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reprinted from

international journal of aeroacoustics

volume 8 · number 3 · 2009

published by MULTI-SCIENCE PUBLISHING CO. LTD.,
5 Wates Way, Brentwood, Essex, CM15 9TB UK
E-MAIL: mscience@globalnet.co.uk
WEBSITE: www.multi-science.co.uk
A study of the correlation of large-scale structure dynamics and far-field radiated noise in an excited Mach 0.9 jet

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ABSTRACT

The main goal of the present work is to excite various instabilities of an axisymmetric Mach 0.9 jet with a ReD of 0.76 × 10⁶, track the ensuing large-scale structures/instability waves, and investigate relations between the dynamics of these structures and the far-field sound. The jet was excited over a large range of Strouhal numbers and several azimuthal modes by eight localized arc filament plasma actuators, equally spaced around the circumference of the nozzle, near the nozzle exit. The flow field and far-field noise were investigated using particle image velocimetry and a three-dimensional array of 12 microphones at 30° polar angle to the downstream jet axis. The microphone array results show that the high amplitude noise radiated to 30° polar angle is originated just downstream of the end of the potential core, in agreement with our previous results and the results in the literature. The streamwise noise source distribution was only sensitive to azimuthal modes around the jet preferred mode. Otherwise, the general trend was that forcing the jet at low Strouhal numbers moves the distribution upstream compared to the baseline jet, and at high Strouhal numbers results in a source distribution similar to the baseline jet. Conditionally-averaged PIV data were used to relate the flow dynamics and noise sources. The growth, saturation, and decay of the conditionally-averaged velocity fluctuations along the jet centerline correlate well with the far-field noise and the noise source distribution estimated using the microphone array. For m = 0 mode excitation around the jet column Strouhal number, the conditionally-averaged streamwise velocity fluctuations correlate well with the noise source distribution. While for m = 1, the correlation is best with the conditionally-averaged cross-stream fluctuations.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>a⁰</td>
<td>POD modal amplitude</td>
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<td>a∞</td>
<td>Ambient Speed of Sound</td>
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1. INTRODUCTION

1.1. Flow field and far-field measurements

The far-field noise radiated from exhausting jets in a jet engine has been a large nuisance since the inclusion of jets on aircraft and has lead to many efforts to study and reduce it. Lighthill [1] crafted the first jet noise theory and predicted that the total radiated acoustic power would scale with the jet exit velocity to the eighth power. It is also known that the sound radiated to the far field reaches a maximum in overall sound pressure level (OASPL) around 30° to the downstream jet axis. At this polar angle (θ), the peak amplitude in the far-field sound has a similar Strouhal number \( (St_D = fD/U_{jet}) \), where \( D \) is the jet diameter and \( U_{jet} \) is the jet exit velocity) as the peak amplitude of the large-scale
structures in the flow field (e.g. Crow & Champagne [2], Fisher et al. [3], Morrison & McLaughlin [4]). The slight difference in these two Strouhal numbers can be explained by the quadratic interactions between the large-scale jet instabilities (Sandham et al. [5]).

Linear phased microphone arrays are traditionally used to locate jet noise sources (e.g. Narayanan et al. [6], Venkatesh et al. [7]) and have shown that high and low $St_\theta$ noise is primarily originated near the nozzle exit and further downstream, respectively. Azimuthal arrays can be used to further characterize the noise sources (Reba et al. [8], Suzuki [9], Hileman et al. [10]) and to perform azimuthal decompositions of the acoustic energy (Juve et al. [11], Brown & Bridges [12]). It has been shown that the first few azimuthal modes make up the majority of far-field sound energy (Juve et al. [11], Michalke & Fuchs [13]).

Techniques using simultaneous flow-field and far-field measurements have also been utilized in attempts to establish a relationship between large-scale structures and the far-field radiated noise (Morrison & McLaughlin [4], Juve et al. [11], Lee & Ribner [14], Sarohia & Massier [15], Schaffar [16], Panda & Seasholtz [17], Guj et al. [18]). Recently, Hileman et al. [10, 19] developed and utilized an experimental technique, which involved a three-dimensional far-field array of eight microphones placed at $\theta = 30^\circ$ and time-resolved planar visualization of the flow field. The origin of sound waves was estimated using the microphone array while the evolution of large-scale structures was recorded using the non-intrusive planar flow visualization. Similar diagnostics were also utilized by Kastner et al. [20] using direct numerical simulation (DNS) database of Freund [21]. Both techniques observed the rapid breakdown of the large-scale structures as being a dominant flow feature during noise generation, which was qualitatively similar to the instability wave breakdown described initially by Morrison & McLaughlin [4] in a low $Re$ supersonic jet. A second approach has also been used for flow field and far-field acoustic correlations. This approach first connects the flow field to the near-field pressure, then to the far-field sound (Picard & Delville [22], Hall et al. [23], Laurendeau et al. [24], Jordan et al. [25], Sinha et al. [26]).

1.2. Jet excitation

The directivity and spectral content of the far-field radiated sound are related to the noise sources within the flow, which are associated with dynamics of turbulence structures. Planar free shear layers are dominated by coherent structures that play a major role in the entrainment and gross mixing entrainment (Brown & Roshko [27]). The frequency associated with these coherent structures /instability waves within the initial shear layer is characterized by Strouhal number, $St_\theta = f \theta_o/U_{jet}$, based on the boundary layer’s momentum thickness just before exiting the nozzle, $\theta_o$. The initial shear layer in an axisymmetric jet behaves in a similar fashion. However, further downstream, the coherent structures in an axisymmetric jet are characterized by the preferred mode instability with a Strouhal number based on the nozzle diameter, $St_D$ around 0.3 (Crow & Champagne [2]). With the growth of the shear layer downstream of the nozzle exit, the shear layer thickness approaches that of the jet radius, and azimuthal/helical modes are amplified with amplitudes similar to the axisymmetric mode (e.g. Cohen & Wygnanski [28]). The helical modes have a similar preferred $St_D$ but different mixing and velocity characteristics (Samimy et al. [29]).
An efficient way to study the role of large-scale structures in flow field dynamics and far-field sound is by using jet excitation. By exciting a jet using various frequencies and azimuthal modes, the flow field as well as the radiated sound field can be influenced, which could shed light on noise sources and correlation between the flow field and far-field noise.

