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# 3aNSa10. Near‐field acoustical holography applied to high‐performance jet aircraft noise

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Structural fatigue, hearing damage, and community disturbances may all result from jet noise, especially as jet aircraft become more powerful. Noise-reduction technologies require accurate characterization of the noise sources within jets. Array-based sound pressure measurements were made in the jet exhaust region of an F-22 raptor to allow for sound-field visualization using near-field acoustical holography (NAH). This is one of the largest-scale applications of NAH since its development in the 1980s, and the most detailed near-field measurements made of high-power jet noise to date. The measurement was made using a large, dense microphone array, which scanned sound pressures over several measurement surfaces near the jet, resulting in more than 6000 measurement points. Fixed reference microphones, measuring simultaneously with each scan, were used to perform partial field decomposition (PFD) of the measurement planes. Guidelines for multi-reference jet-noise measurements in current literature are qualitative at best. The PFD allows for an analysis of reference microphone requirements. A method for determining the adequacy of the reference array using near-field coherence measurements is examined. [Work supported by Air Force SBIR.]

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## I. INTRODUCTION

Accurate characterization of the spatial distribution of noise sources within a jet provides insight into physical noise generation mechanisms in the turbulent flow field. This characterization can help lead to reduction of the noise that can cause significant hearing loss for military personnel and is a disturbance to communities.

Acoustical inverse methods may be used to localize noise sources within the jet of a full-scale military aircraft. Other methods have been employed to localize noise sources within jets (such as particle image velocimetry and hot-wire anemometry), but these methods are not practical for the hot, fast flows of full-scale military jets. Computational models have been developed, which can simulate turbulent flow and relate flow structures to acoustically radiated waves, but the processing times for such models are impractical for high-power flow conditions. Acoustical inverse methods employ a non-intrusive measurement of the sound field outside of the flow, and then use magnitude and phase information to obtain acoustic quantities at the source.

This work is part of a larger ongoing project to identify the sources of noise within a jet using near-field acoustical holography (NAH). Before performing NAH to localize sources, a coherent measurement plane is required. This requirement is met through the use of fixed reference microphones and a partial field decomposition (PFD). Guidelines for the number of reference microphones necessary to obtain an adequate PFD on measurements made near a jet are limited in current literature. The main purpose of this paper is to demonstrate two complementary methods for quantitatively determining reference microphone requirements: one that can be performed simply and prior to holographic measurements, and the other that is performed after the measurement. Jet-noise-source localization results will be reserved for future publications.

Section II of this paper discusses the properties of sound radiation from jets and other aeroacoustic sources. Section III describes acoustical inverse methods for sound source localization and, in particular, introduces the method of near-field acoustical holography. In section IV the process of performing NAH on a full-scale jet, including specific requirements for the NAH implementation, is presented. An important part of this process is emphasized in Section V, which discusses a criterion for determining the necessary number of reference microphones using near-field coherence measurements, before the PFD is performed. Section VI gives details of the physical experiment on a full-scale military aircraft and presents results including measured levels, a PFD, and coherence properties of the sound field.

## II. SOUND RADIATION FROM AEROACOUSTIC SOURCES

While rigorous analyses have been performed on the radiation characteristics of common sources, such as vibrating plates, the noise radiation from a jet is not well understood. For jets on high-power military aircraft, the radiation is particularly complicated. The noise spectra measured near a high-power jet are dominated by very low frequencies, on the order of a couple hundred Hertz. Typical spectra will follow the trends of those shown in Fig. 1. These spectra were calculated from near-field sound pressure measurements of an F-22 Raptor, approximately 12 m from the jet centerline. Note that the noise is broadband with peak frequencies around 100-150 Hz. These spectra with the characteristic "haystack" shape of jet noise are generated by both small and large turbulent structures within the flow field that couple acoustically with the surrounding medium.

