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Cross-Spectral Analysis of the Pressure in a Mach 0.85 Turbulent Jet

Joseph W. Hall*
University of New Brunswick, Fredericton, New Brunswick E3B 5A3, Canada
and
André M. Hall,† Jeremy T. Pinier,† and Mark N. Glauser‡
Syracuse University, Syracuse, New York 13244

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Measurements of the near-field pressure in an unheated Mach 0.85 round jet were performed simultaneously with far-field acoustic pressure measurements at Syracuse University's Skytop Anechoic Chamber facility to directly quantify the strength and frequency content of the propagating portion of the jet's near-field pressure. The largest contributions were determined to be at the lower wave numbers commonly associated with hydrodynamic pressure fluctuations. This indicates that large low-frequency hydrodynamic fluctuations are obscuring a significant source of acoustic fluctuations in the jet and dictates that care must be taken when using single point measurements of near-field pressure spectral decay to differentiate between acoustic (propagating) and hydrodynamic (nonpropagating) fluctuations.

I. Introduction

THE noise produced by jet engines continues to be one of the major concerns of the aviation industry and has long been the focus of considerable research efforts. One of the most significant contributions was the establishment of Lighthill's [1] aerodynamic noise theory that couples the nonlinear equations of motion and the linear theory of acoustics to form the inhomogeneous wave equation:

$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \nabla^2 \rho = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \tag{1}$$

where the left-hand side of the equation represents the acoustic wave propagation and the right-hand side represents the source term. The Lighthill stress tensor T_{ij} is defined as

$$T_{ij} = \rho u_i u_j + \left(p - c_0^2 \rho\right)\delta_{ij} - \tau_{ij} \tag{2}$$

where $\rho u_i u_j$ are the Reynolds stress terms, $(p - c_0^2\rho)\delta_{ij}$ are the entropy terms, and τ_{ij} is the viscous stress tensor. In unheated turbulent jets, the Lighthill stress tensor is often simplified to the $T_{ij} = \rho u_i u_j$. Recent advances in computational aeroacoustics (see reviews by Colonius and Lele [2] and Wang et al. [3]) have shed considerable light on the relationship between the Lighthill source terms and the sound produced by various jets [4–8], but these studies have been limited to low Reynolds numbers and simplified geometries.

Experimentally, the task of fully and accurately capturing the Reynolds stress tensors, let alone the time dependence of the spatial gradients, remains extremely challenging in high Reynolds number turbulent flows. This has led many experimentalists to use causality techniques, coupling turbulent velocity with acoustic fluctuations [9–12], in an attempt to gain a better understanding of the acoustic sources in the jet. These investigations were often limited by the intrusiveness of the instruments employed. For example, hot-wire anemometry proved to contaminate the far-field acoustics due to probe-induced noise.

Recent correlation studies using modern experimental techniques have helped to elucidate some of the details of the contributions to the Lighthill stress tensor in unheated-jet flows. Ukeiley et al. [13] examined the spatial distribution of the fluctuating velocity components of the Reynolds stress source terms in Eq. (1) using particle image velocimetry and found that the sources were the largest downstream of the collapse of the potential core. This finding is in line with those who suggest that the dominant source of noise generation in the jet occurs typically just downstream of the collapse of the potential core region and is linked to the mechanism by which the large-scale vortices interact, pair, and coalesce [11,14–17]. Panda et al. [17] used a spectrally resolved Rayleigh scattering technique to examine in detail the density fluctuations in various speed jets and their correlation with the far-field sound pressure. A far-field 3-D microphone array was used by Hileman et al. [18] to determine that the dominant acoustic source in a Mach 1.3 jet was between 7 and 10 diameters downstream of the nozzle exit. In a subsequent study, they used this array to deduce that the noise-producing events in the jet are related to the alternating formation and destruction of flow features in the mixing layer [16].