Acoustic drivers have been used to excite instabilities in low Reynolds number flows and this has helped to study the relationship between flow instabilities and far-field sound (e.g. Kibens [30], Stromberg et al. [31], Laufer & Yen [32], Ho & Huerre [33], Long et al. [34]). When forcing the jet with a frequency around the jet column instability ($St_D \sim 0.3$), the broadband noise is amplified and there is a high amplitude tone at the forcing frequency in the far field (Bechet & Pfizemair [35], Moore [36], Ahuja & Blakney [37], Zaman & Hussain [38]). The increase in far-field noise has been coupled with an increase in the flow-field turbulence (Samimy et al. [29], Lepicovsky et al. [39]). When forcing non-axisymmetric azimuthal modes ($m = 1, 2, \ldots$) of the jet column instability, the broadband noise is still amplified, but the tones radiated from the actuator are weaker in amplitude compared to those when the axisymmetric mode is excited (Samimy et al. [29], Beecher & Pfizemair [35], Ginevsky et al. [40]). Michalke & Fuchs [13] showed that the acoustic energy is comprised primarily of $m = 0, 1$ and $2$. The exact contribution of each azimuthal mode is angle dependent (Juve et al. [11], Brown & Bridges [12]). Also, exciting higher azimuthal modes, which are inefficient acoustic radiators, appears to be beneficial for noise mitigation (Samimy et al. [29, 41]).

The acoustic field for jets excited at frequencies higher than the jet column instability has also been investigated. Samimy et al., [29] Moore, [36] and Jubelin [42] have all shown some reduction in the broadband noise for $St_D$'s > 1. Forcing the jet with much higher frequencies, near the initial shear layer instability, can increase or decrease the jet noise (Long et al. [34]). Forcing the jet at a frequency corresponding to the maximum amplification amplitude ($St_\theta \sim 0.012$) results in pairing of the initial shear layer vortex rings and leads to strong acoustic tones at the subharmonics of the forcing frequency (Zaman and Hussain [43]). When forcing the jet at a frequency corresponding to the maximum amplification rate, ($St_\theta \sim 0.017$), the saturation, roll-up and breakdown of the initial shear layer vortex rings occur much earlier in the streamwise direction, which prevents the successive paring events. This leads to a reduction in the broadband noise and only a tone at the forcing frequency is present in both the flow field (Zaman and Hussain [44]) and far field (Long et al. [34]).

For low Reynolds number flows, instabilities can be manipulated by introducing perturbations via acoustic drivers. This conventional method of low amplitude forcing at instability frequencies has not been successful in high Reynolds number flows for two reasons. First, high Reynolds number flows possess high dynamic loading and a noisy environment, which necessitate higher amplitude forcing. Second, instability frequencies in a typical laboratory flow are over a large bandwidth. In the present work, excitation is provided by Localized Arc Filament Plasma Actuators (LAFPAs) developed in the Gas Dynamics and Turbulence Laboratory at The Ohio State University (Samimy et al. [29, 41, 45, 46], Utkin et al. [47]). The LAFPAs provide high amplitude perturbations over a large bandwidth which is ideal for controlling high-speed and high Reynolds number flows.
In this paper we will present and discuss our efforts using jet excitation along with flow and far-field measurements to relate the flow dynamics to the far-field sound. The far-field is probed with an array of 12 microphones which is used to find the SPL, OASPL, and estimate the origin of peak sound events radiated to $\theta = 30^\circ$. Then the flow field is studied by using velocity data obtained from particle image velocimetry (PIV). The velocity data are conditionally-averaged to deduce the contribution of large-scale flow features and relate the dynamics of these features to the SPL, OASPL, and jet noise sources.

2. METHODOLOGY

2.1. Jet facility

All experiments were performed in the optically accessible anechoic chamber at The Ohio State University’s Gas Dynamics and Turbulence Laboratory. The jet facility has been described in detail by Kerechanin et al. [48] and complies with ANSI Standard S12.35. High-pressure air is supplied to the facility by three five-stage reciprocating compressors. The air is filtered, dried, and stored at 16.5 MPa (2500 psi) in two high capacity tanks. The flow is conditioned in a settling chamber where the jet stagnation pressure ($P_o$) is controlled by a Fisher Type 667-D control valve capable of maintaining $P_o$ within 1% of the desired value.

The jet in the present work is an unheated, axisymmetric, Mach 0.9 jet exhausting from a converging nozzle with an exit diameter ($D$) of 25.4 mm and a Reynolds number based on $D$ of $7.6 \times 10^5$. The convective Mach number is around 0.5 and therefore the jet is considered weakly compressible. The state of the initial shear layer was estimated by measuring the mean velocity profile near the nozzle exit in previous work (Kastner et al. [49]). The incoming boundary layer profile was more similar to the $(u/U_{jet})^{1/7}$ profile than a Blasius profile and therefore the incoming boundary layer was considered turbulent. The momentum thickness was calculated to be 0.1 mm, which was used to estimate the frequency for the maximum amplitude amplification ($St_\theta = 0.012$) and the maximum amplification rate ($St_\theta = 0.017$) of the initial shear layer instability to be around 50 kHz and 70 kHz, respectively.

2.2. Far-field diagnostics

The noise measurements were carried out using a three-dimensional, far-field, ring array with 12 microphones placed at the polar angle of maximum jet noise radiation, $(X, \theta) = (46D, 30^\circ)$ as shown in Figure 1. The microphones ($1/2$" Bruel & Kjaer Model 4939) were connected to a Bruel & Kjaer Nexus conditioning amplifier that amplified, filtered and conditioned the microphones signals. A National Instruments PXI system with two PXI 6133 A/D boards allowed all 12 channels to be simultaneously sampled at a rate up to 1 MHz. The microphones were calibrated using a Bruel & Kjaer calibrator that provided a 94 dB, 1 kHz sine wave. To ensure a flat frequency response up to 80 kHz, the grid cover that prevents diaphragm damage was removed during the experiments.

The sound pressure level was computed using 100 blocks of 8192 points ($N$) at a sampling frequency ($f_s$) of 200 kHz. Prior to acquisition, the signal was band-pass filtered from 20 Hz to 100 kHz using the Nexus conditioning amplifier. The SPL
measurements have been normalized to a radial distance of $80D$ from the nozzle exit. The uncertainty in the SPL measurements was found to be $\pm 0.4 \text{ dB}$ by using 11 different runs taken at different times and days.

All 12 microphones in the ring array are used to estimate the origin of peak sound events in the microphone time trace through a beam-forming algorithm described by Hileman et al. \[10, 19\]. The algorithm is able to estimate the origin of peak sound events in all three dimensions of space and in time. A brief description of the data acquisition, the beam-forming algorithm and the source location technique is now given.

