ABSTRACT
To better understand the relationship between the near-field pressure and the acoustic far-field, multi-point measurements of the near-field pressure around the periphery of a cold Mach 0.85 round jet are compared to simultaneous multi-point far-field acoustic pressure measurements. The results indicate that the near-field pressure is low dimensional and the instantaneous contribution from both azimuthal mode 0 and 1 is sufficient to accurately recover the dynamics of the near-field pressure. Correlations of the acoustic far-field with the contribution of each azimuthal mode to the near field pressure, however, indicate that only azimuthal mode 0 is well correlated with the far-field pressure, suggesting that the acoustic source in the jet is predominantly axisymmetric. The correlation of the higher azimuthal pressure modes with the far-field acoustic pressure is extremely poor suggesting that the axisymmetric source is weakened by the presence of higher azimuthal modes in the near field of the jet.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$B_{nm}$</td>
<td>azimuthal near-field pressure spectra</td>
</tr>
<tr>
<td>$D$</td>
<td>nozzle exit diameter</td>
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<tr>
<td>$f$</td>
<td>frequency</td>
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<tr>
<td>$F_{nn}$</td>
<td>near-field pressure spectra</td>
</tr>
<tr>
<td>$F_{ff}$</td>
<td>far-field pressure spectra</td>
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<tr>
<td>$F_{nf}$</td>
<td>cross-spectra of near-field pressure</td>
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<tr>
<td>$\tilde{F}_{nf}$</td>
<td>cross spectra of near field azimuthal modes with far field pressure</td>
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<tr>
<td>$m$</td>
<td>azimuthal mode number</td>
</tr>
<tr>
<td>$p$</td>
<td>fluctuating pressure</td>
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<tr>
<td>$R_{nn}$</td>
<td>two point correlation of near-field pressure</td>
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<tr>
<td>$U_j$</td>
<td>exit velocity of jet</td>
</tr>
<tr>
<td>$x$</td>
<td>streamwise coordinate</td>
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<tr>
<td>$\hat{p}_{nf}$</td>
<td>normalized two-point, two-time correlation of near-field azimuthal modes and far-field pressure</td>
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<tr>
<td>$\rho_{nf}$</td>
<td>normalized two-point, two-time correlation of near-field azimuthal and far-field pressure</td>
</tr>
<tr>
<td>$\sigma_n$</td>
<td>standard deviation of near-field pressure fluctuations</td>
</tr>
<tr>
<td>$\sigma_f$</td>
<td>standard deviation of far-field pressure fluctuations</td>
</tr>
<tr>
<td>$\phi$</td>
<td>angle of microphone to jet axis</td>
</tr>
<tr>
<td>$\tau$</td>
<td>time lag</td>
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<tr>
<td>$\theta$</td>
<td>azimuthal coordinate</td>
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INTRODUCTION
Jet engine noise continues to be one of the major concerns of the aviation industry. The near-field pressure region surrounding the turbulent jet has long been the focus of investigation, principally motivated by the attempt to link the near-field dynamics...
in the jet core with the far-field acoustics to understand and ultimately reduce acoustic emissions. The most prominent location of noise generation is just downstream of the collapse of the jet potential core, at 3 to 9 exit diameters downstream, and is related to the mixing mechanism by which the large-scale vortices interact, pair and coalesce, as they evolve downstream of the jet exit [1–3]. Ffowcs Williams & Kempton [4] demonstrated that these large-scale structures contribute greatest to the radiated noise, and the abruptness of their change from growth to decay determines the magnitude of the radiated sound.

Many far-field acoustic studies rely greatly on causality methods modelled in the framework of Lighthill’s [5] acoustic analogy. However, Ko & Davies [6] demonstrated that information from the far-field noise was not detailed enough for one to understand the process by which noise is generated in the jet by turbulence, and suggested that better insight into these sound sources could be gained by examining the near-field pressure region. Michalke & Fuchs [7], Petersen [8], Arndt et al. [9] and more recently Jordan et al. [10], Coiffet et al. [11], Ukeiley & Ponton [12] and Hall et al. [13] have also investigated the near-field pressure region of the axisymmetric jet. One commonality revealed in these studies is the time-averaged, low-dimensional nature of the pressure signature, as the low-order azimuthal modes demonstrated dominance.

