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A preliminary investigation of near-field acoustical holography in characterizing noise from military jet aircraft

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ABSTRACT

Since its introduction, near-field acoustical holography (NAH) has been successfully used in characterizing the vibration of and radiation from a wide class of structural noise sources. In the past several years, some have begun to apply NAH to the characterization of aeroacoustic noise sources. To date, however, research has involved only axial fans and model-scale subsonic jets. In order to meet the growing need for a better description of the source region of high-thrust military jets, we have been investigating the application of NAH to these types of sources. In this paper, we present some of the technical and practical challenges that need to be considered, including instrumentation bandwidth and dynamic range, the large spatial extent and partially correlated nature of the jet noise sources, and acoustical nonlinear effects in near-field propagation.

1. INTRODUCTION

Because current and next generation military jet aircraft are exposing both ground maintenance personnel and the community at large to high levels of noise, the Department of Defense has funded research to develop advanced modeling tools for community noise exposure and for noise reduction techniques. As these tools are being developed to address the overall military jet noise problem, the lack of understanding of the actual jet noise source has been identified as a limiting factor in both implementing these models and realizing the full potential of noise control techniques. Because traditional measurement methods have not provided sufficient information to fully characterize the noise source region of high speed jets, in particular for military turbojets

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on full military and afterburner power, near-field acoustical holography (NAH) is being explored as a method to measure the magnitude, directivity, and spectral content as well as the spatial distribution of the noise field.

This paper describes the results of an initial investigation into requirements and issues that need to be addressed for NAH to be used on a full-scale military jet. After a discussion of the basic NAH methods and potential challenge, a culminating near-field measurement on an F-16C aircraft is described.

2. NAH FOR FULL-SCALE MILITARY AIRCRAFT?

A. NAH Background

Near-field acoustical holography (NAH) is a method that employs acoustical measurements made on a two-dimensional grid to reconstruct a) the vibrational properties of a radiating structure, and b) the acoustical field everywhere. In order to reconstruct the source properties with the greatest accuracy, the measurements are made very close to the source (i.e., in the acoustical near field) in order to capture the evanescent features of the source that do not propagate to the far field. There are three fundamental approaches to NAH. Each of these fundamental approaches then has multiple implementation variations that have been developed as researchers have sought to improve both efficiency and accuracy of the technique. These approaches in their various implementations are now discussed.

The first NAH method, developed by Williams and others (see Ref. 1 and references therein), utilizes a spatial Fourier transform of the acoustic pressure measured on a two-dimensional grid in order to reconstruct the source properties. Because of the properties of the Fast Fourier transform, the traditional holography technique requires that the measurement array area must be four times the size of the source to avoid wrap-around effects, yet the microphone spacing can be no larger than half the wavelength of the highest frequency of interest to avoid aliasing. One refinement to this method, called "patch" holography, involves processing methods that permit the reduction of the measurement grid area to less than that required by ordinary Fourier NAH. Patch holography allows the reconstruction of a portion of the radiating structure and has been implemented in a number of different ways.[2-7] The most common approach is to take the pressure measurement and then extrapolate it over a sufficiently large area using iterative analytic continuation techniques so as to avoid spurious effects in performing the spatial Fourier transform. Patch holography permits the overall measurement aperture to be extrapolated into those regions where measurements could be prohibitively difficult, thus allowing reconstruction of the dominant source region for a given engine condition and frequency.

A second refinement to the traditional NAH method is called "scan-based" holography. This approach requires a limited array of microphones that will be systematically moved to produce a two-dimensional pressure measurement and one or more stationary reference microphones. Although this approach promises to reduce the overall channel count, it also requires more time to make a measurement as the microphones are moved. Lee and Bolton[8] and Lee *et al*.[9] have recently investigated the use of scan-based holography in NAH for aeroacoustic sources, including a subsonic jet.[10]

The second basic method of NAH does not use Fourier transforms, but employs the inverse boundary element method (IBEM). IBEM is essentially a numerical solution technique to the Helmholtz integral theorem, which relates the field acoustic pressure to the pressure and normal velocity on a source surface.[11,12] One main apparent advantage of the IBEM approach is that it avoids the Fourier transform and its restrictions in its solution technique. It is also readily adaptable to interior and exterior radiation problems. The drawback to IBEM, which makes it infeasible for jet plumes, is that the measurement should comprise a closed surface around the radiating structure and, for good reconstruction accuracy, at least six measurement points per wavelength are typically required.