To circumvent the experimental obstacles associated with attempting to relate velocity fluctuations to the resulting acoustic far field, many researchers instead chose to study the relationship between the near-field pressure in the jet flowfield and the acoustic fluctuations [14,19–22]. A widely accepted result is that the near-field pressure fluctuations within the jet are largely hydrodynamic and relatively low-dimensional [14,20,23–25], with the latter due to the pressure spatially filtering the velocity field [26]. As compared with the turbulent velocity field, the low-dimensional nature of the near-field pressure region, along with it being a scalar quantity, makes it a favorable candidate to study from both source-modeling and control standpoints. However, several early attempts to relate pressure measurements captured within the jet flowfield, using pitot probes and shrouded microphones, to the acoustic signature sampled were contaminated by probe-induced noise. A reliable measure of

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*Assistant Professor, Department of Mechanical Engineering. Member AIAA.
†Ph.D. Candidate, Department of Mechanical and Aerospace Engineering. Student Member AIAA.
‡Professor. Associate Fellow AIAA.

fluctuating static pressure was also unavailable, as various compensations were needed to be made for errors owing to probe-induced noise.

In an effort to subdue these difficulties, the near-field pressure region immediately surrounding the jet has become the preferred region of study [14,23–25,27–33]. These measurements, however, are acquired in the region of transition from nonlinear acoustic sources to acoustic linear wave propagation. From an aeroacoustics perspective, the complexities associated with near-field pressure measurements lie in the task of distinguishing the acoustic fluctuations from the larger hydrodynamic pressure fluctuations associated with the flow itself; this problem has been the focus of considerable research effort. For example, Crighton and Huerre [34] examined a sequence of boundary-value problems for the acoustic wave equation. Pressure at the boundary of a two-dimensional unsteady flow was simulated using experimentally determined features of the hydrodynamic near field just outside a turbulent shear layer. In all cases, the pressure fluctuations decayed exponentially close to the boundary and algebraically at sufficiently large distances.

Later, Arndt et al. [14] began with an acoustic approximation to the unsteady Bernoulli equation, dividing the pressure fluctuations into parts consisting of nonpropagating or hydrodynamic fluctuations and propagating or acoustic fluctuations. As a result, the solution for the mean square pressure showed that acoustic fluctuations decayed in accord with an inverse square law, $(kr)^{-2}$, whereas hydrodynamic fluctuations decayed much more rapidly, $(kr)^{-6.67}$. In both cases, kr is the product of wave number (ratio of angular frequency to ambient sound speed, $k = \omega/c_0$) and distance from the source. These predictions agreed quite well with their experimental measurements, in which a single microphone was traversed outward from the edge of the jet shear layer; the measured spectra depicts the modeled trend, as roll-off slopes of $(ky)^{-6.67}$ are seen for $ky < 2$ and $(ky)^{-2}$ for $ky > 2$ (taken as the distance outward from the center of the shear layer). In addition to these investigations, the use of wave-number filtering to separate the acoustic fluctuations from the hydrodynamic fluctuations has also been used by Freund and Colonius [6] and Coiffet et al. [27]. However, there have been no previous measurements that directly assess the validity of using measures of spectral decay to differentiate between hydrodynamic and acoustic fluctuations in the near field. This will be done here using two-point pressure measurements of the jet near-field and far-field pressures in a fully anechoic facility.

II. Experimental Setup

The present experiments were conducted in Syracuse University's fully anechoic chamber, which encompasses a 206 m^3 enclosure, as shown in Fig. 1. The design and construction of this facility is discussed in detail by Tinney et al. [35] and includes a 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 jet was operated at Mach 0.85, corresponding to a Reynolds number of 9.8×10^5 based upon a nozzle diameter of 50.8 mm. The jet exit conditions and bypass air, used to balance flow rate and conditions, were matched and held constant at 19°C and ambient pressure (ambient conditions at similar values). The flow conditions at the nozzle exit exhibit turbulence intensities on the order of 1% on the centerline, and the boundary layer in the nozzle was tripped. The spreading of the outer and inner shear layers was found to be approximately $0.194x$ (11 deg) and $0.096x$ (5.5 deg), respectively, where x denotes the streamwise direction of the jet. The jet potential core was determined to end at approximately $6D$ downstream of the nozzle exit.