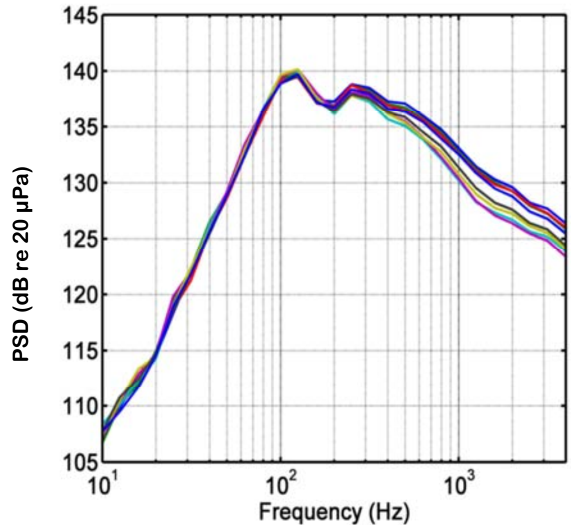


**Figure 1** Power spectral densities in one-third octave bands, measured eight different times about 12 m from the centerline of an F-22 operating at afterburner engine conditions.

Many noise sources do not radiate like simple sources. For example, a large vibrating plate will have significantly different radiation properties than will a point source. A vibrating plate may be considered as a distribution of correlated, radiating monopoles. The phase relationships between each monopole are fixed. This fixed phase relationship causes all the point sources that make up the plate to be coupled in such a way as to generate acoustic radiation into the surrounding fluid very different from that which would be generated by a similar distribution of monopoles all vibrating independently. The fixed-phase relationship may be described by the *correlation* between each monopole.[1] The correlation between two signals describes the degree to which the two signals are related. If the two signals are perfectly related, then the correlation coefficient will have a value of unity. Two fully independent signals will have a correlation coefficient of zero. Because plate vibration is structural, it is a fully correlated source. Signals that are somewhat related will have a correlation coefficient somewhere in between zero and unity. It is well established that aeroacoustic sources are partially correlated over finite distances, and therefore radiate somewhat coherently.[2-3] The correlation lengths within a jet tend to increase as frequency decreases. High frequencies radiate from compact regions and are monopole-like, but the low frequencies that dominate jet noise radiate from larger, non-compact regions and are more highly correlated over larger distances. The exact correlations of the radiating sources within the flow are difficult to measure directly or to simulate computationally.

The radiation of spatially-correlated sources may be described with a sum of multiple wave functions, each with a unique wavenumber. For a given frequency of vibration, certain wave functions will radiate into the far field, while others will decay away exponentially. These two types of waves are referred to as radiating and evanescent waves, respectively. The energy of evanescently-decaying waves remains in the near field of the source. Both radiating and evanescent waves are important contributions to characterizing the source, so both types of waves must be measured to fully determine source radiation mechanisms in a jet. If measurements are made in the far field, evanescent waves will not be detected. Thus, near-field measurements are desired for accurate source localization. The sound field in the vicinity of a jet definitely contains both radiating and evanescent waves, but the details of the individual wave number contributions are unclear.

## III. ACOUSTICAL INVERSE METHODS

There are several acoustical inverse methods that have been employed to localize jet noise sources including the acoustic telescope, the acoustic mirror, the polar correlation technique, and beamforming.[4-7] Typically, these methods assume a source distribution of well-separated compact subsources. Beamforming is a popular jet-noise localization technique. It utilizes an array of microphones and, based on the speed of sound, delays each signal by the proper amount for a given "look" direction, or an assumed angle of incidence. The signals are then summed. For a source truly coming from that direction, the signals will add coherently and describe the source. This method may not be ideal for a non-compact distribution of partially-correlated sources.[4] This is one reason that beamforming tends to give accurate results for localizing high frequencies within a jet, but not low frequencies. These methods are also typically performed with measurements in the far field, and thus do not capture the evanescent waves necessary to fully characterize the source. Measurements made in the far field are also limited to source reconstructions of one-half wavelength. Efforts have been made to modify beamforming algorithms for near-field measurements, and to account for spatially non-compact sources.[4] However, we seek to use NAH as an alternative noise-source-localization technique.

The basic theory of NAH is that, from a two-dimensional hologram measurement in the near field of a noise source, the three-dimensional sound field properties such as pressure, particle velocity, and intensity may be reconstructed in the source region.[8] Measurement in the near field captures some of the evanescent waves and allows for a more accurate, higher resolution reconstruction. The reconstruction is not limited to a resolution of one-half wavelengths. NAH makes no assumptions about the spatial correlation of the source, and can perform well for noncompact sources.