The last fundamental means for achieving NAH is a pressure field expansion method. This approach, which is superficially similar to modal analysis, decomposes the measured pressure field into orthogonal functions. Once this decomposition has been performed, the pressure field at any other point can be calculated. One technique that falls in this field expansion category is the Helmholtz least-squares (HELS) method, developed by Wu and colleagues.[13,14] This approach expands the measured pressure field in terms of spherical wave functions that are solutions to the Helmholtz equation. Another technique is statistically optimized near-field acoustical holography (SONAH), which utilizes planar or cylindrical basis functions in its expansion.[15] Although HELS employs spherical basis functions and SONAH planar or cylindrical functions, both methods may potentially be applied to problems of arbitrary geometry because of the least-squares-fit nature of the solution technique.

B. Potential Challenges in the Application of NAH

There are several possible challenges, both technical and logistical, that need to be considered when deciding to employ NAH to characterize the noise sources within a jet plume. First, consider the measurement environment itself. The majority of NAH uses documented in the open literature have occurred in laboratory-type environments. NAH for a military jet aircraft will most likely take place during a static engine run-up, where the aircraft is tied down on the tarmac by the tail hook or some other means. The measurement environment challenges could include wind that can substantially shift the direction of the plume, the ground plane, severe temperature gradients caused by both the tarmac and heating due to the adjacent plume, and dust and debris kicked up by the plume incident on the ground. These factors can potentially impact the ability to make high-fidelity measurement and the interpretation of NAH results.

Another consideration is the sheer size of the source. Although the spatial extent of the source for a given engine condition and frequency is currently unknown, a simple example can illustrate this challenge. Let us assume that we want to implement patch Fourier NAH over the dominant source region of the plume. For simplicity, we assume some symmetry and desire to make a measurement over a quarter cylinder, 8 ft from the center line and extending 30 ft downstream. If we allow 0.15 m (about 6 in) between each measurement location, the two-measurements-per-wavelength restriction allows NAH to be performed up to about 1.1 kHz. However, this microphone spacing requires 61 measurements along the length of the plume, 26 measurements along each quarter circle, and 1586 total measurements. Because the complexity and cost of a NAH system that used that many microphones would be prohibitively high, a scan-based NAH system would be preferred. However, this increases the complexity and cost of the systemin its own right, as automated motion control would be required, as well as increases the total engine run-up time and jet fuel required.

A different source-related challenge that needs to be taken into account is the basic characteristics of jet noise. Jet mixing noise may be generally characterized as a broadband spectrum with a characteristic “haystack” shape. Examples, which are one-third octave spectra measured along different angles 61.0 m from the F-22 Raptor, are shown in Fig. 1. The peak frequency in the spectrum is related to the characteristic length scale of the turbulence as it evolves along the length of the plume. Consequently, the high-frequency and low-frequency noise components in the plume could have very different source regions as measured in the near field, thus requiring a large, dense scan of the plume.

A second feature of military jet aircraft noise is the high-intensity acoustic pressure fluctuations in the near field. Along the maximum directivity angle, overall sound pressure levels measured 18 m from the nozzle on an F/A-18E Super Hornet were 150 dB at afterburner.[16] If cylindrical spreading, rather than spherical spreading (due to the extended nature of the source) were assumed, the overall sound pressure level 3 m from the nozzle would be approximately 6 dB greater. Beyond the large overall sound pressure levels, another challenge is the large crest factor within a typical jet noise pressure signature. Although overall sound pressure levels (the decibel equivalent of the root-mean-square pressure) may be within the dynamic range of typical Type-1 6.35 mm or smaller pressure microphones, crest factors of ~10 dB induced by large compressive pressure spikes found in jet noise time series (see Fig. 2), could cause the preamplifier to clip or the microphone response to be distorted.