The jet's far-field acoustic response was acquired by 6 G.R.A.S. Sound & Vibration type 40BE $\frac{1}{4}$ in. prepolarized free-field condenser microphones. Excitation was provided by G.R.A.S. Sound & Vibration type 26CB $\frac{1}{4}$ in. preamplifiers. The frequency response of the microphones were flat from 100 Hz–40 kHz. The microphones were arrayed along a boom, arced within the anechoic chamber, each positioned 85 diameters from the center of the jet exit plane. Each microphone was supported by a $\frac{3}{8}$-in.-diam threaded rod extending

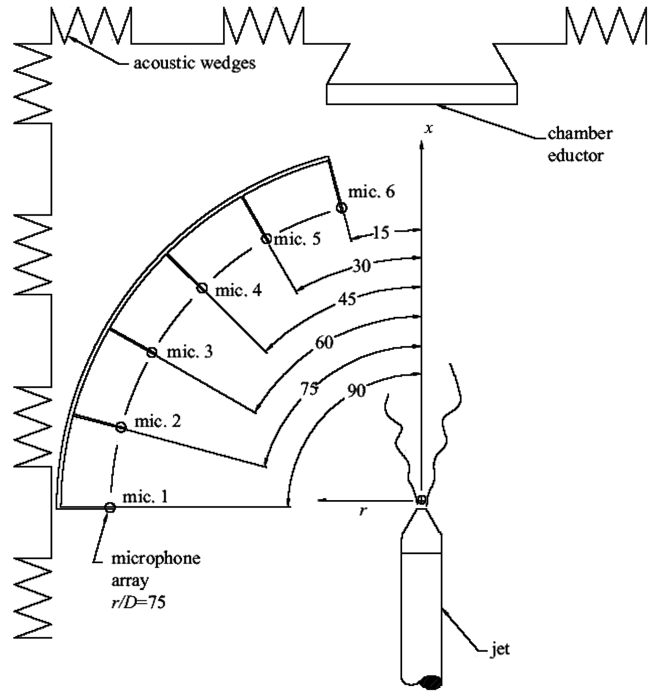


Fig. 1 Schematic of experimental facility.

from the boom toward the jet to increase the distance between the microphones and the boom, making its final position 75 diameters from the nozzle exit. This was intended to help reduce reflection from the boom to the microphone. The first microphone was placed perpendicularly to the jet axis at $\phi = 90$ deg from the jet axis, with each subsequent microphone placed $\Delta\phi = 15$ deg from the last, with the sixth microphone $\phi = 15$ deg from the jet axis. The near-field pressure was measured using a $\frac{1}{4}$ in. B&K free-field condenser microphone mounted on a traverse. These measurements were performed at a streamwise location of $x/D = 8$, with the microphone positioned 15 mm outside the spreading shear layer and traversed radially outward in increments of 10 mm (Table 1). The jet spreading rate of $0.2x$ fixes these locations between 96 and 136 mm from the centerline.

All signals were digitized using a National Instruments PXI system equipped with three NI-4472 boards with 24-bit resolution. Each channel was low-pass filtered just below the Nyquist frequency and then sampled at 40.96 kHz. The mean pressure for the full record from each channel was subtracted from the instantaneous pressure, and these time records were then Fourier transformed from time to frequency and used to compute cross spectra. All spectra in this investigation were computed using 300 blocks of 8192 samples, yielding an uncertainty in the estimate of the magnitude of the spectra of $\pm 11\%$ at the 95% confidence interval.