The microphone signals were band pass filtered from 500 Hz to 10 kHz, 100 blocks of $N = 16384$ data points were acquired at a sampling rate $f_s = 1 \text{ MHz}$, and then analyzed off-line to estimate the noise source location. The off-line analysis begins by normalizing each pressure time trace by its standard deviation ($\sigma_p$). This allows comparison between cases with different sound pressure levels. Next, positive peak sound events are identified within microphone 1’s and 7’s time traces. A sample pressure time trace from microphone 1 for the Mach 0.9 jet is presented in Figure 2. A positive peak sound event is identified when the following two requirements are met:

1) The pressure is above a predetermined threshold of $1.5\sigma_p$.

2) The pressure is at the local maximum during the time above the threshold.

A negative peak sound event occurs when the pressure amplitude is below a threshold of $-1.5\sigma_p$ and is at the local minimum. The high sampling rate of 1 MHz allowed a more accurate determination of the time at which the local pressure maximum/minimum was reached for a given peak sound event. The use of 16384 points increased the number of peak sound events. Using other threshold levels to identify a peak event has been

\begin{figure}
\centering
\includegraphics[width=\textwidth]{schematic.png}
\caption{Schematic of a three-dimensional, far-field, microphone ring array at polar angle $\theta = 30^\circ$.}
\end{figure}
investigated by Hileman et al. [10], and it was shown that increasing the threshold resulted in the estimated origin moving slightly downstream.

For each peak sound event in microphone 1’s time trace, the same peak event is searched for in the time traces of the other microphones within the array. As an example, along with microphone 1’s pressure time trace, Figure 2 presents the pressure time trace for microphone 2. The two time traces have peak sound events labeled as 1 for microphone 1 and 2 for microphone 2. The peaks labeled in microphone 1’s time trace precede peaks labeled in microphone 2’s time trace. The time delay between when the peak reached microphone 1 and microphone 2 ($\Delta t_{12}$) is defined by the maximum in the cross-correlation between the two signals. This time delay is then inputted into the beam-forming algorithm.

The beam-forming algorithm first requires the microphone locations in three-dimensional space, $\mathbf{M}_i = [X_i, Y_i, Z_i]$, where $i$ is the microphone number. The goal of the algorithm is to estimate a source vector, $\mathbf{S}_e = [X_e, Y_e, Z_e]$, where the subscript $s$ denotes a source and the subscript $e$ denotes the event number. After finding the time delay between microphones ($\Delta t_{ij}$), an equation can be set up for each event

$$\Delta t_{ij} = \frac{\| \mathbf{M}_i - \mathbf{S}_e \| - \| \mathbf{M}_j - \mathbf{S}_e \|}{a_{\infty}}$$  \hspace{1cm} (1)

with the only unknown being the source vector $(\mathbf{S}_e)$ for that event.

The equation is over-defined because there are up to 10 time delays ($\Delta t_{ij}$) and only 3 unknown directions necessary to estimate $\mathbf{S}_e$. Instead of trying to find an exact solution, the error is minimized to determine $\mathbf{S}_e$. To minimize the error, a dummy variable, $Q_e$, is used and estimated by:

$$Q_e = \frac{\| \mathbf{M}_i - \mathbf{S}_e \| - \| \mathbf{M}_j - \mathbf{S}_e \|}{a_{\infty}} - \Delta t_{ij}$$  \hspace{1cm} (2)
The algorithm then finds the $\hat{S}_e$ that minimizes $Q_e$ through multiple iterations. To minimize the iterations it is important to select the proper microphone pairs for a given direction of the source vector. For example, microphones 1, 2 and 3 all have the same Y and Z coordinate and are used to estimate $x_e$. Microphone pairs $(i,j) = (4, 12), (5, 11)$, and $(6, 10)$ share the same X and Y position and are used to estimate $z_e$. Microphone pairs $(4, 6)$ and $(10, 12)$ share the same X and Z position and are used to estimate $y_e$. To minimize the potential refraction effects of sound waves passing through the shear layer of the jet, only microphones closest to the noise source are used. For example, if the peak sound event reaches microphone 1 before microphone 7, it implies the event most likely is originated within the top half of the jet and the algorithm uses microphones 1 through 5, 11, and 12 since all are in the top half of the jet.

The results are then presented as a probability distribution function (PDF) based on the number of peak events ($e$) recorded by microphone 1 ($e \sim 3600$ with the present sampling parameters). The uncertainty in the measurement of the streamwise component of the noise source location is $\pm 1.0D$ while in the cross-stream components is negligible (Hileman et al. [10]). Source location results using the present array (Hileman et al. [10]) were shown to be consistent with phased-array results (Venkatesh et al. [7]).

2.3. Flow field diagnostics

Two-component Particle Image Velocimetry (PIV) measurements were made using a LaVision system to find the streamwise and cross-stream velocity components ($u$ and $v$) on the $x$-$y$ plane shown in Figure 3. To initiate the data acquisition process, the system triggers a dual-head Spectra Physics PIV-400 Nd:YAG laser operating at a wavelength of 532 nm. The raw images are acquired by a 2000 by 2000 pixel Redlake CCD camera and processed using DaVis, a LaVision data processing software. The camera views the streamwise laser sheet from $X/D = 0.5$ to 9.2. This experimental setup produces a velocity vector grid of 115 by 65, which translates into approximately 1.9 mm separation between velocity vectors. The laser sheet thickness was less than 0.3 mm. The time
separation between two consecutive PIV images was 1.8 µs so the velocity field from a pair of PIV images was almost instantaneous. Initially, an interrogation window of 64 × 64 pixels was used. Then the reduced data with 64 × 64 pixel window was used as a reference in final processing with an interrogation window of 32 × 32 pixels. Each consecutive interrogation windows were overlapped by 50% to increase spatial resolution. The flow was seeded with Di-Ethyl-Hexyl-Sebacat fluid introduced 2.75 meters upstream of the jet exit to ensure the particles were well dispersed in the jet flow before the measurement location. The entrained air was seeded by injecting fog into a very low-speed co-flow formed in a 38 cm diameter cylinder concentric with the nozzle. The fog was injected 2 meters upstream of the nozzle exit to ensure the particles were well dispersed in the co-flow before the measurements location. The average droplet size is about 0.7 and 1.0 µm for the jet flow and co-flow seed, respectively.

2.4. Plasma actuators

The jet is controlled by eight plasma actuators housed in a Boron Nitride extension attached to the nozzle exit as shown in Figure 4. Each actuator consists of a pair of pin electrodes separated by 3 mm. Tungsten wires 1 mm in diameter are used for the electrodes. The electrodes are distributed around the nozzle perimeter, approximately 1 mm upstream of the nozzle exit plane. Details of the current, voltage and power output of the actuators are given in Samimy et al. [43, 46] and Utkin et al. [47].

