Experimental Investigation of the Pressure-Velocity Correlation of a M=0.6 Axisymmetric Jet

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A quantitative measure of the strength of the pressure-velocity correlation of a Mach 0.6, axisymmetric jet, with an exit nozzle diameter of 50.8mm is examined. The exit flow temperature is held constant at a temperature of 25°C, and is pressure and temperature balanced with ambient conditions. The fluctuating pressure field is sampled by an azimuthal array of (15) dynamic transducers, evenly spaced at 24°. These are held fixed and positioned just outside the shear layer near the jet exit at z/D=0.875, and 1.75R from the centerline, where the pressure field has been shown to be hydrodynamic. The instantaneous velocity measurements are simultaneously acquired using a multi-component LDA system whose measurement volume is traversed along several radial and streamwise locations within the potential core, and mixing layer regions of the flow. From this multi-point evaluation, the cross-correlation between the near-field pressure array, and streamwise component of the velocity field are examined as a function of radial, streamwise, and also azimuthal separation. The results illustrate a coherence on the order of 25% between the near field pressure and the velocity field. Analysis of the coherency spectra illustrates the frequency band of the correlations and suggests that the potential core and mixing layer regions of the flow are, in general, governed by the high and low frequency motions of the flow, respectively. The azimuthal modal distribution of the cross-correlation shows the dominance of the column mode of the jet, with no higher modes exhibited within the potential core region, and only modes 1 & 2 within the shear layer.

I. Introduction

Previous investigations of axisymmetric shear flows have shown that the presence of turbulent vortices contribute to much of the dynamics of the flow field, such as, entrainment, growth of the shear layer, and momentum transfer. One of the first groups to identify the role these vortices play in shear flows was Winant & Browand.15 They found that at the onset of shearing, small instability waves dominate the flow field. These waves grow, under the natural forcing of the flow, into discrete vortices which then roll up and interact with each other. This process is known as vortex pairing and ultimately leads to the development of a fully turbulent mixing layer. The interaction of these vortices also creates pressure fluctuations as they evolve downstream from the jet exit. This suggests that there is a definite coherence between the velocity field and the corresponding fluctuating pressure field observed in the axisymmetric jet. Petersen 12 later confirmed their findings, showing that the large scale turbulent structures of the axisymmetric jet shear layer (Re=5.2E4), was well correlated with the near-field pressure region. These turbulent structures consisted of rings of concentrated vorticity that distorted with downstream distance until statistical axisymmetry disappeared.

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More recent investigations of the axisymmetric jet shear layer, including azimuthal and radial decomposition of the velocity field by Glauser & George, Citriniti & George, and Jung et al. at lower Reynolds numbers, have given insight into the structures that govern a moderate to large percentage of the mixing mechanism. These investigations found that the near-field region, prior to the collapse of the potential core, exhibits a distribution of energy in the lower modes 0,1,& 2, as well as the higher azimuthal modes 4,5,& 6. Ukeiley et al. and Tinney et al. extended these techniques to include a range of Mach numbers and Reynolds numbers and have found similar results. The near-field pressure region surrounding the axisymmetric jet has also been the focus of numerous investigations, most notably because it has been found to play an intermittent role in translating information between the acoustic sources of sound, and the perceived acoustic far-field sound. Fuchs, Petersen, Arndt et al. and Coiffet et al. in investigating the relationships between the large scale motions of the flow, and its responding signature in the near-field pressure regions, found that the decomposed pressure field was dominated by only the first few Fourier-azimuthal modes.

These previous investigations lead to the conclusion of a coherence between the motion of the large scale turbulent structures and the near-field pressure region. However, with the differences observed in the azimuthal modal distribution, higher modes for the velocity and the first few for the pressure field, that coherence is less clear. Particularly of interest, is whether or not these higher modes are still embedded in the pressure field signature, and what role the azimuthal modal distribution plays in the coherency observed between the two. Thus, in the current investigation, we will couple near field pressure measurements with single point measurements of the velocity field. This will provide a more quantitative understanding of the relationships between the motion of the large scale turbulent structures and the near-field pressure region.

II. Experiment Setup

In the present investigation, the axisymmetric nozzle is operated at a core exit velocity of Mach 0.6, corresponding to a Reynolds number of 6.4E5 based on a nozzle diameter of 50.8mm. The exit flow temperature and bypass air conditions were matched at ambient pressure and a constant temperature of 25°C. Extensive 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 rate of the outer and inner shear layers were also found to be approximately 0.194z(11°) and 0.096z(5.5°), respectively, where z denotes the streamwise direction of the jet.