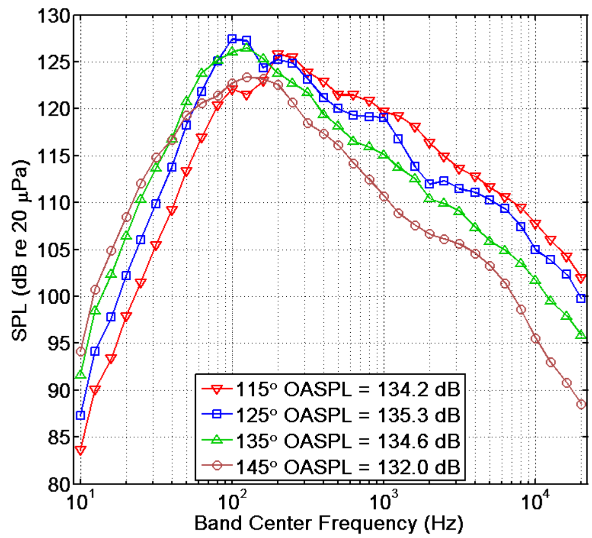

Figure 1: Haystack spectrum measured 61 m from an F-22 Raptor.

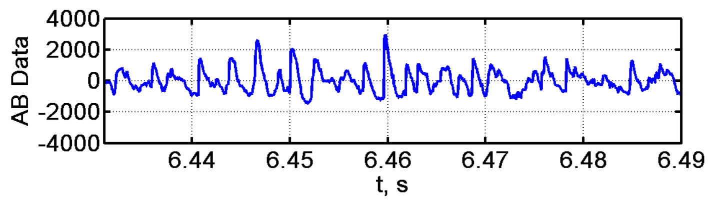

Figure 2: Example of a small portion of a pressure time series for an F-18E aircraft at afterburner, showing the asymmetry as manifest by relatively large positive peak pressures.

Another source-related challenge is the partially correlated nature of a supersonic jet plume. Traditionally, NAH has been implemented to find the structural vibration properties of a source. A structural source often exhibits good coherence between different spatial positions. The source produces the noise and a transfer function or cross spectrum between a stationary reference microphone and a scan-based array is used to map the relative phase between spatial positions. In a jet plume, the turbulent nature of the noise generation process causes the coherence to vary as a function of frequency and position, but can be very poor. The need for a coherent sound field has been removed with measurement and processing techniques developed by Hald[17] and validated for aeroacoustic sources by Lee and Bolton[9,10] and Lee *et al.*[8] The method, called the "virtual coherence technique," utilizes a singular value decomposition of cross spectra between multiple reference microphones and a scan-based array to decompose the measured pressure field into mutually incoherent partial fields. NAH can be performed on each partial field and the fields summed on an intensity basis. Despite the possibility of successfully using this technique on full-scale jet noise, the number and locations of reference microphones required to implement it need to be determined.

The final technical challenge that merits mention is the possibility of nonlinear propagation effects between the measurement locations and the source reconstruction location. The nonlinearity of high-amplitude military jet noise propagation has been well established,[15,18] but only in the far field over significant distances. Because NAH is based on the Helmholtz equation, which assumes linearity, nonlinear effects that alter the shape of the waveform and transfer energy between spectral components could cause results to be erroneous. However, a recent study by Shepherd *et al*.[19] suggests that nonlinear effects may not likely impact NAH results over short distances for the frequencies, provided that the only nonlinear effect is waveform steepening. This is an issue that merits further study.

A logistical challenge to the application of NAH to full-scale military aircraft is the time required to obtain the measurements and the need to optimize the measurement procedure so as to effect a quality high-bandwidth measurement within allowable time constraints. There are two issues here. First, there is the cost of jet fuel. Second, during a static engine run-up, the time an aircraft can be at afterburner is limited to a minute or so because the lack of airflow around the fuselage causes heating of the jet fuel. Consequently, multiple run-ups and significant downtime between runs will be required, putting the measurement at the greater mercy of stable environmental conditions for the sake of issues such as data quality and personnel safety.

3. FULL-SCALE FEASIBILITY EXPERIMENT: RESULTS AND DISCUSSION

As a first step to developing a measurement and processing system for NAH, F-16C (GE100) near-field acoustical data were collected on 25 September 2007 on the flight line at Hill Air Force Base. The data were collected during maintenance engine checks on a non-interference basis. Thus, the engine power levels were restricted to intermediate power settings (maximum of 85% RPM). The objectives of this test were to: validate the field performance of the data acquisition system (sensors, cabling, A/D, software), determine the correlation between microphones along an 18-ft array, measure the repeatability of sound levels in different runs at the same engine power setting; and to obtain an estimate of the maximum distance downstream of the nozzle exit plane that measurements will be required.