The actuators are capable of operating from a few Hz to 200 kHz. The phase and frequency of each actuator can be controlled independently. With the current 8-actuator set up, simple azimuthal modes 0, 1, 2, and 3 can be excited. Combined modes (m = ±1, ±2, and ±4) can also be excited, but are not part of the present study. More details about these modes can be found in Samimy et al. [46]. Traditionally, when an acoustic driver is used for excitation, the input signal amplitude to the driver is sinusoidal. A positive rectangular wave is used as the input signal to a plasma actuator. A rectangular wave has a forcing frequency ($f_F$) and phase like a sine wave, but also a duty cycle. The duty cycle was roughly 20 µsec regardless of the $f_F$, which corresponded to 2% and 40% of the forcing period for 1 kHz and 20 kHz, respectively. A flow visualization investigation by
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Samimy et al. [46] confirmed that indeed varying the phase between the plasma actuators resulted in the generation of azimuthal modes very similar to the traditional azimuthal modes. More details about the plasma perturbation physics are described by Samimy et al. [29, 46] and Utkin et al. [47]

3. RESULTS

3.1. Influence of jet excitation on flow field

Preliminary PIV results, primarily the jet centerline Mach number and turbulent kinetic energy, were reported earlier showing significant effects of forcing frequency and azimuthal modes on the jet flow field (Samimy et al. [29]). In the current work, a two-component PIV system was used to provide detailed planar measurements of the streamwise ($u$) and cross-stream ($v$) velocity components for a variety of forcing cases. Then the snapshot POD analysis of Sirovich [50] was used with the velocity fluctuations ($u'$ and $v'$) to investigate the influence of jet excitation on the flow structures. The snapshot method is more suited for time-uncorrelated PIV images with good spatial resolution. [51]

POD objectively identifies dynamically significant structures in the flow as a combination of $N$ eigenfunctions $\{\varphi_i^n(\overline{X})\}$ or spatial modes:

$$u'(\overline{X}) \equiv \sum_{n=1}^{N} a_i^n \varphi_i^n(\overline{X})$$

where $a$ is the modal amplitude, the subscript $i$ denotes the velocity component (1 for streamwise velocity and 2 for cross-stream velocity) and the superscript $n$ represents POD mode number. Up to 700 POD modes are available ($N = 700$) since 700 instantaneous PIV images were acquired and used in the POD analysis. The first $v'$ POD mode, $\varphi_1^v(\overline{X})$ for excitation of $m = 0$ at $St_{DF}$ of 0.09, 0.36, 0.72 and 1.08 is shown in the top row of Figure 5. As can be seen, all cases show some large-scale features. It should be noted that the second POD mode was very similar to the first POD mode except there was a 90° phase shift in the position of the large-scale flow features. Increasing the $St_{DF}$ leads to smaller flow features that are amplified and visible only closer to the nozzle exit. The POD domain spans from $X/D$ of 0.5 to 4.5 for the highest $St_{DF}$ and $X/D$ of 0.5 to 9 for the lowest $St_{DF}$ in order to better visualize the large-scale flow features from forcing. All cases (except $St_{DF}$ of 0.09) show features in the top and bottom of the initial shear layers consistent with the $m = 0$ mode. At a given streamwise location, the cross-stream velocity fluctuations in the top and the bottom mixing-layer are in opposite directions, on the average, since the large-scale structures are in phase. For example, a positive $v'$ on the bottom mixing-layer and a negative $v'$ in the top mixing-layer are both entraining air into the mixing layer. For the much lower forcing frequency ($St_{DF}$ of 0.09), disturbances are amplified after the potential core is collapsed
Samimy et al. [29]) and the shear layer is no longer receptive to excitation of \( m = 0 \) mode (Cohen and Wygnanski [28]).

Projection of \( \frac{v}{H} \) from a single PIV image onto the 1st \( v \) POD mode, \( \phi_2^1(\tilde{x}) \), provides the modal amplitude for each velocity snapshot:

\[
a^1_2(k) = \int v'(\tilde{x}, k) \phi_2^v(\tilde{x}) d\tilde{x}
\]  

where the subscript 2 and superscript 1 represent the cross-stream velocity and the 1st POD mode, respectively, and \( k \) represents the PIV image number (\( k = 1 \) to 700). The modal amplitude is largest for the PIV images that strongly correlate with the first \( v \) POD mode. Selecting PIV images that have the highest correlation with \( \phi_2^1(\tilde{x}) \), essentially when \( a^1_2 \) is above a certain threshold, provides a condition that allows the PIV to be conditionally sampled. Similar conditional sampling techniques have used spatial correlations instead of POD modes (Konstantinidis et al. [52], Kim et al. [53]). The forty PIV images which had the highest correlation with the 1st \( v \) POD mode (highest \( a^1_2 \)) were selected and then ensemble averaged to form conditionally-averaged velocity fields.

The bottom row in Figure 5 presents the conditionally-averaged cross-stream velocity, \( \tilde{v} \), using the respective POD mode in the top row as the condition. As can be seen, all cases are similar to their respective \( v \) POD mode, as expected. If the conditional sampling was not successful, the images would have been smeared with no distinguishable features. The fluctuations for the lower \( St_{DF} \)'s are around 40 m/s while they are only about 25 m/s for the higher \( St_{DF} \)'s.

The energy distribution for the first 8 \( v \) POD modes of the larger domain (\( X/D = 0.5 \) to 9) is presented in Figure 6 and is consistent with the amplitude of the velocity fluctuations in the conditionally-averaged images. Compared to the baseline jet, forcing causes the modal energy in POD modes 1 and 2 to significantly increase. It is seen that

\[\text{Figure 5:}\quad \text{First} \ v \ \text{POD mode (top) and conditionally-averaged cross-stream velocity} \ (\tilde{v}) \ (\text{bottom}), \text{for excitation of} \ m = 0 \ \text{at} \ St_{DF} \ \text{of} \ 0.09 \ (a), 0.36 \ (b), 0.72 \ (c), \text{and} \ 1.08 \ (d).\]
the highest percent energy contained in the first POD mode is for a $St_{DF}$ of 0.36 (8%). This case has almost twice the energy contained in the baseline case. A $St_{DF}$ of 0.36 is closest to the jet preferred mode and both the first and second POD modes and the conditionally-averaged images support this case having the largest fluctuations. The other $St_{DF}$’s show an increase compared to the baseline, but not as significant as the jet preferred $St_D$. The higher POD modes, 5 to 8, have a modal energy percentage similar to that of the baseline jet regardless of the forcing case. However this does not necessarily mean the modal shapes are the same. A similar analysis was done on the $u'$ velocity component, but the results are not presented since they do not add much to the conclusions. However, the $u'$ velocity component is presented and discussed later with relation to noise generation.