NAH was developed in the 1980s for measuring the vibrations of solid structures. It has only been applied to jet noise within the past decade or so.[9] Lee and Bolton[10-11] performed NAH on a laboratory-scale subsonic cold jet with a 1 cm nozzle by surrounding the jet exhaust region with 32 microphones. Applying NAH to jets on military aircraft is a large jump, and requires a more rigorous approach. In the following section the process of NAH as applied to high-power jet noise is outlined.

## IV. THE PROCESS OF NEAR-FIELD ACOUSTICAL HOLOGRAPHY

It should be noted here that this paper emphasizes fulfilling reference array requirements for the partial field decomposition (PFD) of the measured hologram before NAH is applied. To put the importance of the reference array in context, this section provides an overview of the entire process for performing NAH on a full-scale jet.

NAH requires a coherent measurement over the hologram surface. This means that there must be a fixed phase relationship among all the points on the hologram. There are two ways to achieve this. Sound pressures may be measured simultaneously over an entire hologram surface using an array of microphones that spans the entire source region. This kind of measurement is impractical for large sources, such as high-power jets, if a high-resolution is desired. For this work a patch-and-scan measurement is used. A small dense array of microphones is traversed over the hologram surface. The discontinuities in phase information between scans may be accounted for with an array of fixed reference microphones that measure sound pressures simultaneously with each scan and are then be used to tie together the scans in a process called partial field decomposition (PFD).

In PFD, cross spectral matrices between the reference pressures and hologram pressures are used to decompose the measurement hologram into a set of linearly independent, self-coherent partial fields. These partial fields form a basis set for the total sound field. Summing these partial fields on an energy basis returns the total measured hologram surface magnitude.

Several PFD methods exist. In this work, the virtual coherence method is used.[12-13] This PFD process performs a singular value decomposition (SVD) on the pressures measured by the reference microphones. This generates a linearly independent basis of "virtual references," each of which contains information from all the individual physical reference signals. The singular values that describe the strength of each of these virtual references are sorted in descending order. The measurement hologram is then decomposed into partial fields, each of which is fully correlated with one virtual reference. Therefore, the partial fields are also sorted by strength. This is mathematically the "ideal" decomposition, since as much of the sound field energy as possible is packed into the first partial fields.

The total number of partial fields that come out of the decomposition will equal the number of reference microphones. The first partial fields contain information relevant to the source, and the rest contain noise. Therefore, a sufficient number of partial fields must be selected to reconstruct the source, and the rest may be discarded. Returning to the example of a vibrating plate, the entire source is correlated. Only one partial field will contain relevant information. Consequently, only one reference microphone is needed to perform PFD. A sound field generated by $N$ independent subsources requires $N$ (well-placed) reference microphones, and is decomposed into $N$ partial fields. More reference microphones may be used, which produces more partial fields and helps to limit the effects of measurement noise, but only the first $N$ will contain useful information. If the number of subsources is unknown, the singular values of the SVD on the reference microphones may be observed. For $N$ independent sources, there will be a sharp drop in magnitude from the singular value $N$ to the $N$+1 singular value. For a jet, the number of independent subsources is ambiguous. The singular values tend to decrease somewhat gradually (see Figs. 8-9). The number of partial fields and the minimum number of reference microphones required to fully characterize the source must be determined. The virtual coherence method provides a way to determine this number.

For a chosen frequency three cross-spectral matrices are calculated: one containing cross spectra between all sets of two virtual references $\mathbf{C}_{vv}$, one containing the cross spectra between all hologram microphones $\mathbf{C}_{pp}$, and a third containing cross spectra between each virtual reference signal and each measured hologram microphone signal $\mathbf{C}_{vp}$. Here, a subscript $v$ denotes a virtual reference, and a subscript $p$ denotes a hologram measurement position. The value of the virtual coherence function (from which the method derives its name) between the $i$th virtual reference and the $j$th measurement position in each scan is given by

$$\gamma_{j,i}^2 = \frac{\left|\mathbf{C}_{v_i p_j}\right|^2}{\mathbf{C}_{v_i v_i}\mathbf{C}_{p_j p_j}} \,. \qquad (1)$$