Thirty-six 6.35 mm Type I GRAS microphones were mounted in a linear array on an 18-ft long angle iron rig (see Fig. 3). In addition to the array of microphones, two stationary reference microphones were located 10.5 ft off the centerline, 12 and 18 ft downstream of the nozzle. In the first set of measurements, the array microphones were 5 ft off the ground and the rig was positioned 12 ft off the jet centerline. Measurements were made with the array extending from the nozzle exit plane to 18 ft downstream, then 12 to 30 feet downstream, then 24 to 42 feet downstream. The same set of measurements (in reverse order) was then made at positions 18 feet off the centerline. The linear microphone array was then lowered to a position 1.5" off the ground and the entire measurement procedure repeated. The positions of the array relative to the aircraft are shown in Fig. 4. Data acquisition was carried out with a National Instruments PXI system sampling at 96 kHz, which was controlled by a laptop-based LabVIEW program that streamed the time data directly to an external RAID-0 hard drive. Figure 5 shows the data acquisition system on the right and the array with the microphones 1.5" off the ground on the left.

Figure 3: Microphone array with microphones 5 ft off ground, left; reference microphone on tripod in front of array, on right.

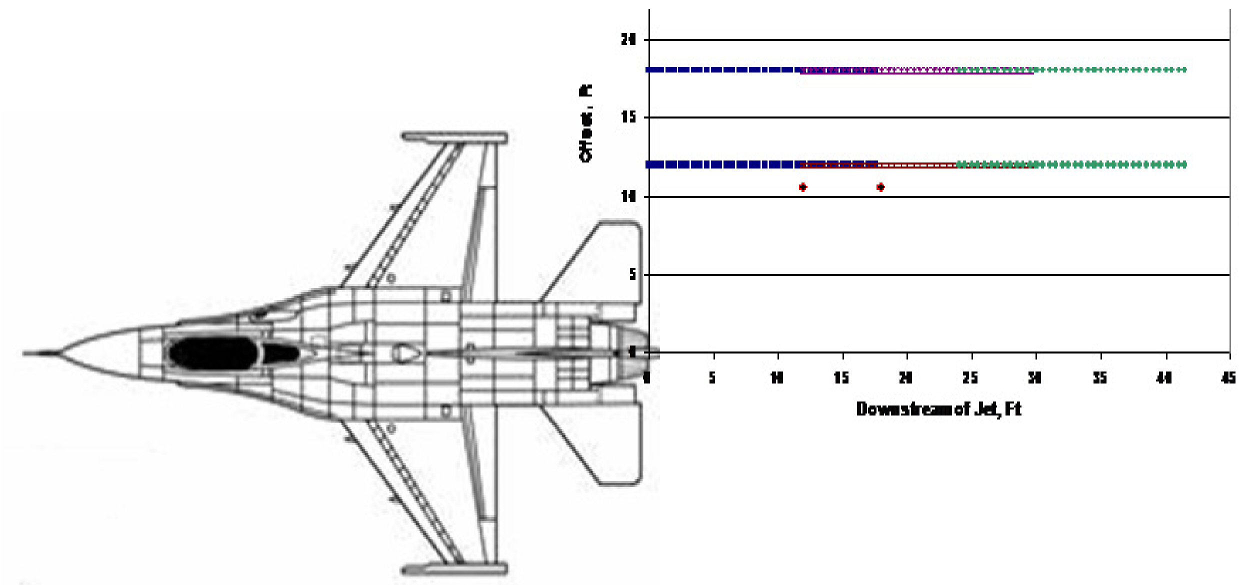

Figure 4: Measurement array and reference microphone locations relative to jet.

Figure 5: Array with microphones 1.5” off the ground, left; Measurement chassis, hard drive, and laptop showing LabVIEW-based data acquisition code, on right.