To look at the effects of excitation of azimuthal modes, the first $v'$ POD mode and the conditionally-averaged cross-stream velocity, $\tilde{v}$, for excitation of $m = 0, 1, 2,$ and $3$ at $St_{DF}$ of 0.36 are presented in Figure 7. Similar to Figure 5, the large-scale flow features in the first $v'$ POD mode and $\tilde{v}$ are very similar. At this excitation frequency, which is the jet preferred mode frequency, the large-scale flow features are present for all azimuthal mode cases. As expected, the biggest difference between the different azimuthal modes is the sign of the cross-stream velocity in the top and bottom mixing layers at a given streamwise location - the signs are opposite for $m = 0$ and 2 while they are the same for $m = 1$ and 3. The conditionally-averaged images also show $\tilde{v}$ is on the order of 40 m/s for $m = 0$ and 1, and only on the order of 30 m/s for the higher azimuthal modes, $m = 2$ and 3. Once, again the amplitude of the velocity fluctuations is consistent with the percent energy contained in the 1st POD mode (Figure 8). It is interesting that $m = 1$ has the highest percent energy, and this will be related to the jet noise sources later in the paper.

Figure 6: Distribution of modal energy in the first 8 $v'$ POD modes for the baseline jet and excited jet with $m = 0$ at a several $St_{DF}$’s.

![Figure 6: Distribution of modal energy in the first 8 $v'$ POD modes for the baseline jet and excited jet with $m = 0$ at a several $St_{DF}$’s.](image)
Figure 8 presents the modal energy distribution in the first 8 $v'/H_{11032}$ POD modes using the same streamwise domain as Figure 7. Compared to the baseline case, all forced cases have a significant increase in modal energy particularly in the first two $v'/H_{11032}$ POD modes. The $m=0$ and 1 cases have the most significant energy increase, while the higher two azimuthal modes ($m=2$ and 3), especially $m=3$ mode, do not show as large of an increase. All cases, including the baseline jet, have a similar amount of modal energy in POD modes 5 to 8.

Figure 7: First $v'$ POD mode (top) and conditionally-averaged $\overline{v}$ (bottom) for excitation of $m=0, 1, 2, \text{and } 3$ at $St_{DF}$ of 0.36.

Figure 8: Distribution of modal energy in the first 8 $v'$ POD modes for the baseline and forcing at $St_{DF} = 0.36$ with $m = 0 \text{ to } 3$.

Figure 8 presents the modal energy distribution in the first 8 $v'$ POD modes using the same streamwise domain as Figure 7. Compared to the baseline case, all forced cases have a significant increase in modal energy particularly in the first two $v'$ POD modes. The $m=0$ and 1 cases have the most significant energy increase, while the higher two azimuthal modes ($m=2$ and 3), especially $m=3$ mode, do not show as large of an increase. All cases, including the baseline jet, have a similar amount of modal energy in POD modes 5 to 8.

The 1st $v'$ POD mode for the baseline jet is presented in Figure 9 for both the large domain and the small domain. The features in the first mode are consistent with an asymmetric mode and the features are smaller in the smaller domain covering the near nozzle exit region. For the larger domain, the features are similar in size as those in the lower $St_{DF}$'s. The similarities between the baseline mode and the forced cases help
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Support using jet excitation to study the jets evolution. However, the baseline jet is not dominated by a single frequency or azimuthal mode and the modal energy is more distributed compared to the forced jets.

3.2. Far-field sound of a forced jet

The effects of forcing on the far-field sound at polar angle $\theta = 30^\circ$ will be presented and discussed in this section. Detailed SPL results using the same plasma actuators can be found in Samimy et al. [29]. The SPL for the excited jet with $m = 0, 1, 2, \text{ and } 3$ near the jet preferred frequency ($St_{DF} = 0.36$) is presented and compared to the baseline jet in Figure 10. The first difference between the spectra of the baseline and the excited jet is the presence of tones at the $St_{DF}$ and its harmonics in the excited jet. The tonal amplitude at the $St_{DF}$ decreases with increasing azimuthal mode, which has been reported in the literature (e.g. Ginevsky et al. [40]). They are from the noise radiated from the actuators. Comparison of these results with the results from a recent work using a jet from an approximately 7.5 times larger exit diameter nozzle showed similar tonal amplitude in both the smaller and the larger jets (Samimy et al. [53]). Since noise intensity scales with the nozzle diameter squared, contributions of actuation tones become much smaller in the larger nozzle. The second difference between the spectra of the baseline and the excited jet is the changes in the broadband amplitude and shape. The broadband amplitude has been increased for $m = 0$, but its shape has not changed much compared to the baseline jet case. For $m = 1$ excitation, the broadband amplitude has been increased with a distinct hump around the broadband peak ($St_D \sim 0.18$). For $m = 2$ excitation, the broadband has been decreased at low $St_D$’s and increased at higher $St_D$’s, and the broadband shape is flatter around the peak. For $m = 3$ excitation, the broadband amplitude and shape are similar to those of the baseline jet. The differences in the SPL is related to the differences seen in the conditionally-averaged images of Figure 7, and these differences will be discussed in more detail after the OASPL and noise source distribution results are presented.

The influence of forcing Strouhal number on the far-field noise is quantified by the difference in the Overall Sound Pressure Level ($\Delta$OASPL) between a forced jet and the baseline jet. The OASPL for each case was found by integrating the SPL from $St_D$ of 0.02
to 4.5 (200 Hz to 50 kHz). Further increasing the bandwidth did not significantly change the OASPL because the amplitude is very low at the outer frequency limits. To ensure only broadband changes are investigated, the tones from the SPL are removed from the forced cases before calculating the OASPL. A similar approach was previously used in Moore [36] and Ahuja & Blakney [37].

Table 1 shows the ∆OASPL for excitation of $m = 0, 1, 2,$ and $3$ at $St_{DF}$ of 0.36.

