

Center Frequency, Hz	Speaker Location		
	For 42.5"	For 6.5"	Aft 26.5"
631.2	No	No	No
796.9	No	No	No
1000.0	No	No	No
1257.4	No	Yes	No
1590.5	No	Yes	No
2000.0	No	Yes	No
2505.0	No	Yes	No
3156.1	No	Yes	No
3984.3	No	Yes	Yes
5010.0	No	Yes	Yes
6312.3	No	Yes	Yes
7968.6	No	Yes	Yes
10000.0	No	Yes	Yes
12574.3	No	Yes	Yes
15905.4	No	Yes	No
20000.0	No	Yes	No
25148.7	No	No	No
31810.8	No	No	No
40000.0	No	No	No

Constant: Mach 0.15, 2"Boundary Layer

Center Frequency, Hz	Mach 0.15	Mach 0.10	Mach 0.05
631.2	No	No	No
796.9	No	No	No
1000.0	No	No	No
1257.4	Yes	Yes	No
1590.5	Yes	Yes	No
2000.0	Yes	Yes	Yes
2505.0	Yes	Yes	Yes
3156.1	Yes	Yes	Yes
3984.3	Yes	Yes	Yes
5010.0	Yes	Yes	Yes
6312.3	Yes	Yes	Yes
7968.6	Yes	Yes	Yes
10000.0	Yes	Yes	Yes
12574.3	Yes	Yes	Yes
15905.4	Yes	Yes	Yes
20000.0	Yes	Yes	Yes
25148.7	Yes	Yes	No
31810.8	No	Yes	No
40000.0	No	No	No

Constant: Speakers 6.5" For, Boundary Layer 16"

V. Conclusions

The minimum source levels detectable with a 24-element phased microphone array were recently characterized during a study of the NASA Ames 32- by 48-inch subsonic wind tunnel at Mach 0.05, 0.10, and 0.15. These levels were estimated with both wind-on speaker sources and composite signals comprised of wind-off speaker measurements and empty-test section background noise measurements, with similar results between the two methods. Speaker sources were detectable 2-10 dB below the peak background noise level. Deconvolutional processing with TIDY reduces apparent source size and sidelobe levels. CSM background noise subtraction further improved the detectability of the speaker noise source level by approximately 10 dB over many frequencies.

Beamforming was consistently poor when the center beamforming frequency was lower than 1000 Hz or higher than 25148 Hz , likely due to the size of the test section and phased array and the limited high-frequency speaker response. For future acoustic tests in the 32- by 48-inch wind tunnel, the analysis showed that sources of approximately 90 dB or higher can be resolved at frequencies as low as 1257 Hz while sources of only 70 dB are usually resolved at frequencies up to 10 kHz. Many aeroacoustic configurations of interest have incoherent source distributions, and for these situations the sources may be detectable only at higher levels than the acoustically compact speaker sources used in this study.

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