III. Experimental Results

The power spectra of the far-field pressure signals at each microphone normalized by the dynamic head of the jet (and not the more traditional sound pressure level scaling) are shown in Fig. 2. These spectra were estimated using

Table 1 Near-field microphone positioning

Label	r/D
R1	1.90
R2	2.09
R3	2.29
R4	2.49
R5	2.68

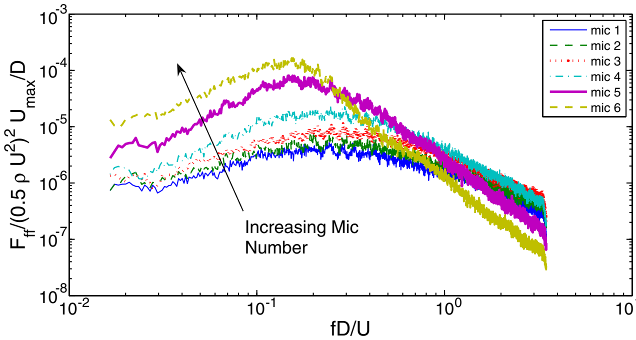


Fig. 2 Far-field acoustic pressure spectra.

$$F_{ff} = \frac{1}{T}\langle \hat{p}_f(f)\hat{p}_f{}^*(f)\rangle \tag{3}$$

where

$$\hat{p}(f) = \int_{-T/2}^{T/2} p(t)e^{-i2\pi f t}\mathrm{d}t \tag{4}$$

is the Fourier coefficient for a given block. The asterisk in Eq. (3) denotes the complex conjugate, T is the block length, $< >$ denotes the block average, The subscript f is used herein to denote far-field acoustic pressure and the subscript n will be used to denote near-field acoustic pressure. The spectra at microphones 1 through 3 are more broadband and lower than for microphones 5 and 6, consistent with the known directional nature of the jet's acoustic field. Tam [36] argued that the weaker and more broadband pressure fluctuations at large angles from the jet axis (microphones 1 and 2) are due to fine-scale turbulence, and the larger, more narrowband fluctuations at small angles (such as microphones 5 and 6) are caused principally by the large-scale vortex structures in the flow.

The near-field pressure spectra F_{nn} measured at $x/D = 8$ are shown in Fig. 3. This downstream position was selected for study because it was previously determined to be the location of the dominant source in this jet [32,37]. The spectra have been normalized by the square of the dynamic head of the jet and using the kr wave-number scaling proposed by Arndt et al. [14]. For values of $kr > 3$, the spectra decay in accord with $(kr)^{-2}$, indicating that the measured pressure fluctuations at these kr values are primarily acoustic. For $kr < 3$, the magnitude of the pressure fluctuations for a given frequency decrease proportionally to $(kr)^{-6}$, consistent with the decay expected for hydrodynamic fluctuations. The present investigation, however, will show that the delineation between acoustic and hydrodynamic fluctuations is not so simple and that a significant portion of the pressure at $kr < 3$ is, in fact, radiated to the acoustic far field.

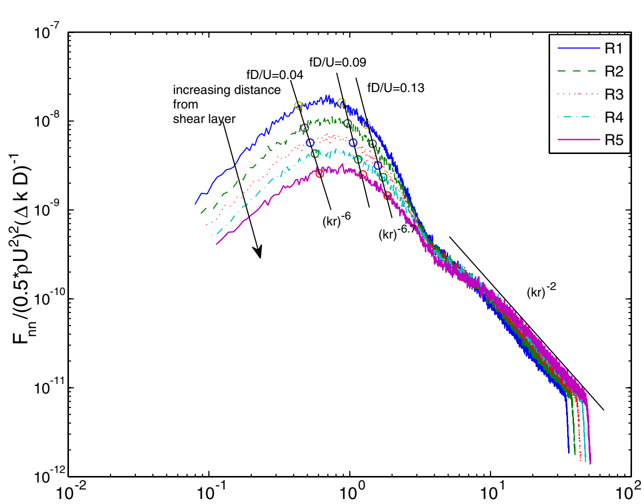


Fig. 3 Variation of the near-field pressure spectra with increasing distance from shear layer at $x/D = 8$.