<table>
<thead>
<tr>
<th>$St_{DF}$</th>
<th>$m = 0$</th>
<th>$m = 1$</th>
<th>$m = 2$</th>
<th>$m = 3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09</td>
<td>1.0</td>
<td>1.1</td>
<td>0.9</td>
<td>1.6</td>
</tr>
<tr>
<td>0.36</td>
<td>1.9</td>
<td>2.1</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>0.72</td>
<td>0.5</td>
<td>0.5</td>
<td>–0.1</td>
<td>–0.5</td>
</tr>
<tr>
<td>1.08</td>
<td>–0.3</td>
<td>–0.3</td>
<td>–0.5</td>
<td>–1.2</td>
</tr>
<tr>
<td>1.81</td>
<td>–1.2</td>
<td>–1.2</td>
<td>–1.1</td>
<td>–1.2</td>
</tr>
</tbody>
</table>

Figure 10: Far-field SPL at polar angle $\theta = 30^\circ$ for the Mach 0.9 jet forced with $m = 0, 1, 2,$ and $3$ at $St_{DF}$ of 0.36.
A study of the correlation of large-scale structure dynamics and far-field radiated noise in an excited Mach 0.9 jet

3.

$St_{DF}$ of 1.08 is near the maximum OASPL attenuation for $m = 3$.

$St_{DF}$ of 1.81 is near the maximum OASPL attenuation for $m = 0, 1, \text{and} 2$.

The present work is focused on understanding the jet noise sources. Therefore, distinct cases with both OASPL increase and decrease are investigated. However, noise mitigation strategies using the plasma actuators have been explored in Samimy et al. [29, 41]

3.3. Noise source distribution

All 12 microphones in the ring array were used to estimate the source locations of peak sound events. Figure 11 is the streamwise distribution of the origin of peak sound events for the baseline jet and excitation with $m = 0$ at various $St_{DF}$’s. Details of the distributions are presented in Table 2. The results are presented as a probability distribution function based on roughly 3,400 peak events recorded by microphone 1 or 7. The bin size is $1.0D$. The streamwise distribution for the baseline jet has a maximum around $X/D = 8$ and a mean around $X/D = 9.2$. The distribution moves upstream compared to the baseline jet for all excited cases, except for the highest forcing frequency case, which is very similar to that of the baseline jet. The upstream shift is similar for $St_{DF}$ of 0.36 and 0.72 and is the largest of all the excited cases shown. As the $St_{DF}$ increases above 0.72 or below 0.36, the distribution peak moves back downstream.

In general, the peak for all cases is located in a region where the jet centerline velocity

**Figure 11:** Probability distribution function in the streamwise direction of the origin of peak sound events for the Mach 0.9 baseline jet and excited jet with $m = 0$ at various $St_{DF}$’s.
has begun to decay (near the end of the potential core). A direct comparison between the centerline velocity decay and the noise source distribution will be given later.

Figure 12 shows the streamwise distribution for excited jets at three $St_{DF}$'s and azimuthal modes $m = 0, 1, 2$ and $3$. The details of the distributions are presented in Table 2. Significant differences in distributions occur at $St_{DF}$ of 0.36, where only $m = 0$ and 2 have the same peak location ($X/D = 6$), but different peak values. This is consistent with the SPL where there were significant differences in the spectral shape of the different azimuthal modes at this $St_{DF}$. At the $St_{DF}$ of 1.81, there are only minor differences between the distribution shape and peak location for the baseline and excited jets. These results imply that the azimuthal modes play a significant role as far as the streamwise distributions for the jet noise sources are concerned only near the jet preferred mode frequencies.

Since the array is three-dimensional, it can also be used to estimate the origin of peak sound events in the cross-stream plane ($y$-$z$ plane). The cross-stream noise source distribution is presented in Figure 13 for the baseline jet and for excitation of $m = 0, 1,$
A study of the correlation of large-scale structure dynamics and far-field radiated noise in an excited Mach 0.9 jet

Table 2: Details of noise source PDF for the baseline and various excited cases.

<table>
<thead>
<tr>
<th>St_{DF}</th>
<th>m = 0</th>
<th>m = 1</th>
<th>m = 2</th>
<th>m = 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09</td>
<td>7 / 8.2 / 3423</td>
<td>8 / 8.7 / 3333</td>
<td>8 / 8.1 / 3491</td>
<td>8 / 8.6 / 3314</td>
</tr>
<tr>
<td>0.36</td>
<td>6 / 6.6 / 3490</td>
<td>8 / 8.5 / 3398</td>
<td>6 / 7.3 / 3734</td>
<td>7 / 7.7 / 3501</td>
</tr>
<tr>
<td>0.72</td>
<td>6 / 6.7 / 3545</td>
<td>7 / 8.4 / 3522</td>
<td>7 / 7.0 / 3653</td>
<td>6 / 6.8 / 3737</td>
</tr>
<tr>
<td>1.08</td>
<td>8 / 8.6 / 3455</td>
<td>8 / 9.7 / 3480</td>
<td>7 / 8.5 / 3576</td>
<td>7 / 8.0 / 3552</td>
</tr>
</tbody>
</table>

2 and 3 at St_{DF} of 0.36. The cross-stream distribution has been averaged over the x-direction and has a bin size of 0.20D. The grey-scale bar has been multiplied by 100. The black circle in each distribution represents the nozzle lip line. Similar to the baseline case, all the forced cases have a fairly circular distribution with a peak near the jet centerline and a majority of the events inside the nozzle lip line. The differences between various azimuthal excitations are on whether the distribution is localized or diffused and the magnitude of the peak amplitude. The results presented in Figures 13 are summarized in Table 3, along with the results for other excitation Strouhal numbers. The table shows the peak value in the cross-stream distribution, the radius of a circle necessary to capture 70% of the noise events, and the ∆OASPL already presented in Table 1. At St_{DF} of 0.36, the two lowest azimuthal modes, m = 0 and 1, have the highest peak values and their distributions are slightly more localized. These cases also correspond to the largest OASPL amplification.

The cross-stream noise source distribution is not presented for excitation of m = 0, 1, 2 and 3 at other St_{DF}’s for the sake of brevity, instead the characteristics of each distribution is summarized in Table 3. The peak amplitude of the distribution changes as the St_{DF} changes. The highest peak values occur at the low St_{DF}’s, which is consistent with the streamwise distribution. For m = 0 and 1, the maximum peak amplitude is for a St_{DF} of 0.36 and 0.72, while the maximum peak amplitude is at St_{DF} of 0.09 for m = 2 and 3. It appears that forcing around the jet preferred frequency tends to make the noise sources more compact compared to the baseline jet. For the higher St_{DF}’s, the maximum peak values are slightly lower than the baseline jet. The streamwise and cross-stream noise source distributions are not significantly different between azimuthal modes at the highest St_{DF} of 1.81. The shape of the SPL and OASPL attenuation at this St_{DF} was similar regardless of which azimuthal mode was excited (Samimy et al. [29]).