Because the 85% RPM levels are closer to the high power settings for which the eventual development of an NAH system is intended, and for the sake of brevity, only those measurement results are discussed here. The overall sound pressure levels (OASPLs) measured at the array microphones are displayed in Fig. 6. The overall levels at the two reference microphone positions for the first six recordings (six array positions) at 85% RPM are shown in Fig. 7. At both 12 and 18 ft off the centerline, the OAPSL along the array increases as a function of distance downstream from the nozzle exit plane. It is important to note how consistent the OASPLs are in the overlap regions (within 1 dB), even though these data were recorded during separate engine runs. (The aircraft was powered down to idle while the array was moved.) The ability of the aircraft operator to recreate the 85% engine setting and the stability of the overall sound levels at this setting are verified by the data in Fig. 9, which show that the variation in source level for six separate run-ups at 85% was within 1 dB. Sound pressure spectra recorded 12 ft off the centerline are presented as a function of distance from the nozzle exit plane in Fig. 10. As expected, the peak frequency decreases as the distance downstream increases.

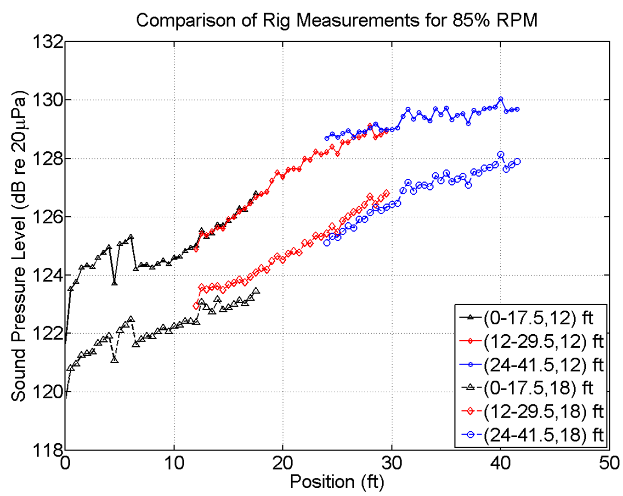

Figure 6: OASPL as a Function of Distance Downstream of Nozzle Exit Plane. Legend indicates: (location of array downstream of nozzle exit plane, lateral offset).

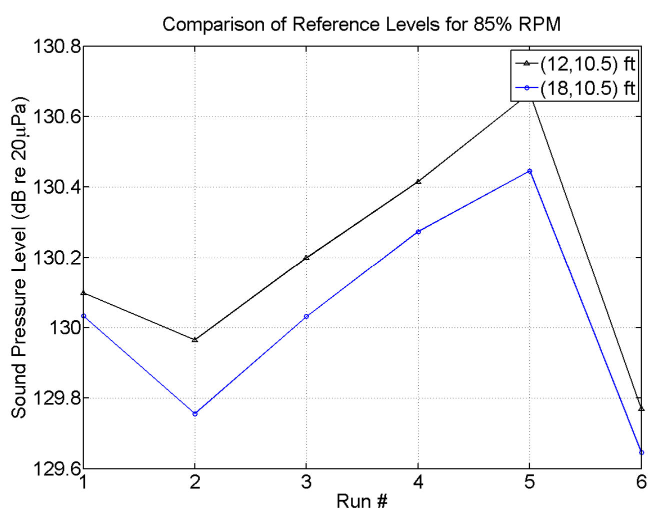

Figure 7: Comparison of OASPL values at the two reference microphones for first six runs at 85% RPM.

Although the results in Figs. 6 and 8 show that the array did not capture the full radiation region as the OASPLs and peak levels were still increasing 42 ft downstream, these results merit further comment. First, the array was aligned to be parallel to the centerline, not parallel to the shear layer. Consequently, the microphones are closer to the source downstream, which biases the results somewhat. Furthermore, the radiation from a jet is directional; had the measurements been made closer than 12 ft to the centerline, the peak-frequency "hotspot" of radiation that dominates the spectrum and OASPL would have occurred farther upstream. This illustrates a key point: the measurement array should be aligned parallel to and placed as close as possible to the shear layer of the jet.