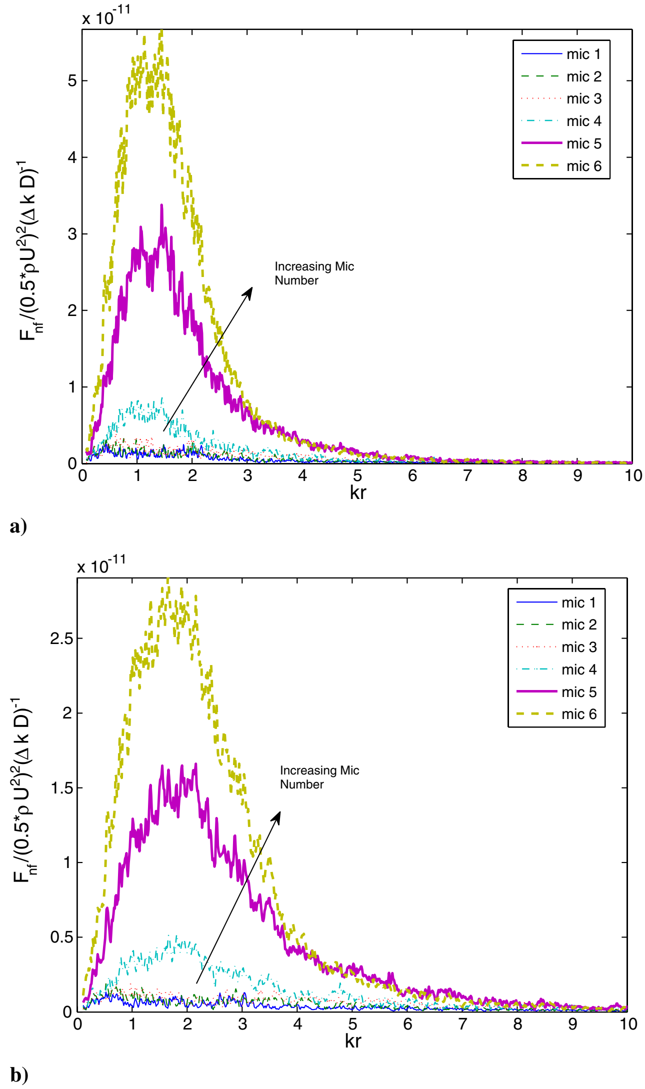


Fig. 4 Magnitude of cross spectra between near-field pressure at a) R1 and b) R5 with far-field acoustic pressure at the 6 microphone positions (note the different magnitudes on the *y* axis).

The amount of correlated energy for $kr < 3$ can be observed in the cross spectra between the far-field microphones and the near-field microphone, shown in Fig. 4. These spectra were estimated in a similar manner to the near-field spectra:

$$F_{nf} = \frac{1}{T}\langle \hat{p}_n(f)\hat{p}_f{}^*(f)\rangle \tag{5}$$

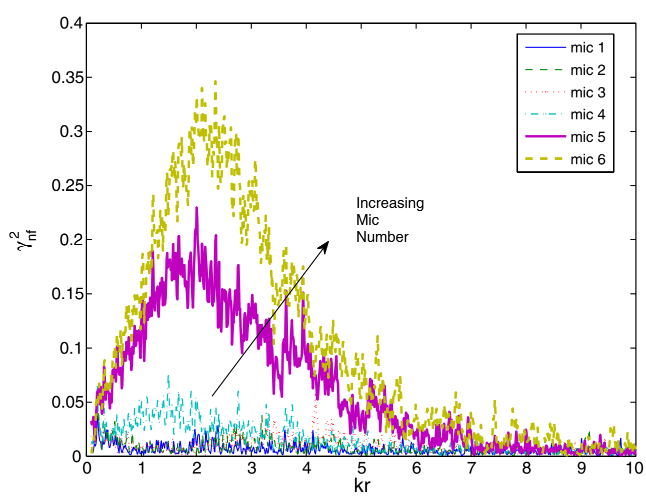
The cross spectra are plotted with linear scales so that the area under the curve can be interpreted as the amount of correlated energy that leaves the near field and travels to the acoustic far field. The spectra are again normalized using the square of the jet's dynamic head and presented using the kr scaling, where r is the distance of the near-field microphone from the jet centerline. Although using the near-field value of kr for normalization may seem somewhat unusual because the cross spectrum is a measure of the correlated energy over two kr values, scaling the cross spectra in this manner allows the correlated energy referenced to the near-field kr values to be examined. A simple inspection of the area under each curve for $kr < 3$ indicates that not only does a significant portion of the near-field pressure propagate to the far field, but that these kr values are, by far, the dominant source of acoustic pressure fluctuations in the jet at this downstream location. This is particularly true for the microphones at small angles to the jet axis (microphones 5 and 6).