Comparison of the m = 3 to the m = 0 and 1 cases shows a relationship between the noise source cross-stream distribution and the ∆OASPL. For m = 3, the cross-stream distribution peak values begin to decrease after St_{DF} of 0.09, while for m = 0 and 1 they do not seem to decrease until St_{DF} of 1.08. For a St_{DF} of 0.72, the breadth of the distribution is very sensitive to the azimuthal mode. The distribution is more localized for m = 0 and 1 and the OASPL is increased, while the distribution is much less localized for m = 3 and the OASPL is decreased. These results imply that noise reduction shown...
using excitation of the jet with \( m = 3 \) at high frequencies (Samimy et al. [29]) does not result in any changes in the streamwise noise distribution, see Figure 12b, but rather in changes in the cross-stream distribution.

**Figure 13:** Cross-stream noise source distribution for the baseline jet and excitation of \( m = 0, 1, 2 \) and 3 at \( St_{DF} \) of 0.36.
3.4. Flow-field results

The results in the previous section showed the origin of peak sound events to be near the jet centerline between $X/D$ of 6 and 9, depending on the forcing case. Detailed PIV results obtained in this region of the flow field will be presented and discussed in this section.

Figure 14 shows the normalized jet centerline mean velocity ($U/U_{jet}$) for the baseline jet and the jet excited with $m = 0, 1, 2,$ and $3$ at various $St_{DF}$'s. The jet centerline is of particular interest since this is where the cross-stream noise source distribution is peaked. The general trend is that forcing at lower $St_{DF}$'s tends to shorten and at higher $St_{DF}$'s do not change the potential core length in comparison with that of the baseline jet core. In exciting the first three azimuthal modes ($m = 0, 1, \text{and } 2$), the shortest potential core length is for $St_{DF} = 0.36$, while the shortest potential core for exciting $m = 3$ is at $St_{DF} = 0.09$. The OASPL was significantly amplified for the first three azimuthal modes at a $St_{DF}$ of 0.36 and for $m = 3$ at a $St_{DF}$ of 0.09. The filled circle on each line in Figure 14 corresponds to the location of the peak of streamwise noise source distribution given in Table 2. The noise generation is in a region where the jet centerline velocity is decaying for all cases, but it does not appear that there is any direct relation between the estimated source origin and the rate of velocity decay.

3.5. Conditionally-averaged velocity

The conditionally-averaged velocity fluctuations are shown in Figure 15 for excitation of $m = 0$ at $St_{DF}$ of 0.09, 0.36, 0.72, and 1.08. The $\bar{v}$ velocity field was already presented in Figure 5, but now the $\bar{u}$ velocity field is also shown. The white dashed line in Figure 15 indicates the location of the peak of noise source distribution presented in Table 2. The length of the line is twice the radius over which the cross-stream noise source distribution captures 70% of the noise events (Table 3). The interaction and breakdown of the conditionally-averaged velocity associated with the coherent structures correlate very well with the peak noise location for excitation near the jet preferred frequency ($St_{DF} = 0.36$). For this excitation case, as shown in Table 1, the OASPL had maximum amplification. Also, the cross-stream noise source distribution is fairly localized along the jet centerline (Figure 13) as is the $\bar{u}$ term.
For excitation at $St_{DF}$ of 0.09, which is significantly lower than the jet preferred Strouhal number, the peak noise source location seems to mark the beginning of the interaction between coherent velocity fluctuation features. However, for the excitation at higher $St_{DF}$’s (0.72, and 1.08), the peak noise source location is significantly downstream of where the large-scale coherent velocity fluctuation features start breaking up. This offers a clue for the similarity of the noise source distribution for the high $St_{DF}$’s excitation cases and the baseline jet.

The development and interaction along the jet centerline of the large-scale flow features associated with the $\bar{u}$ and $\bar{\nu}$ terms are significantly different. For example, for $\bar{u}$ term at the jet preferred frequency ($St_{DF} = 0.36$) case, the large-scale flow features are robust and periodic in the top and bottom mixing-layer, before they start interacting around $X/D = 4$. For the same excitation case, the $\bar{\nu}$ term also shows the growth of the robust large-scale flow features within the early development of the mixing-layer. Unlike $\bar{u}$ features, as $\bar{\nu}$ features grow, and as the two sides of the mixing layer begin to interact, $\bar{\nu}$ features appear to rapidly disintegrate. The same type of interaction across

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**Figure 14:** Normalized mean velocity along the centerline for the baseline jet and for the excited jet with $m = 0$ (a), 1 (b), 2 (c) and 3 (d) at $St_{DF}$ of 0.09, 0.36, 0.72, 1.08, 1.81.
Figure 15: Conditionally-averaged streamwise ($\bar{u}$) and cross-stream ($\bar{v}$) velocity components for excitation of $m = 0$ at $St_{DF}$ of 0.09 (a), 0.36 (b), 0.72 (c), and 1.08 (d).

The jet centerline moves further upstream at higher excitation frequencies - for example, at $St_{DF}$ of 0.72, it starts occurring for $\bar{u}$ by $X/D = 2$. One should exercise caution in interpreting these results, as breaking up of the structures and a significant loss of phase would result in similar images.

Figure 16 presents the influence of excitation of azimuthal modes at the jet preferred frequency ($St_{DF} = 0.36$) on the conditionally-averaged velocity field. The results for excitation of $m = 0$ at this $St_{DF}$ were already presented in Figure 15 and discussed. For $m = 1$ case, the development and interaction between the top and bottom flow features are quite different than those for $m = 0$ case. First, the large-scale features seem to interact across the jet centerline and slowly decay for $\bar{v}$ while there is no strong interaction across the jet centerline for $\bar{u}$. This is directly related to the sign of the velocity terms as the two sides of the mixing-layer begin to interact. The $\bar{v}$ component in the top and bottom mixing layer have the same sign at a given streamwise location for $m = 1$, whereas it is the $\bar{u}$ component that have the same sign for $m = 0$. Thus as the two sides of the mixing layer interact, these components tend to grow. On the other hand, when the terms in the top and bottom mixing layer have opposite sign at a given streamwise location there is no significant growth along the jet centerline, particularly in the region of noise generation. The selective amplification of either $\bar{u}$ or $\bar{v}$ is closely related to dynamics of the generated large-scale structures (Kim et al. [53]).