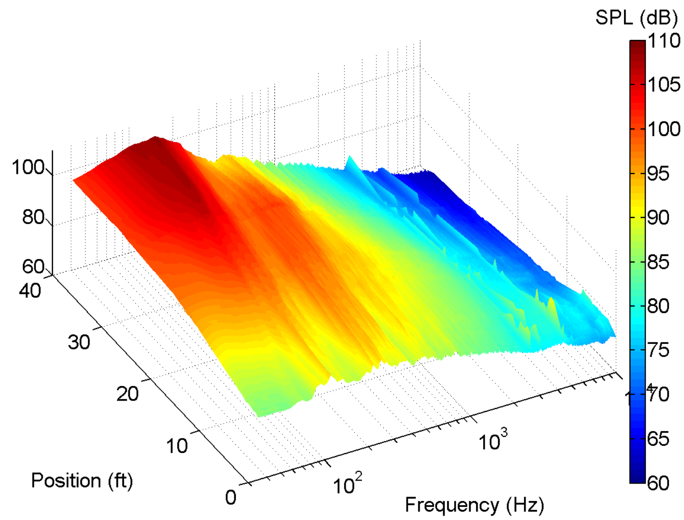

Figure 8: SPL map as a function frequency and position downstream relative to the nozzle exit plane at 85% RPM and 12 ft off the centerline.

Despite the biasing of overall and spectral levels from array alignment, to capture the entire source region NAH measurements will need to be made over a length exceeding 50 ft for this jet at military power. For a scan-based system, the number and locations of reference microphones depends on the number and locations of coherent sources. To begin to get at this issue, measured sound pressures were cross correlated and the peak correlation coefficient plotted as a function of separation distance in Fig. 9. These plots and the spectra of Fig. 8, consistent with model jet noise studies, indicate small-scale (high-frequency) sources with a short correlation length near the nozzle exit plane. What is surprising, however, is the pronounced increase in correlation length from 15 ft to 24 ft downstream of the nozzle exit plane. These results, which confirm that high-frequency sources with short correlation lengths originate near the nozzle exit plane and low-frequency sources with longer correlation lengths originate farther downstream, clearly imply that careful thought regarding the number and locations of reference microphones is required to optimize NAH performance for a broad range of frequencies.

Two last observations regarding the F-16C field measurements can both be made based on Fig. 10. In this figure, the spectra measured at the same location and power setting (85% RPM) at 5 ft and 1.5" off the ground are compared. The spectrum at 1.5" off the ground reflects constructive interference at low frequencies; the spectrum at 5 ft shows a broad destructive interference dip from 150-250 Hz. Due to the extended nature of the source and the different path lengths involved, this dip is not extremely pronounced. So, the first observation to be drawn from Fig. 10 is that the ground effect will vary substantially across a two-dimensional measurement array (with the greatest variation in the vertical direction) and the influence on the NAH calculations must be addressed. Finally, the spikes present in the 5 ft spectrum in Fig. 10 were caused by high-quality-factor structural resonances of the rig. The broadband acoustic levels in the near-field are such that care must be taken to carefully design support structures for a NAH array so as to eliminate acoustical excitation of the structure.