The magnitude of the preceding cross spectra were normalized to form the coherence function given by

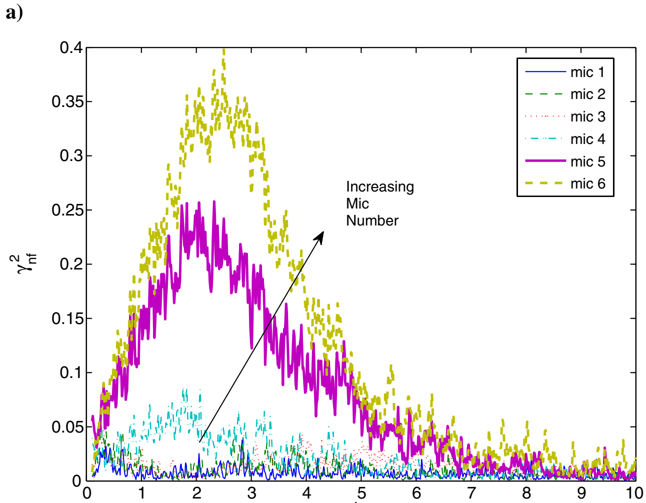
$$\gamma_{nf}^2 = \frac{|F_{nf}(f)|^2}{F_{nn}(f)F_{ff}(f)} \tag{6}$$

so that the efficiency of the near-field pressure as an acoustic radiator could be examined. The coherence of the near-field pressure with each microphone is shown in Fig. 5. The results indicate that the magnitude of the coherence for a given far-field microphone does increase as the near-field microphone is traversed away from the jet. In both cases, the highest coherence is for values below $kr = 3$, and again there is still significant coherence in the range $0 \leq kr \leq 3$, indicating that not only do pressure fluctuations at wave numbers in the so-called hydrodynamic range contribute the most overall energy to the far field, but they are also strongly related to the far field. The coherence for $3 < kr < 5$ is also reasonably high, suggesting that even though these pressure fluctuations are small they are coherent with the far field. The peak coherence of the near-field pressure at R1 with the far-field microphones 1 and 2 is almost zero, but increases rapidly for the smaller angle microphones to over 0.25. These values are even higher as the near-field microphone is traversed away from shear layer, reaching values as high as 0.4 at microphone 6.

Two-point correlations of the near- and far-field pressure were computed by inverse Fourier transforming the cross spectra to examine how the behavior at all frequencies affects the magnitude of the overall correlation. The effect of this positioning is illustrated in Fig. 6. In all cases, there were negligible differences in the location of

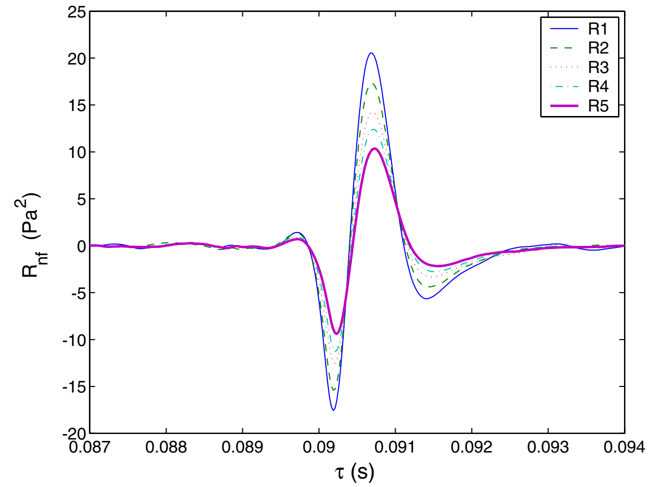


a)