The results for excitation of the two highest $m$ cases have some similarities to those of the lower $m$ cases. The main difference is that in the latter a stronger interaction exists between the top and bottom mixing-layer along the jet centerline and the SPL showed significant changes in the broadband shape with excitation around the preferred $St_{DF}$. For the higher $m$ cases, the broadband amplitude was flatter, which could be due to the weaker interactions across the jet centerline.
Around the jet preferred frequency, the dynamics observed by conditional averaging are similar to previous results of Hileman et al. [19] obtained in the baseline jet using time-resolved flow visualization. In the results obtained by Hileman et al., the large-scale flow features initially in the top or bottom mixing-layer broke down in the region of noise generation. The break-down was accompanied by a growth of image intensity along the jet centerline, which was attributed to an increase in mixing. In the present work, the large-scale flow features seen in the velocity field has one conditional-averaged velocity component decaying while the other velocity component is growing along the jet centerline in the region of noise generation. Which component decays and which component grows along the jet centerline are sensitive to the excited azimuthal mode. For $m = 0$ and 2, the azimuthal interactions along the centerline cause $\tilde{v}$ to break down and $\tilde{u}$ to grow along the centerline. For $m = 1$ and 3, the dynamics are similar but the azimuthal interactions lead to $\tilde{v}$ break down and $\tilde{u}$ growth along the centerline.

We will further investigate the excitation cases near the jet preferred frequency ($St_{DF}$ of 0.36) and will only include excitation of $m = 0$, 1, 2, and 3 at $St_{DF}$ of 0.36. Given that the majority of the peak sound events are originated in a region along the jet centerline, conditionally averaged velocity terms along the centerline are presented in Figure 17. The most striking feature is the dominance along the centerline of $\tilde{u}$ term for $m = 0$ case, $\tilde{v}$ term for $m = 1$ case, and how both terms are smaller for $m = 2$ case. Fitted to these two dominant terms are envelope functions that capture their growth, saturation, and decay.

Forcing the jet with either $m = 0$ or 1 increases the OASPL and for each case one of the conditionally-averaged velocity terms has a significant growth, saturation and decay along the jet centerline. On the other hand, forcing the jet with $m = 2$ only slightly increases the OASPL, and both conditionally-averaged velocity terms (especially $\tilde{u}$ ) lack significant growth, saturation, and decay along the jet centerline. This variation in

![Figure 16](image-url)
A study of the correlation of large-scale structure dynamics and far-field radiated noise in an excited Mach 0.9 jet

the development of a conditionally-averaged velocity term along the jet centerline also complements the SPL results. The SPL had a broadband shape similar to the baseline for excitation of $m = 0$ case, had a distinct hump at the broadband peak amplitude for $m = 1$ case, and had a flattened spectrum for $m = 2$ case. The shape of the broadband is influenced by the dynamics of the large-scale structures, which is related to the type and strength of interaction between the large-scale structures from the two sides of the mixing layer.

The noise source distributions should also correlate with the envelope functions in Figure 17 if the noise is largely related to the large-scale flow features. Figure 18 shows the streamwise noise source distributions (shown earlier in Figure 12a) and the envelope functions for $m = 0$ and 1. No curve has been fitted to the noise source distribution, which is why the $m = 1$ curve is fairly flat around the peak, as the spatial resolution of the acoustic array for noise source localization is approximately $1D$ in the streamwise direction. Both the envelope functions and the streamwise noise source distributions have been normalized by their maximum value. The peak as well as a significant part of the noise source distribution resides in the decay phase of the envelope function for both $m$ cases. For $m = 0$ case, both the source distribution and the envelope function peak farther upstream than for $m = 1$ case. The decay phase for the two azimuthal modes occurs at two different spatial rates. Initially the decay is slow and then a few jet diameters further downstream the spatial decay rate is much higher. The peak in the noise source distribution coincides with the region where the decay rate changes. The exact reason for the change in decay rate is not presently known, but it is most likely related to one of two things. First, the robust large-scale features from forcing are breaking down. Second, the change in the decay rate is in a region where the mean velocity has significantly decayed and the structures are no longer receiving as much energy from the mean flow.
4. CONCLUSIONS
Results were presented from an investigation of noise sources in an excited high-speed, high Reynolds number jet. Localized arc filament plasma actuators were used to excite an axisymmetric Mach 0.9 jet with a Reynolds number of $0.76 \times 10^6$ at a variety of $St_{DF}$’s and azimuthal modes, $m = 0, 1, 2, \text{ and } 3$. The flow field was investigated using velocity data provided by PIV measurements, and the far field was investigated using data from an array of twelve microphones. The results illuminate the importance of the forcing Strouhal number ($St_{DF}$) and azimuthal mode to the jet’s flow field, far field, and noise sources.

The influence of azimuthal mode is significant when forcing the jet at lower $St_{DF}$’s ($St_{DF} < 1.5$). For $m = 0, 1 \text{ and } 2$, the maximum OASPL amplification is around $St_{DF}$ of 0.36, near the jet preferred instability frequency, while the maximum OASPL amplification for $m = 3$ is around $St_{DF} = 0.09$. The cross-stream distribution of noise

**Figure 18:** Comparison between the envelope function (Figure 17) and the streamwise noise source distribution for $m = 0$ (a) and $m = 1$ (b) (Figure 11).
source events tends to change from being localized along the jet centerline when the OASPL is amplified to being rather diffused when the OASPL is attenuated. The streamwise noise source distribution was only sensitive to azimuthal modes around the jet preferred mode. Otherwise, the general trend was that forcing the jet at low $St_{DF}$’s moves the distribution upstream compared to the baseline jet, while forcing at high $St_{DF}$’s results in a source distribution similar to the baseline jet.

The velocity field was conditionally sampled to investigate the correlation of dynamics of the large-scale flow features from forcing to the far-field sound and jet noise sources. When forcing the jet at $St_D$’s higher than the preferred mode, the large-scale flow features appear to grow, saturate, and decay closer to the nozzle exit. When forcing the jet near the preferred $St_D$, the large-scale flow features are very robust in the region of noise generation. The growth, saturation, and decay of the conditionally-averaged velocity terms along the jet centerline correlate well with the far-field results and the noise source distribution. The noise source distribution peaks in the decay region for both $m = 0$ and $m = 1$, and the decay rate is changing near the noise source distribution peak for the two cases.

ACKNOWLEDGEMENTS
The support of this research by NASA Glenn Research Center and by the Ohio Department of Development is greatly appreciated. We would like to thank our colleagues Dr. Igor Adamovich, Dr. Yurii Utkin, Dr. Jim Hileman, Dr. Edgar Caraballo, Jesse Little, Dr. James Bridges, Dr. Jonathan Freund, and Clifford Brown for their assistance in different facets of this research.

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