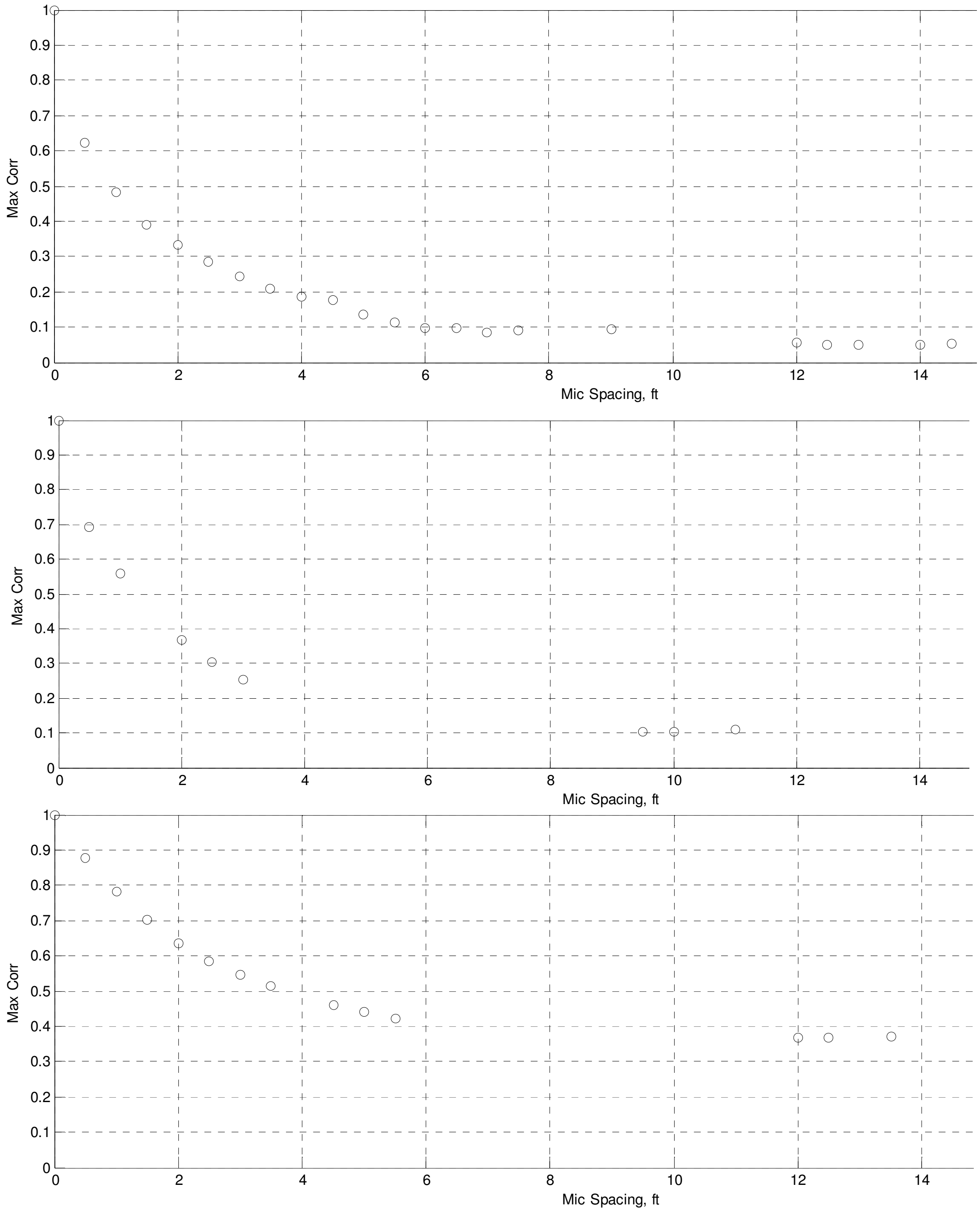

Figure 9: Peak Correlation Coefficient Between Microphones (18 ft off centerline) as a Function of Microphone Spacing: top – 1st microphone at 0 ft downstream of nozzle exit plane; middle – 1st microphone 15 feet downstream of nozzle exit plane; and bottom – 1st microphone 24.5 ft downstream of nozzle exit plane.

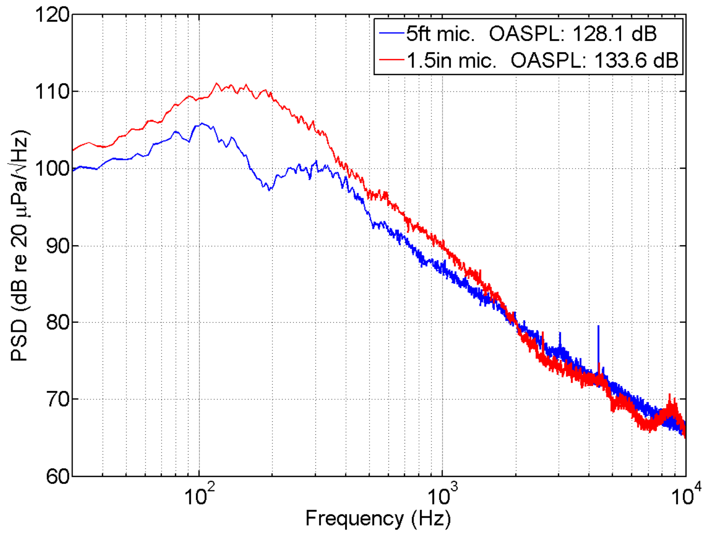

Figure 10: Comparison of spectra measured at the same downstream and lateral position downstream, at heights of 5 ft. and 1.5 in.