A perfect coherence between two measured pressures would return $\gamma_{j,i}^2 = 1$, and a value of zero would denote no relation. To select the number of partial fields retained in the PFD, this virtual coherence function is summed over the first *R* elements of *i*, iteratively increasing *R* until a coherence criterion is met, namely

$$\sum_{i=1}^{R} \gamma_{j,i}^2 \geq \text{coherence criterion} \,. \qquad (2)$$

Once the coherence criterion is reached for every measurement position *j* in a scan, the given *R* value is equal to the necessary number of partial fields. A value of *R* is returned for each scan. The median of these *R* values is selected as the number of partial fields that are processed using NAH. In practice, a coherence of unity is nearly impossible to achieve. The coherence criterion chosen in this experiment is 0.9. This corresponds to a signal-to-noise ratio (SNR) of approximately 10 dB by the relation

$$\mathrm{SNR} = 10 \log\left(\frac{\gamma^2}{1-\gamma^2}\right) \,, \qquad (3)$$

where the numerator in the log function represents the coherent power, and the denominator corresponds to noise, or incoherent power.

Once the appropriate number of partial fields has been determined, each one is propagated individually using NAH algorithms. The specific NAH method employed in this work is statistically-optimized near-field acoustical holography (SONAH).[14-18] SONAH is a patch method, chosen because it avoids windowing effects by avoiding the direct use of a spatial DFT operation on the measurement surface when the measurement aperture does not extend far beyond the source region. A larger-than-source aperture is not feasible for measurement of a jet that is tens of meters long. SONAH breaks up each partial field into a set of wave functions. Then, it propagates these wave functions to a reconstruction surface using a transfer matrix that describes sound wave propagation between each of the geometrical locations of the hologram and reconstruction surfaces. After each partial field has been propagated to the reconstruction surface, the reconstructed partial fields are added on an energy basis, giving the estimated total sound field at that location.

## V. COHERENCE LENGTHS

The above-outlined method for estimating the necessary number of partial fields is very useful for determining the sufficiency of a reference array used in the hologram measurement. However, it would be useful to have guidelines to aid in the design of a reference array before a full NAH measurement is performed.

In 2009, Gardner[19] presented a method for determining a sufficient number of references *R*, which could be performed with simple measurements of the near-field coherence of a partially correlated source. For a given frequency, the coherence between one reference microphone and the entire reference array is calculated. The coherence between the chosen microphone and itself is, of course, unity, and the coherence tends to decrease moving away from the chosen reference location. In this work a local coherence length $L_c$ is defined as the physical distance over which the coherence drops from unity to 0.5. This value is assigned to the location of the chosen microphone. For the reference microphones away from the aperture edge, there will be a coherence length defined on both sides, which will result in two values. When this occurs, the average of these two values is determined to be the coherence length. The local coherence lengths may be determined over a range of frequencies and over the reference microphone array aperture. This can visually give a sense of coherence lengths in the vicinity of the jet.

Once a coherence length value has been assigned to all reference microphone locations, the local coherence lengths may be averaged over the reference aperture, resulting in a mean coherence length. By calculating the coherence lengths near the jet the number of reference microphones required may be determined before performing NAH using Gardner's method.[19]

## VI. EXPERIMENTAL RESULTS

### A. Experiment

In July 2009, near-field measurements of the jet on a Lockheed Martin/Boeing F-22 Raptor were taken at Holloman Air Force Base in New Mexico. A 5 x 18 array of G.R.A.S ¼" microphones, with 0.15 cm (6 in.) spacing, scanned an approximately 2 x 24 m region as near to the jet as would not cause the microphones to clip (see Figs. 2-3). This was repeated for three more measurement surfaces some distance further from the jet. In addition, 50 fixed reference microphones were placed on the ground with 0.6 m (2 ft.) spacing, spanning more than 30 m, (shown in Fig. 4). Measurements were repeated for four engine conditions ranging from idle to full afterburner. Figure 5 shows the overall sound pressure levels measured in relation to the aircraft location for the afterburner engine condition at all measurement surfaces. There were a total of more than 6000 measurement positions, making this the largest-scale acoustic measurement of a high-power jet ever performed.