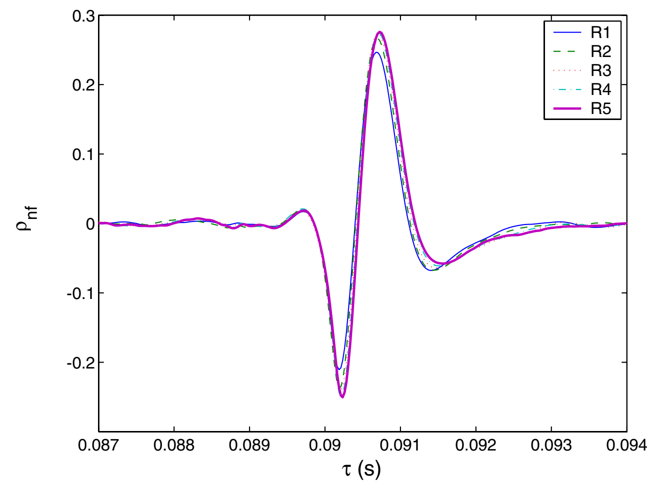


b)

Fig. 5 Coherence of the near-field pressure at a) R1 and b) R5 with the far-field acoustic pressure.



a)



b)

Fig. 6 Two-point correlation of the near-field pressure with the far-field pressure at microphone 6 in a) dimensional, and b) normalized fashion.

the peak correlation with increasing microphone position, owing to the small changes in distance between the two probes. However, consistent with the cross spectra, the magnitude of the peak in the dimensional correlation drops as the near-field microphone is traversed away from the shear layer. This is due to the attenuation of the portion of the acoustic pressure, present in the jet near field, at approximately the square of distance from the source. Thus, the proximity of the microphone to the source field is reflected in the strength of the correlation. The magnitude of the normalized correlation coefficient, however, varies little with distance from the near-field microphone to the jet. This indicates that the radial position of a near-field microphone does not significantly impact the results, providing, of course, that the microphone is not placed within the shear layer and contaminated with self-induced noise.

The normalized correlation between the near-field microphone at R1 and R5 is shown in Fig. 7. The correlation at small angles to the jet axis is quite high, approaching values of 30% with microphone 6. The correlation quickly decreases with increasing angle from the jet axis to 5% at microphone 3 and then to approximately zero at microphone 1, consistent with the known directional nature of the jet acoustic field. The normalized correlation values at microphone 5 are significantly higher than those obtained by Panda et al. [17] in which the ρuu term in Eq. (2) (the dominant term in unheated jets) was measured on the centerline of a Mach 0.8 jet and correlated with the far-field acoustic pressure. In particular, the peak correlation in that case was only 0.022 versus a peak correlation of approximately 0.25