To evaluate the spatial, as well as temporal pressure-velocity correlation lengths, the pressure field is sampled at a fixed location (0.875D downstream of the jet exit and 1.75R from the centerline) while velocity measurements are simultaneously acquired at several radial and streamwise locations. An evenly spaced (24°) azimuthal array of fifteen Kulite model XCE-093, 0-34.4kPa transducers with a frequency response range from DC to 50kHz was used to sample the fluctuating pressure field. 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 azimuthal array was symmetric with respect to the flow. The signal from each transducer is digitized using a National Instruments PXI system equipped with two NI-4472 boards. Each board contains 8 single and differential channels with 24-bit resolution, capable of sampling up to 102.4kHz per channel. In addition, each channel contains an independent Delta-sigma A/D converter with built in low pass filter.

Velocity field measurements were acquired using Laser Doppler Anemometry (LDA) for its high achievable sampling rates and non-intrusive nature. The system used was a Dantec Dynamics LDA, powered by a 3-Watt argon-ion laser head, operated using
backward scatter. Olive oil was used as the seeding medium (on order 1µm diameter), supplied by a pressurized PIV tech twelve Laskin-nozzle seeder, injected far upstream from the nozzle’s contraction to ensure proper mixing of the particles. The entrainment region of the jet was seeded using a TSI model-9307 oil droplet generator (also capable of producing a 1µm diameter particle using a Laskin style nozzle). The LDA is traversed through several spatial locations in the streamwise and radial plane, to capture the velocity field. A two degree-of-freedom Dantec Dynamic traversing system, with spatial resolution on the order of 6.25µm was employed in positioning the measurement volume.

Imperative to the evaluation of the coherency between the pressure and velocity fields, is the simultaneous sampling of both signals. The PXI system (with 16 available channels) is used to synchronize the experiment, sampling all fifteen transducer, as well as the start and stop signals from the LDA measurement. This information is used in post processing to phase align the pressure data with the corresponding duration of the velocity measurement.

The reference, or 0º transducer, is positioned in the horizontal plane that marks the centerline of the nozzle exit. The LDA measurement volume is held fixed within this plane, and traversed for several radial and streamwise locations. Each radial location chosen in the measurement grid corresponds to a position, extending out from the center of the jet axis, to the outside edge of the shear layer (Fig. 2). Locations were selected along the centerline, the edge of the potential core, along the edge of the jet lip, and the outside edge of the shear layer. To resolve a more dense measurement grid, positions directly centered between each of the previously mentioned locations, were also sampled. This is done for streamwise locations in the range from to 1D-5D, in increments of 1D. (5D denotes the end of the potential core region, determined from separate profile measurements). An overview of the experiment can be seen in Fig. 1.

III. Velocity Analysis

The use of LDA to acquire velocity measurements presents the added challenge of manipulating an irregularly sampled data set, dependent only upon the rate at which particles randomly pass through the control volume. To calculate a power spectral density, a continuous time series is required. To get the LDA data into this form, a ‘zeroeth’ order interpolation scheme is used. This creates a continuous time series of step functions. The new time series can then be re-sampled at desired frequency (30kHz was chosen to align with pressure data). This technique has been shown by Adrian & Yao to introduce error in the estimation of the power spectral density function in the form of step noise, or white noise. This acts as a low pass filter, attenuating the spectral estimate at frequencies above (sf/2π), much lower than that of the Nyquist criteria of half the sampling frequency. However, adhering to a criterion of sampling 10-20 times the frequency of interest has been shown to limit this effect of step noise and low pass filtering. The average data rates achieved in these experiments were on the order of 25kHz. This is well within the range specified by Adrian & Yao, as the frequencies of interest of the jet was observed to be in the range of 1.5-2kHz (St=0.37-0.50).