**Figure 2** BRRC 90-microphone array, scanning the near field of the jet on an F-22 Raptor.

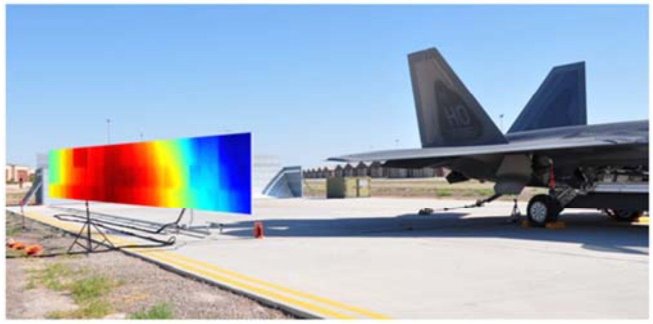

**Figure 3** An example sound pressure level map overlaid with the jet photo at the approximate measurement location.

**Figure 4** Fifty reference microphones were placed on the ground 12 m from the jet centerline, which measured sound pressures simultaneously with each scan.

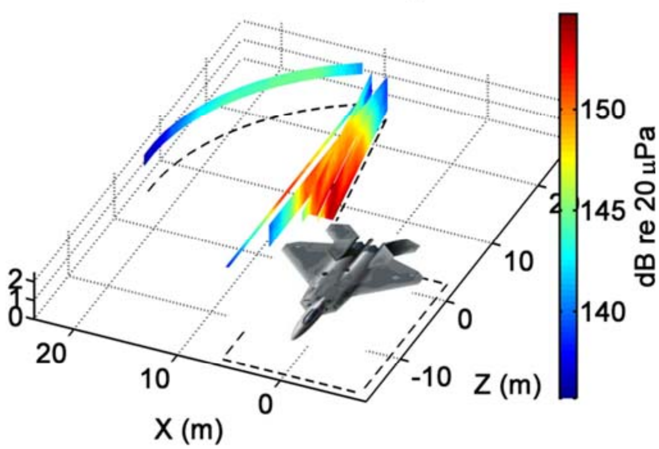


**Figure 5** Overall sound pressure levels measured in the jet vicinity for the afterburner engine condition.

## B. Virtual Coherence

Virtual coherence was performed on the measured hologram data. Results are shown for afterburner engine conditions measured at the closest plane for the near-peak frequency of 105 Hz and for 450 Hz in Figs. 6-7. Parts (a) in each figure are the total measured sound pressure levels for the given frequency. Parts (b) show the first six independent partial fields after performing virtual coherence.

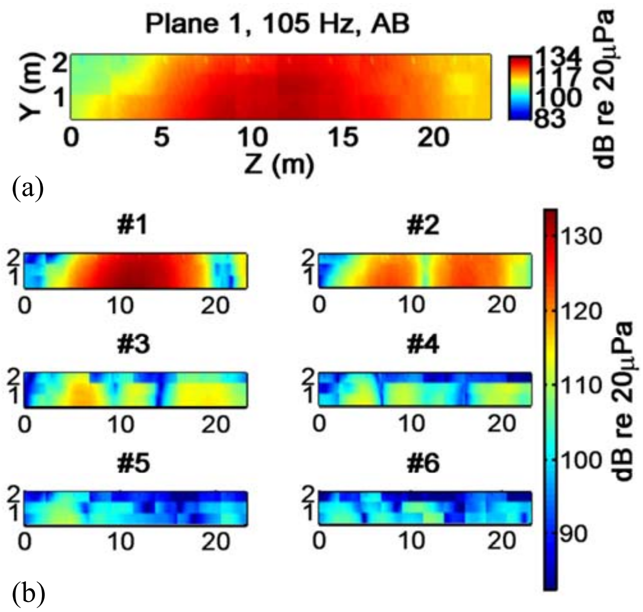


**Figure 6** Measurement and virtual coherence results for 105 Hz: (a) SPL at hologram; (b) first six partial fields after PFD using virtual coherence.