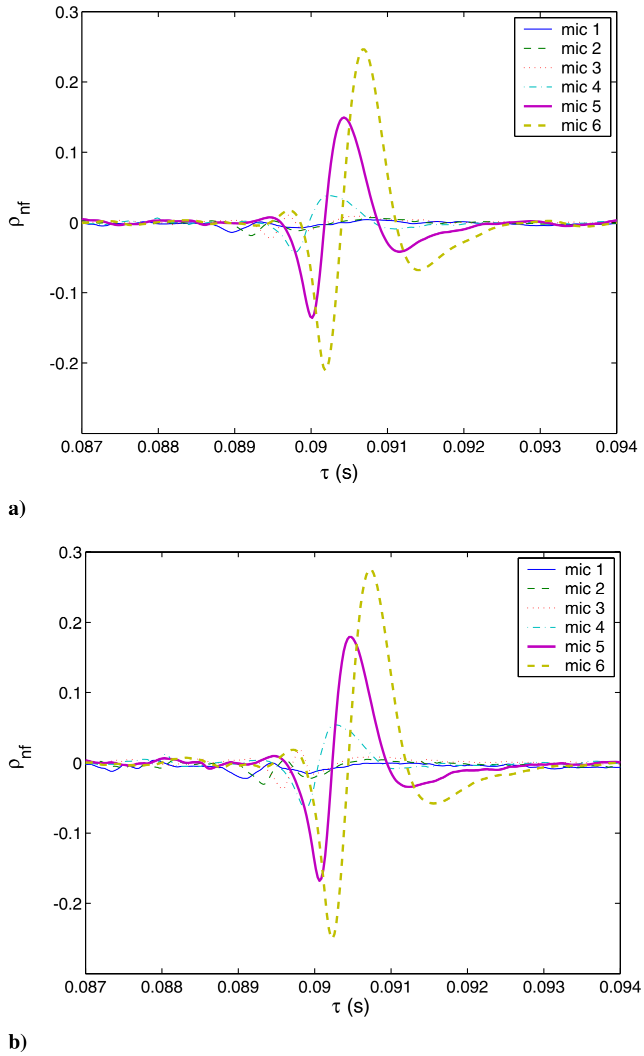


Fig. 7 Two-point correlation of the near-field pressure at a) R1 and b) R5 with the far-field acoustic pressure at the 6 microphone positions.

obtained here. This diminished level of correlation again highlights the complexities associated with attempting to relate inflow velocity fluctuations to the generation of pressure fluctuations and the resultant far-field acoustic signature.

Recently, Laurendeau et al. [38] performed similar measurements in a Mach 0.3 jet. In their measurements, however, the peak correlation values in that study are 4 to 5 times lower than those measured here; Laurendeau et al. report peak ρ_{nf} values of approximately 0.05 with microphones located 40 diameters away from the sound-producing region of the jet. Their results also do not display the strong coherence between the near-field pressure and the far-field pressure that occurs in this study for $kr < 3$. It is presently unclear as to the reason for these differences. Laurendeau et al. suggest that this is likely attributed to the differences in Mach number between these two jets. Ruling out that there are no significant flow differences between the two jets (as should be the case, because both jets were formed using contoured nozzles in anechoic facilities), this logically suggests that the differences must be attributed to Mach number. It is likely, as Laurendeau et al. propose, that the differences are caused by the acoustic fluctuations in the near field that increase in proportion to U^8, overwhelming the hydrodynamic pressure in the near field in the larger Mach number jet. Further experimentation is required to definitively answer this question.

IV. Conclusions

Near-field pressure measurements were performed around the periphery of a compressible jet simultaneously with measurements of the acoustic far field to allow the relationship between the near-field pressure and the far-field acoustic pressure to be examined. The near-field pressure spectra here decayed in a $(kr)^{-2}$ fashion for kr values greater than 3 and decayed in accord with $(kr)^{-6}$ for kr values less than 3. Even though the measured near-field pressure was largely hydrodynamic in nature, significant evidence remains of the acoustic pressure signature in the near-field pressure fluctuations, as indicated by coherence values as high as 40%. Furthermore, the present results indicate that the largest source of acoustic pressure fluctuations in the jet are hidden in the near field beneath large hydrodynamic fluctuations for $kr < 3$. This indicates that care must be taken when using near-field spectral decay to differentiate between acoustic and hydrodynamic fluctuations, because doing so may overlook a significant portion of the acoustic fluctuations in the jet.

The present findings are quite useful from a flow-control standpoint. In particular, these results imply that significant noise reduction may be achieved using control strategies that focus on *relatively* low frequencies in the jet; this is significantly easier to implement from a flow-control perspective than trying to control flow structures associated with higher frequencies. This finding may also be of use in wave models of the jet such as those used by Suzuki and Colonius [30] and Reba et al. [31], in which the models seemed to yield the best results near the peak frequencies in the near-field pressure spectra.

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E. Gutmark
Associate Editor