4. CONCLUSION

This paper has addressed work begun to take steps toward implementation of near-field acoustical holography (NAH) on a full-scale military jet aircraft. The number of challenges—both technical and logistical—is large, but so is the potential payoff, as this method could significantly aid in characterizing the aeroacoustic source regions inside the jet. The F-16C experiment highlighted the importance of placing the array parallel to and as close as possible to the jet shear layer to minimize the length of measurement aperture required to enclose the source region. The field experiment also showed that 1) ground reflection effects will vary at the array microphones and this will impact the NAH reconstructions; 2) a dynamic analysis of the NAH array structure is required to ensure that it operates free of resonance effects when placed in the measurement field; and, as hindsight makes sages of us all, 3) logistics dictate that the array be largely pre-assembled including cable bundles, so as to minimize set-up, cable runs, and connections required in the field.

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REFERENCES

[1] E. G. Williams, *Fourier Acoustics*: *Sound Radiation and Nearfield Acoustical Holography* (Academic Press, San Diego, 1999).

[2] J. Hald and J. Gomes, “A comparison of two patch NAH methods,” Proc. Inter-Noise 2006, Honolulu, HI.

[3] M. Lee and J. S. Bolton, “Patch near-field acoustical holography in cylindrical geometry,” J. Acoust. Soc. Am. **118**, 3721-3732 (2005).

[4] E. G. Williams, B. H. Houston, and P. C. Herdic, “Fast Fourier transform and singular value decomposition formulations for patch nearfield acoustical holography,” J. Acoust. Soc. Am. **114**, 1322-1333 (2003).

[5] M. Lee and J. S. Bolton, "A one-step near-field acoustical holography procedure," Proc. Inter-Noise 2006, Honolulu, HI.
[6] E. G. Williams, "Regularization methods for near-field acoustical holography," J. Acoust. Soc. Am. **110**, 1976-1988 (2001).
[7] J.-H. Thomas and J.-C. Pascal, "Wavelet preprocessing for lessening truncation effects in nearfield acoustical holography," J. Acoust. Soc. Am. **118**, 851-860 (2005).
[8] M. Lee and J. S. Bolton, "Scan-based near-field acoustical holography and partial field decomposition in the presence of noise and source level variation," J. Acoust. Soc. Am. **119**, 382-393 (2006).
[9] M. Lee, J. S. Bolton, and L. Mongeau, "Application of cylindrical near-field acoustical holography to the visualization of aeroacoustic sources," J. Acoust. Soc. Am. **114**, 842-858 (2003).
[10] M. Lee and J. S. Bolton, "Source characterization of a subsonic jet by using near-field acoustical holography," J. Acoust. Soc. Am. **119**, 382-393 (2006).
[11] E. G. Williams, "Approaches to patch NAH," Proceedings of Internoise 2003, pp.2187-2194.
[12] B.-K. Kim and J.-G. Ih, "On the reconstruction of the vibro-acoustic field over the surface enclosing an interior space using the boundary element method," J. Acoust. Soc. Am. **100**, 3003-3016 (1996).
[13] Z. Wang and S. F. Wu, "Helmholtz Equation-Least Squares (HELS) method for reconstructing the acoustic pressure field," J. Acoust. Soc. Am. **102**, 2020-2032 (1997).
[14] N. Rayess and S. F. Wu, "Experimental validations of the HELS method for reconstructing acoustic radiation from a complex vibrating structure, J. Acoust. Soc. Am. **107**, 2955-2964 (2000).
[15] Y. T. Cho, J. S. Bolton, and J. Hald, "Source visualization by using statistically optimized near-field acoustical holography in cylindrical coordinates," J. Acoust. Soc. Am. **118**, 2355-2364 (2005).
[16] K. L. Gee, T. B. Gabrielson, A. A. Atchley, and V. W. Sparrow, "Preliminary analysis of nonlinearity in military jet aircraft noise propagation," AIAA J. **43**, 1398-1401 (2005).
[17] J. Hald, "STSF – a unique technique for scan-based near-field acoustic holography without restrictions on coherence," Brüel & Kjær Technical Review no. 1, 1989.
[18] K. L. Gee, V. W. Sparrow, M. M. James, J. M. Downing, C. M. Hobbs, T. B. Gabrielson, and A. A. Atchley, "Measurement and prediction of noise propagation from a high-power jet aircraft," AIAA J. **45**, 3003-3006 (2007).
[19] M. R. Shepherd, K. L. Gee, and M. S. Wochner, "On the application of near-field acoustical holography to reconstruct a finite-amplitude noise source," submitted to J. Acoust. Soc. Am. Express Letters (2008).