The power spectral densities of the streamwise fluctuating velocity are shown in Figs. 3 & 4, as a function of radial position at z/D=1 and z/D=3, respectively. These were calculated using 8192 sample size blocks to produce a spectral resolution of δf = 3Hz, and were ensemble averaged over 70 blocks. At z/D=1, the spectra at all radial locations, extending from the potential core to the shear layer, are broadband and exhibits no distinct peak. The overall energy spectrum is also seen to increase with increasing r. The maximum values being exhibited in the region of highest shear, the interaction between the high velocities of the potential core and the low velocities of the surrounding fluid. Further downstream at z/D=3, we notice a similar trend, as the energy content is shown to again increase with increasing radial location. However,
Figure 3. Velocity power spectra as a function of radial location $z/D=1$.

Figure 4. Velocity power spectra as a function of radial location $z/D=3$.

Figure 5. Velocity power spectra as a function of streamwise location $r/R=0$ (centerline).

Figure 6. Velocity power spectra as a function of streamwise location $r/R=1$ (center of shear layer).
at this location, the spectra exhibits a pronounced peak in the region of the potential core. Ko & Davies\textsuperscript{11} proposed that the development of the axisymmetric jet is a function of exit Mach number. They found no noticeable peak in the energy spectrum of the potential core until \( z/D = 1.0 \) for a \( \textit{Mach} = 0.20 \) jet, and \( z/D = 1.5 \) for \( \textit{Mach} = 0.30 \). This is in concert with the spectra observed in the current investigation. Also noticeable in Fig. 4 is the shift in peak frequencies with increasing radial distance from the centerline. As \( r \) extends beyond the potential core into the shear layer, the scales of the vortices (structures) within the flow field are known to become more broadband as represented by the flattened spectrum.

The velocity spectral densities are expanded in Figs. 5 & 6 to include more detail about the development of the jet, along the center of potential core \( (r/R = 0) \), and the center of the shear layer \( (r/R = 1.0) \). The collapse of the potential core, the onset of a pronounced peak is seen at \( z/D = 2 \), with a maximum occurring at \( z/D = 3 \). As we move further downstream, that peak begins to become less prominent. The turbulent spectrum is also shown to increase in energy as the jet continues to develop downstream from the nozzle lip, and past the region where the potential core collapses (around \( z/D = 5 \)). This agrees well with the previous observations made in the spectra as a function of radial location. This is also in accord with results presented by Glauser & George\textsuperscript{8} for the incompressible jet mixing layer. The collapse of potential core is a result of the entrainment of the free-stream flow across the entire shear layer. The spectrum demonstrates that the energy content is a direct measure of this increased mixing as the jet develops with increasing \( z \). Along the center of the shear layer \( r/R = 1 \), a similar trend is exhibited in the production of the turbulence. However, a more broad distribution of energy across the lower spectrum of scales is noticed. Also, the characteristic frequency (frequency at roll off), is clearly seen to decrease with increasing streamwise location. The \( f^{5/3} \) slope of the spectra seen in the inertial subrange, is indicative of a high \( Re \) turbulent flow field.

\section*{IV. Pressure Analysis}

The power spectral densities of the fluctuating pressure field are analyzed in similar fashion (to the velocity measurements) by using the same number of ensembles and block sizes. As a result of the flow’s mean azimuthal symmetry, the pressure spectral density should collapse, if the position of all the transducer’s are the same in the inhomogeneous coordinates \( (r \) and \( z) \). To account for small discrepancies between the outputs of the various probes, during post processing individual transfer functions (based on the averaged spectral density over all transducers) were applied to create identical power spectral densities. The raw spectral densities of all the probes are shown in Hall,\textsuperscript{9} and are nearly identical (both in magnitude and phase). This suggests that the averaged azimuthal pressure field surrounding the jet is invariant, thus justifying the small corrections made in applying each transducer’s transfer function.

The resultant average spectral densities are shown in Fig. 7 in terms of wave number spectrum, following the form used by Arndt \textit{et al.}\textsuperscript{2} in their investigation of the pressure field surrounding the axisymmetric jet. Their investigation used a simple model based on a point-source solution to the spherical wave equation in order to divide the pressure fluctuations into two forms, acoustic fluctuations and hydrodynamic fluctuations. Using the assumption that long wavelength disturbances are associated with large sources and that short wavelength disturbances are associated with small sources, they created an expression for the intensity of the hydrodynamic field (for a constant wave number \( \omega = a_k \) which should have a spatial decay of \( I \propto n^{-6} \) \( (n \) denotes radial distance, so as not to confuse the reader with \( r \)). While at constant \( n \), in the inertial subrange, the spectral variation should be something of the order of \( I \propto k^{-2/3} k^{-6} \propto k^{-6.67} \). They showed that the transition between these two slopes (between the hydrodynamic near field and the acoustic far field regions of the pressure) occurred predominantly around \( ky = 2 \), where \( y \) denotes outward radial distance from the center of the shear layer. Another important conclusion was that the dividing line
between the near-field and the far-field was frequency dependent, rather than a fixed region in space. In the current investigation, the pressure spectral densities depict similar behavior to that shown in the Arndt et al. investigation. The influence of the radiated acoustic field, clearly marked by the shift in roll off slopes at $k_y=2$, is also seen here, even at a location this close to the jet exit, $(y = 19.05mm, z/D = 0.875)$.