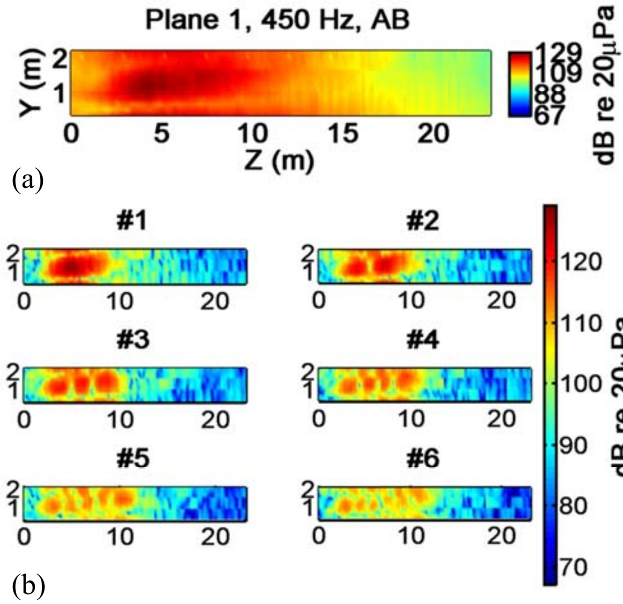


**Figure 7** Measurement and virtual coherence results for 450 Hz: (a) SPL at hologram; (b) first six partial fields after PFD using virtual coherence.

For each frequency individually, parts (a) and (b) are on the same color scale. Both the color scales in the two figures span approximately 62 dB. Note that the difference between the peak levels for the first and sixth partial fields for the 105 Hz case is approximately 30 dB. However, for the 450 Hz case, the peak difference is only around 10 dB. This demonstrates the trend that as frequency decreases more relative energy is contained in the first partial fields, suggesting that fewer partial fields are required to fully determine the sound field. In other words, there are "fewer" independent subsources within the jet at lower frequencies.

In Figs. 8-9 the singular values $\lambda_i$ of the virtual references for each frequency may be compared. As is typical of the singular values for measured jet noise, the trend is a steady decrease. Note an important difference between the lower and higher frequency, namely that the first several singular values in the 105 Hz case decrease rapidly, and then the slope decreases to a steady monotonic descent. This is consistent with the partial fields shown above, and also suggests that only a few partial fields are required to meet the coherence criterion and are thus sufficient to characterize the source for lower frequencies. The partial field cutoff point is designated by a dashed red line on each figure. It turns out that while 21 partial fields are required to fully determine the measured sound field for the 450 Hz case, only 5 partial fields are sufficient at 105 Hz, which is near the peak frequency. For certain low frequencies and engine conditions, as few as two or three partial fields are sufficient.

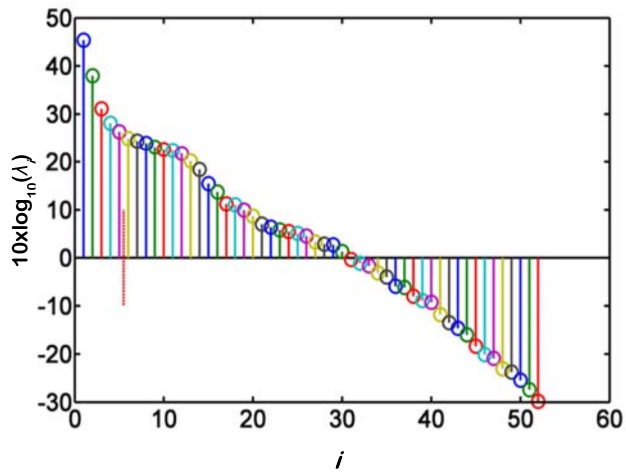


**Figure 8** Singular values of the reference cross-spectral matrix after SVD for the 105 Hz case. The number of singular values left of the red dashed line represent the number of partial fields required to meet the coherence criterion.

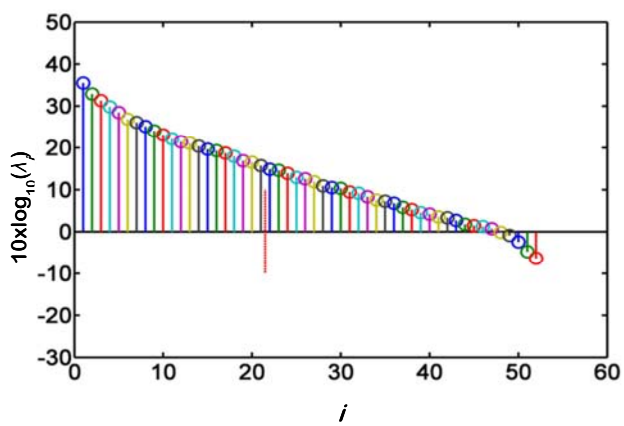


**Figure 9** Singular values of the reference cross-spectral matrix after SVD for the 450 Hz case. The number of singular values left of the red dashed line represent the number of partial fields required to meet the coherence criterion.