The focus of recent work at Syracuse University conducted by Tinney et al. [14] and Hall et al. [15] has been aimed at identifying how well the near field pressure signature around the jet is able to characterize the turbulent flow field, and ultimately its ability to convey information relating to the noise source mechanism. Results to date have indicated that an accurate low-dimensional description of the instantaneous turbulent velocity field can be estimated using measurements of the fluctuating pressure sampled near the jet exit alone (with minimum effect on the far-field pressure region). Michalke & Fuchs [7], Petersen [8], Arndt et al. [9] and more recently Jordan et al. [10], Coiffet et al. [11], Ukeiley & Ponton [12] and Hall et al. [13] have also investigated the near-field pressure region of the axisymmetric jet. One commonality revealed in these studies is the time-averaged, low-dimensional nature of the pressure signature, as the low-order azimuthal modes demonstrated dominance.

Experimental Setup

The present experiments were conducted in Syracuse University’s fully anechoic chamber which encompasses a 206m$^3$ enclosure, as shown in Figure 1. The design and construction of this facility is discussed in detail in Tinney et al. [16], and include the installation of a new industrial make-up-air unit for controlling the ambient temperature (of the chamber), and an electric circulation heater for heated jet studies up to 540°C. The axisymmetric nozzle is centerline velocity of Mach 0.85, corresponding to a Reynolds number of 9.8 x 10$^5$ based on a nozzle diameter of 50.8mm. The flow’s exit conditions, and bypass air, were matched and held constant at 19°C and ambient pressure. Preliminary measurements have shown that the exit conditions of the nozzle exhibit turbulence intensities on the order of 1% in the potential core. The spreading of the outer and inner shear layers was found to be approximately 0.194x (11°) and 0.096x (5.5°), respectively, where x denotes the streamwise direction of the jet. The potential core in this jet has also been shown to collapse at approximately 6D.

To examine the dominant pressure signature of the jet near-field, a (Δθ = 24°) ring array of fifteen evenly spaced Kulite model XCE-093, 0-34.4kPa transducers with a flat frequency response from DC to 50kHz was used. The probes are positioned radially approximately 10 mm outside the shear-layer. Measurements are acquired at several streamwise locations, from 1D to 11D, as the ring array is traversed downstream. Special attention was given to the orientation of each probe to ensure that their individual outputs were similar in amplitude, and that their position along the array was symmetric with respect to the flow at each streamwise location. The signals from the transducers are digitized using a National Instruments PXI system equipped with three NI-4472 boards with 24-bit resolution. Each channel was low pass filtered at the Nyquist frequency and then sampled at 40.96kHz. The mean pressure for the full record from each channel was subtracted from the instantaneous pressure, $p$,
to compute a record of the fluctuating pressure, $p$. These time records were then Fourier transformed from time to frequency and used to compute cross-spectra. The cross-spectra for the different azimuthal separation distances were then Fourier transformed in the azimuthal direction to compute the azimuthal frequency spectra, similar to Hall and Ewing [17]. All spectra in this investigation were computed using 100 blocks with the mean of the overall time series removed, thus yielding an uncertainty in the estimate of the magnitude of the spectra of $\pm 20\%$ at the 95\% confidence interval.

The jet’s far-field acoustic response is acquired by 6 G.R.A.S. type 40BE 1/4 inch pre-polarized, free field condenser microphones. Excitation is provided by G.R.A.S. type 26CB 1/4 inch preamplifiers. The frequency response of the microphones are is flat from 10Hz-40kHz, and the dynamic range is 166dB ref. 20\(\mu\)Pa. The microphones are arranged along a boom array in the anechoic chamber, positioned 85 diameters from the center of the jet exit plane. Each microphone is supported by a 3/8 inch diameter threaded rod extending from the boom towards the jet, as to increase the distance between the microphones and the boom, making its final position 75 diameters from nozzle exit. This is intended to help reduce reflection in and around the microphone from the boom array. The first microphone is placed perpendicular to the jet axis at $\phi = 90^\circ$ from the jet axis, with each subsequent microphone $\Delta \phi = 15^\circ$ from the last, placing the sixth microphone $\phi = 15^\circ$ from the jet axis (Figure 1).

**EXPERIMENTAL RESULTS**

The power spectra, $F_{ff}(f, \phi)$ computed from the far-field pressure signals are shown in Figure 3. The subscript $n$ will be used herein to denote near-field pressure and $f$ will be used to denote far-field acoustic pressure. The spectra at microphones 1 through 4 are considerably more broadband and lower than for microphones 5 and 6, consistent with the known directional nature of the jet acoustic pressure field [1]. Tam and Chen [18] argued that the weaker and more broadband pressure fluctuations at large angles from the jet axis (such as microphones 1 and 2) are due to fine-scale turbulence in the jet and the larger more narrow-band fluctuations at small angles (such as microphones 5 and 6) from the jet axis is mixing noise caused by the large-scale vortex structures in the flow.