V. Pressure-Velocity Correlation

The two-point cross-correlation coefficient between the fluctuating pressure and streamwise component of the velocity can be expressed as in Eqn. (1), with the time lag $\tau$ applied to the velocity time series. This is appropriate since both signals are simultaneously sampled with the pressure measurement occurring at $(z_1, t_1)$ and velocity at $(z_2, t_2)$. The time lag is defined as $\tau = t_2 - t_1$, where $\tau \propto \Delta z/U_c$ and $U_c$ is a proportionality constant based on the convection velocity of an event. The $k^{th}$ component of pressure refers to azimuthal position along the array. The cross-correlation coefficient may also be expressed as Eqn. (2), where the numerator denotes the inverse Fourier transform of the cross-spectrum, $S_{pu}$. The latter is used to calculate the correlation coefficient in this investigation.

$$\rho_{pku}(\tau) = \frac{\langle p_k(t)u(t+\tau) \rangle}{\sigma_p \sigma_u}$$  \hspace{1cm} (1)$$

$$\rho_{pku}(\tau) = \int S_{pu}(f)e^{i\tau f} df \sigma_p \sigma_u$$  \hspace{1cm} (2)$$

The use of a circular arrangement of pressure transducers gives an added domain, $\theta$ (denoting azimuthal separation), over which the correlation can be evaluated. It can be expected however, since the velocity measurements were acquired in the plane of the $0^\circ$ transducer, that this location would demonstrate the strongest correlation. This is clearly the case seen in Figs. 8 and 9 illustrating the variations in amplitude as the azimuthal distance between the pressure sensing location and the LDA reference plane (at $0^\circ$) increases. The velocity measurements were acquired at streamwise locations of $z/D = 2$&4, and at the center of the shear layer, $r/R = 1$ in both cases. A slight increase in time lag is also noticed as the peak moves to higher $\tau$, with increasing azimuthal separation. The profile is nearly symmetric, as this trend is mirrored on the opposite side, denoted as the ‘second’ $180^\circ$ of separation. This is more clearly articulated at $z/D = 4$, suggesting the presence of a helical structure. Correlations are now presented using only the reference transducer (at $0^\circ$), to demonstrate maximum coherence.

Figure 8. Surface plot of pressure-velocity correlation at $r/R=1$, $z/D=2$.

Figure 9. Surface plot of pressure-velocity correlation at $r/R=1$, $z/D=4$.

In the cross-correlation plots, the peak is not at the origin as would be seen in an autocorrelation plot; there is now a time lag, $\tau$, between the two signals. With each measured location, the magnitude of the correlation goes high as the signals move into phase, drops below zero (out of phase), and then begins...
to level off to zero as the signals no longer correlate. As we now evaluate the cross-correlation at several streamwise locations, \( z/D = 2 \) through \( z/D = 5 \) (Figs. 10-13) as a function of \( r \), it is seen that the magnitude increases with increasing radial location at first. This occurs until a location along the edge of the potential core, where it then begins to fall off with increasing radial location. Positions above \( r/R = 1 \) demonstrate little correlation. The peak values, approximately 25\%, are consistently noticed at the locations measured just outside the centerline, however still within the potential core region.

The time lag, \( \tau \), associated with each peak, is also seen to decrease with increasing radial location. This shift is consistent with increases in radial location. One explanation for this is the decrease in relative distance as the LDA is traversed outward in the radial direction towards the transducer. Hence, the time lag associated with the correlation between the signals decreases slightly as seen in Figs. 10-13. The width of the peaks can also be very revealing about the growth of the structures, as we extend radially, from the potential core into the shear layer. They illustrate the temporal length scales over which the structures are correlated. Within the potential core, the peaks are sharp and indicate a correlation with a consistent length scale. In the shear layer, the peaks observed are more broad, and indicate larger distribution of structures resulting in lower magnitudes.