## C. Coherence Length Analysis

The coherence lengths measured at the reference microphone array give additional insight to why so few partial fields are needed for low frequencies. Figure 10 shows the coherence between a reference microphone 18 m downstream of the jet nozzle and all the other reference microphones for the 105 Hz afterburner case. At this location and frequency a coherence length of approximately 6 m is calculated. Repeating this calculation over a range of frequencies and across the entire reference aperture the results shown in Fig. 11 are obtained. The trend of increasing coherence length with decreasing frequency is consistent with the fact that fewer reference microphones are necessary for lower frequencies. The remarkably high coherence lengths toward the downstream end of the jet seem to follow the trend of Tam's two-source jet noise model.[2]

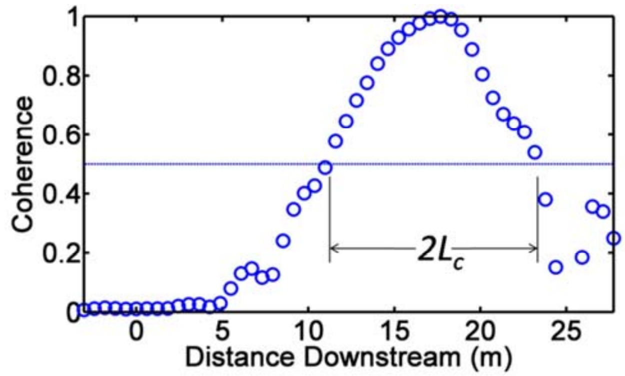


**Figure 10** Coherence measured between the reference microphone 18 m downstream of the jet nozzle, and all other reference microphones, for the 105 Hz afterburner case. The coherence length $L_c$ is determined to be the average distance over which coherence drops from 1 to 0.5.

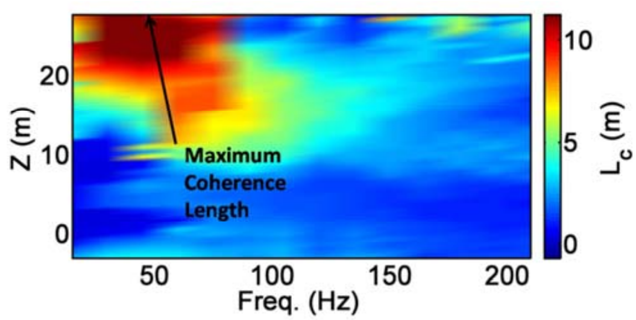


**Figure 11** Coherence lengths plotted against position on the reference array and frequency. The maximum coherence length exceeds 16 m and occurs 27 m downstream of the jet nozzle, and at 45 Hz.

For 105 Hz, the mean coherence length over the entire aperture is 3.4 m. The reference array spans approximately 30 m, so using the criterion of one reference per coherence length over the reference array aperture, this suggests that the minimum number of reference microphones required to perform NAH on this jet at 105 Hz is approximately nine. The partial field decomposition is less sensitive to noise as the number of reference microphones increases. Since the virtual coherence results suggest that five partial fields are sufficient, then it stands to reason that five well-placed microphones might be acceptable. By increasing the coherence criterion (and consequently the signal-to-noise ratio) the estimated reference microphone requirement increases.

## VII. CONCLUSIONS

We have shown two complementary methods of determining the number of reference microphones necessary to perform PFD on measured hologram data for jet noise source localization: one based on the virtual coherence method, which is performed in conjunction with a scan-based NAH measurement; and another from Gardner[19] that utilizes measurements made of the near-field spatial coherence properties. The latter method may be implemented if near-field coherence lengths are known. The estimate given by this method is a conservative one, and proper reference microphone placement may relax the requirement. The estimated requirement can be verified and compared to the reference microphone requirements determined using the post-measurement assessment of the virtual coherence method.

*The title of the paper presented by the author at the 159th Meeting of the Acoustical Society of America is "Application of near-field acoustical holography to high-performance jet aircraft noise." Tracianne B. Neilsen has been added as a coauthor to the POMA version of this paper.*

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