The near-field pressure spectra, $F_{nn}(\Delta \theta = 0, f)$ at each downstream location are shown in Figure 4. In all cases, the spectra have single dominant peaks whose frequency continually decrease with downstream position. This behaviour is consistent with the results of Ukeiley and Ponton [12] who examined this feature of the near-field pressure in detail using both Fourier and wavelet analysis. The magnitude of the spectra at each downstream location is much smaller than that in the acoustic far-field indicating that only a small portion of the fluctuating pressure at each downstream location is reaching the far-field pressure. This is partially due to the dissipative nature of the loosely spherical wave propagation but is primarily because the near field pressure, at least at lower frequencies, is largely a measure of the passage of the large-scale vortical structures in the flow [9, 19].

The azimuthal three-dimensionality of the near-field pressure at each downstream location can be examined using the two point, two time correlation of the near-field pressure signals,

$$R_{nn}(\Delta \theta, \tau) = <p_n(\theta, t)p_n(\theta + \Delta \theta, t + \tau)>,$$

or in normalized fashion, as

$$\rho_{nn}(\Delta \theta, \tau) = \frac{R_{nn}(\Delta \theta, \tau)}{\sigma_n(\theta)\sigma_n(\theta + \Delta \theta)}$$
where \( \sigma_n \) is the standard deviation of the fluctuating pressure. The two point correlations were not computed directly here using (1), but were computed using the frequency cross-spectra as discussed, for example, by Bendat and Piersol [20]. These near-field pressure correlations were Fourier transformed in azimuth using

\[
B_{nm}(m) = \frac{1}{2\pi} \int_0^{2\pi} R_{nn}(\Delta \theta, \tau = 0) e^{-i2\pi m \Delta \theta} d\Delta \theta,
\]

so that the azimuthal content of the near-field pressure could be examined. The variation of \( B_{nm}(m) \) for azimuthal modes 0 through 3 and the decay of all modes, \( \sigma_n \), is shown in Figure 5. Here, both positive and negative azimuthal modes have been summed so that the contribution from both the left-handed and right-handed higher azimuthal pressure modes can be examined. The contribution from all modes gradually decreases until \( x/D = 7 \) before generally increasing, although there is some variability in the amplitude of the downstream measurements due to difficulties associated with positioning the microphones in the near-field pressure array at these locations. Unlike the variance, azimuthal modes 0 and 1 grow slightly until \( x/D = 3 \) before decreasing until \( x/D = 6 \). Downstream of this point the energy contained in azimuthal modes 0 and 1 behave similar to the variance of the near-field pressure, suggesting this behaviour may be due to the aforementioned difficulties setting the microphones. In all cases there is significantly less energy in the higher azimuthal modes, as discussed by Hall et al. [13].

The instantaneous contribution of azimuthal modes 0 and 1 to pressure field can be examined by decomposing the near-field pressure into azimuthal modes at each instant. This decomposition was then used to compute low-order reconstructions of the pressure field by retaining only selected modes; i.e.,

\[
p^{\text{rec}}(r, \theta, t) = \sum_{m=-M}^{M} \hat{p}(r, m, t)e^{im\theta},
\]

where \( \hat{p}(r, m, t) \) is the Fourier coefficient of the pressure in the azimuthal direction and \( M \) is the number of modes retained in the reconstruction. The instantaneous contribution of azimuthal modes 0, 1, and 0 and 1 compared to the unfiltered fluctuating pressure signal at \( r/D = 8 \) and \( \Delta \theta = 0^\circ \) are shown in Figure 6. Although azimuthal mode 0, or mode 1 on their own accurately recover some of the dynamics of the fluctuating pressure field, these modes must be combined at all times to accurately recover the dynamics of the near-field pressure. Note, that this does not necessarily mean, as discussed below, that both modes propagate equally well to the far-field. This will be determined from two-point correlations measurements of the near-field pressure with the far-field pressure.

The correlation of the near-field pressure with the far-field pressure were computed similarly to (1). The downstream varia-
Figure 7. STREAMWISE VARIATION OF NORMALIZED TWO-POINT CORRELATION BETWEEN NEAR-FIELD PRESSURE AND FAR-FIELD ACOUSTIC PRESSURE FOR MICROPHONES 1 (TOP) THROUGH 6 (BOTTOM).