Near the end of the potential core, \( z/D = 5 \), the magnitude of the correlation at the centerline has become the dominant signal at 16\%, relative to the magnitude at other radial locations (Fig. 13). The peak correlation magnitude again begins to fall off with increasing \( r \), to nearly zero above \( r/R = 1 \). This can be expected as
the collapse of the potential core signifies the growth of the shear layer. Therefore, all positions except the centerline are now within the shear layer, and demonstrate a weaker correlation (lower magnitude) as compared to that at the centerline.

The magnitude of the cross-correlation is now more closely examined as a function of streamwise location. The values are plotted for a fixed radial location corresponding to the line marking the center of the potential core (Fig. 14), the edge of the potential core (Fig. 15), and the center of the shear layer (Fig. 16). These plots clearly demonstrate the increase in time lag associated with increasing downstream location. Each peak experiences a noticeable increase in $\tau$ at larger $z/D$ separation. The magnitude of each peak is also observed to decrease with increasing streamwise location. This indicates that as the flow develops and becomes more random at downstream locations, the correlation between the signals starts to decay. This is supported by the slight changes in magnitude of the correlation observed along the centerline, as this is a region of consistent scales (Fig. 14). The changes in the width of the peaks, again indicating the changes in consistency of length scales, is also seen here. Within the potential core region, the width of each curve is nearly constant as we move downstream. However, it is observed along the edge of the potential core (high shear region), that there is an increase in the width of each successive peak, thus indicating a randomness of length scales. Along the center of the shear layer, this trend is again noticed, as a pronounced difference in the width of each peak is seen. The structures in this region of highest fluctuation, are known to interact and coalesce as they propagate downstream, causing an increased randomness of scales. This is thought to account for the spreading of the shear layer.

VI. Cross-Spectral Analysis

Similar to the cross-correlation function, the cross-spectrum also serves as a measure of the correlation between two signals. The cross-spectral density and the cross-correlation function form a Fourier transform.
pair,

\[ S_{pu}(r,z,\theta, f) = \int R_{pu}(r,z,\theta, \tau)e^{-ij\tau} d\tau \]  

(3)

The cross-spectrum is generally complex, having a real and imaginary part. \((r,z, \theta \ have \ been \ suppressed \ for \ simplicity)\)

\[ S_{pu}(f) = \Lambda_{pu}(f) - j\Omega_{pu}(f) \]  

(4)

This is generally presented as an amplitude and phase spectrum. Where amplitude, \(\alpha_{pu}(f)\), and phase, \(\phi_{pu}(f)\), are as follows,

\[ \alpha_{pu}(f) = \sqrt{\Lambda_{pu}^2(f) + \Omega_{pu}^2(f)} \]  

(5)

\[ \phi_{pu}(f) = \arctan(-\Omega_{pu}(f)/\Lambda_{pu}(f)) \]  

(6)

However a more common presentation, more closely related to the cross-correlation coefficient, is the squared coherency spectrum, \(\kappa_{pu}^2(f)\). It provides a non-dimensional measure of the correlation between two signals as a function of frequency.

\[ \kappa_{pu}^2(f) = \frac{\alpha_{pu}^2(f)}{S_{pp}(f)S_{uu}(f)} \]  

(7)

The coherency spectra at \(z/D=3\) & \(z/D=5\) (Figs. 17 & 18) are now examined as a function of radial location. The similarity between these plots, and the cross-correlation coefficient plots (Figs. 11 & 13) is clearly illustrated here. The magnitudes are nearly identical and follow similar trends. The peak frequencies exhibited are also in good agreement when compared to the reciprocal of the period from each corresponding curve in the cross-correlation plots. This again affirms the strength of the correlation between the two signals.