The axial variation of the maxima in each of the aforementioned correlations is shown more clearly in Figure 8. For all microphones, the correlation initially starts of at approximately zero and increases gradually as the jet evolves downstream, reaching a maxima between $x/D = 6$ and $9$ before decreasing. This indicates that that the acoustic sources in the jet are the strongest in the jet from $x/D = 6$ to $10$, just downstream of the collapse of the potential core of the jet. This source location is reasonably consistent with findings from other investigations [1,2]. The correlation of the near-field pressure with microphones 1 to 4 is less that 0.1, and is consistent with the notion that the largest contribution to the off axis jet noise is due to small scale, high frequency instabilities which do not change appreciably with downstream position [22]. The near-field pressure is quite well correlated with the far-field pressure at microphones 5 and 6 reaching values as high as 0.25 and 0.35, respectively. These values are significantly higher than for correlations of the turbulent velocity field with the far-field acoustic pressure or of the correlations of the Lighthill source terms with the far-field pressure [3].

To examine how the azimuthal three-dimensionality of the near-field pressure influences the correlation with the far-field acoustic pressure, the contribution of the individual near-field azimuthal modes to the far-field cross-spectra spectra was calculated using

$$
\tilde{F}_{nf}(m,f) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{0}^{2\pi} R_{nf}(\Delta \theta, \tau) e^{-i(m\Delta \theta + 2\pi f \tau)} d\tau d\Delta \theta.
$$

Following Hall and Ewing [17,23], (5) was Fourier transformed from frequency back into time allowing the normalized two-
point, two-time correlations of each azimuthal mode,

\[ \hat{\rho}_{nf}(m, \tau) = \frac{R_{nf}(m, \tau)}{B_{nf}(m)^{1/2} \sigma_f}, \]

(6)
to be examined. To ensure the accuracy of this technique the instantaneous time series of azimuthal modes 0 through 5 were computed using (4) and then correlated with the far-field using (1) with good agreement obtained for both methods.

Typical results for the normalized correlation of azimuthal mode 0, mode 1 and the sum of azimuthal mode 0 and 1 with microphone 5 at \( x/D = 8 \) are shown in Figure 9. The correlation of the near-field pressure tap at \( \Delta \theta = 0^\circ \) with the far field acoustic pressure (all modes) is also included. The normalized correlation of azimuthal mode 0 is approximately 60% higher than the correlations for the full pressure field, indicating that azimuthal mode 0 is an effective acoustic source. The normalized correlation of only azimuthal 1 and of all the other higher azimuthal modes, such as mode 5, are extremely poor acoustic sources, at least from a time averaged perspective. In fact, as shown by the sum of the contribution of mode 0 and mode 1, the inclusion of azimuthal mode 1 reduces the correlation of the sum of these two modes. These results are consistent with the predictions of Michalke [24] who demonstrated that the efficiency of a ring distributed monopole source decreased with increasing azimuthal mode number, although this does not appear to have been previously shown in a compressible, high Reynolds number jet.

Similar to Figure 8, the variation in the maxima of these correlations with downstream position for all modes and azimuthal modes 0, 1 and 5 is shown in Figure 10. It is evident that the correlation of azimuthal mode 0 is much larger at all locations than for the other azimuthal modes and tends to grow and decay similar to the conventional correlations. At all downstream positions, the correlations of the higher azimuthal modes are much smaller than for mode 0. Together, these results indicate that azimuthal mode 0 is primarily causing the downstream variation in the correlation of the near-field pressure with the far-field pressure and that the higher near-field azimuthal modes are inefficient acoustic sources.

**CONCLUDING REMARKS**

Measurements of the near-field pressure around the periphery of a compressible jet and simultaneous measurements of the acoustic far-field were performed, allowing the relationship between the near-field pressure and the far-field acoustic pressure to be examined. Although previous results have indicated the near-field pressure is largely hydrodynamic in nature, there is still significant correlation between the near-field pressure and the far-field acoustic pressure, particularly in the region \( x/D = 6 \) to 10, suggesting that this is the dominant source region of the jet. The time-lag for the acoustic waves to propagate from the near to the far-field is also consistent with this source location. This downstream distance is reasonably consistent with the results of previous investigations using different source detection techniques [1–3].

As shown previously from a time-averaged perspective, the
near-field pressure is dominated by azimuthal modes 0 and 1 [13]. The present results indicate that the instantaneous contribution from both these modes at all times is required to accurately recover the features of the near-field pressure signal. Only azimuthal mode 0, however, is well correlated with the far-field pressure over the source region of the jet indicating that the portion of near-field pressure which propagates to the far-field is predominantly axisymmetric. The poor correlation of the higher azimuthal modes with the far-field acoustic pressure suggests that the axisymmetric acoustic source can be weakened by destroying the azimuthal coherence of the source. Work is presently underway to extend the present analysis by examining the coherence of the axisymmetric source at different frequencies and to establish the relationship between the axisymmetric near field pressure mode and the turbulent velocity field.

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REFERENCES

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