VII. Azimuthal Modal Distribution

The azimuthal modal distribution of the cross-spectrum is found by applying a cosine transform in the theta direction.

\[ B_{pu}(r,z,m,f) = \int S_{pu}(r,z,\theta,f)\cos m\theta d\theta \]  

(8)
Since 15 transducers were used to sample the pressure field, only the first 7 azimuthal modes can be resolved. Figures 19 & 20 show the modal distribution along both the centerline and center of the shear layer at \(z/D = 3\) and \(z/D = 5\), respectively. A mode 0 dominance is seen at \(z/D = 3\) both in the center of the potential core and center of the shear layer. However, in the shear layer, modes 1&2 are present, whereas in the potential core, these show no significant energy. As we move downstream to the end of the potential core region, we see that the centerline is still mode 0 dominant. The shear layer again exhibits a broad distribution across the first three modes. The presence of higher modes within the shear layer of the flow is in agreement with work of others. It has been found that as the jet develops, the structures within the shear layer become more rich and exhibit a dominance in the higher azimuthal modes, extracted from velocity alone, as demonstrated in previous investigations. If we suppress the frequency dependence of the azimuthal spectra by summing the absolute value over all frequencies, the dominance of the column mode is clearly seen along the centerline. As the jet develops, the total energy in mode 0 is shown to increase through \(z/D=5\), whereas the higher modes exhibit little energy. Along the center of the shear layer the figure illustrates a fairly even distribution of energy in all first three modes, 0, 1, & 2. It is also noticed that the total energy of each decreases with increasing streamwise location.

![Figure 19. Pressure-velocity cross-spectrum modal distribution at \(z/D=3\), \(r/R=0\) (top) and \(r/R=1\) (bottom).](image19)

![Figure 20. Pressure-velocity cross-spectrum modal distribution at \(z/D=5\), \(r/R=0\) (top) and \(r/R=1\) (bottom).](image20)

![Figure 21. Pressure-velocity cross-spectrum modal distribution as a function of streamwise location (summed over frequency).](image21)

![Figure 22. Spatial pressure cross-spectrum modal distribution.](image22)

The modal distribution of the cross-spectrum presented here appears to be largely a function of the
The fluctuating pressure signal. The decomposition of the fluctuating pressure field $B_{pp}$, again calculated using the cosine transform, is shown to exhibit a dominance in the lower azimuthal modes (0 & 1) (Fig. 22). As observed in previous investigations of the near-field pressure region by others mentioned previously, and most recently by Coiffet et al. 4 in a $M=0.3$ jet, the fluctuating pressure signal does not contain any information in the higher azimuthal modes. The mode number spectra shows the presence of only the first few modes (0, 1, & 2) as far downstream as $5D$. It has also been shown, as previously mentioned, that as the axisymmetric jet develops, the velocity field is dominated by the higher azimuthal modes. However, at the onset of development, it demonstrates a mode 0 dominance, suggesting that the contribution of mode 0 decays with evolving downstream distance. The cross-correlations presented earlier exhibited a decrease in the magnitude with increasing downstream distance, as well as outward radial distance. The modal distribution presented in Fig. (21) shows this to be the case along the center of the shear layer. However along the centerline, the column mode’s contribution is shown to first increase as the jet develops and decreases near the end of the potential core. This same trend is illustrated in Fig. (14) as the magnitude of the correlation increases as the jet develops downstream and also starts to decrease near the end of the core region. This implies that the coherency between the two signals is governed by azimuthal mode 0, and therefore predisposed to the fluctuating pressure field.

VIII. Conclusion

The fluctuating pressure field of a $Mach=0.6$ ($Re = 6.4E5$) axisymmetric jet, sampled at $z/D=0.875$, $r/R=1.75$ by an azimuthal array of transducers, 24° apart, has been shown quantitatively to exhibit a strong cross-correlation with the fluctuating velocity field. The largest correlation is exhibited between the 0° transducer, positioned in the plane of LDA velocity measurements, and regions within the potential core just outside the centerline. Magnitudes on the order of 25% are seen. Within the shear layer, the level of correlation exhibited differs greatly within the inner region than that of the outer, the entrainment region; from 15% to less than 5%.

Cross-spectral analysis reaffirms that the signals are well correlated, as the coherency spectra exhibits similar magnitudes as the cross-correlation function. The dominant frequencies seen, are also in good agreement with the frequency evaluated from cross-correlation coefficient as the reciprocal of the period. The modal distribution shows mode 0 dominance throughout the flow field, to the end of the potential core region, with higher modes (1 & 2) exhibiting significant energy only within the shear layer. The pressure signal is also shown to be dominated by the lower azimuthal modes (0, 1, & 2) as well, with a majority of energy in mode 0. This suggests that the coherency between the two signals is governed by the column mode 0.

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References


