Effects of excitation around jet preferred mode Strouhal number in high-speed jets

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Abstract It has been widely reported in the literature that the jet preferred mode Strouhal number varies over a large range of 0.2–0.6, depending upon the facility where the measurement is made as well as the measurement techniques and the location in the jet plume where the measurement is taken. This study investigates this wide variation and potential explanations for it. Active flow control is used to show that the jet is receptive to excitation over a large range of Strouhal numbers and azimuthal modes. The wide variation in the preferred mode Strouhal number is shown to be tightly linked to the evolution, spacing, and scale of the coherent flow structures, which dominate the jet shear layer’s development. The low-end of the range is determined by the minimum Strouhal number at which structures begin to interact with one another in the jet plume. Below this range, structures have no significant effect on the plume’s statistical properties. For Strouhal numbers at the high-end of the range, the development of coherent flow structures shifts upstream toward the nozzle exit and the structures disintegrate earlier in the jet plume. The earlier development and disintegration prevent these structures from strongly impacting the entire flowfield. The results imply that upstream perturbations in the flow present in various facilities could be responsible for the variations in the measured jet preferred mode Strouhal number. Experimental results from schlieren imaging and near- and far-field microphone measurements are used to investigate the preferred mode Strouhal number across this range.

1 Introduction

1.1 Overview

The formation and development of coherent flow structures in the shear layer of jet plumes have been studied extensively in the literature. In highly turbulent jet flows, special effort is required to observe the existence and the development of coherent flow structures. The pioneering work of Crow and Champagne (1971) showed the different stages of evolution of flow structures in the jet plumes formed by exciting the jet with various forcing Strouhal numbers and amplitudes. By comparing the fluctuation levels measured on the jet centerline, they showed the existence of a preferred mode Strouhal number around 0.3, which generates the maximum fluctuation levels. Moore (1977) used an instability wave model to describe the evolution of coherent large-scale structures in the jet shear layer. Near the nozzle exit, the jet shear layer undulates, and eventually rolls up into coherent structures. The structures entrain the ambient air into the mixing layer while simultaneously growing and convecting downstream. It was observed that in the turbulent mixing layer (Brown and Roshko 1974), the flow structures gradually grow in scale, merge (often multiple times), and eventually break up further downstream. Additionally, the concept of azimuthal mode and the azimuthally coherent flow structures were investigated experimentally (Cohen and Wygnanski 1987; Fuchs and Michel 1978) and numerically (Plaschko 1979; Tam and Burton 1984). Consequently, it has been known that the flow field and pressure fluctuation levels vary with the presence of structures with different azimuthal modes and Strouhal numbers.

In a free shear layer, the evolution of flow structures is dominated by the shear layer instability with the most amplified Strouhal number \( S_{MA} = f_0/U_{\infty} \) scaling with
the initial momentum thickness ($\theta_\infty$) of the shear layer and the free stream velocity ($U_\infty$) (Ho and Huerre 1984). In the annular shear layer of jet plumes, there is an additional length scale, which is the nozzle exit diameter (D). In the jet shear layer, the evolution of flow structures is dominated by the jet preferred mode or jet column mode Strouhal number ($St_{PM} = f_p D / U_\infty$), which corresponds to the flow structure passage frequency ($f_p$) around the end of jet potential core where the annular jet shear layer merges and interacts. Kibens (1979) showed the relation between $St_{MA}$ and $St_{PM}$ by studying the development and pairing of the flow structures. The recent work (Sinha et al. 2012) explores this further and shows that in the low Strouhal number (impulse) excitation of the shear layer instability, there is no structure interaction or merging. As the Strouhal number increases to periodic excitation, the interaction of structures leads to $St_{PM}$. The value of $St_{PM}$ is measured around the end of the jet potential core and is typically an integer fraction of $St_{MA}$. As the flow structures grow and convect downstream, they go through multiple merging/pairing processes. The measured structure passage Strouhal number is then halved after each stage of pairing, as clearly shown by Kibens (1979) in low Reynolds number (50,000) jets excited with an acoustic driver. Vortex pairing has also been observed in a recent work by Crawley et al. (2016) in high Reynolds number (600,000) jets using plasma actuators for excitation. Additionally, below the critical value of around 125 for D/2$\theta_\infty$, the jet preferred mode Strouhal number is shown to inversely scale with the initial momentum thickness in the shear layer (Drubka 1981; Ho and Hsiao 1983). Across different jet facilities, therefore, any disparate upstream perturbations (Bogey et al. 2012) or boundary layer conditions (Zaman 1985) could affect the natural excitation of the shear layer instability. The development and pairing processes of the coherent structures in the jet shear layer are affected by these disparities in upstream perturbations and result in variations of the jet preferred mode Strouhal number (Chambers and Goldschmidt 1982).

In order to explore the effect of azimuthal modes and Strouhal number on the evolution of coherent flow structures, jet shear layers are excited via one of the several different techniques: acoustic drivers (Zaman and Hussain 1981), glow discharge plasma actuators (McLaughlin et al. 1975), and fluidic injection (Raman and Cornelius 1995), to name a few. There are numerous techniques for jet excitation, but each has different capabilities and limitations. About a decade ago, a class of high-frequency and high-amplitude plasma actuators (Samimy et al. 2007; Utkin et al. 2007) called localized arc filament plasma actuators (LAFPAs) was developed at the Gas Dynamics and Turbulence Laboratory (GDTL) of the Ohio State University. LAFPAs have been shown to perform well in active flow control of high-speed and high Reynolds number flows: e.g., subsonic (Kearney-Fischer et al. 2009) and supersonic (Samimy et al. 2007) jets; as well as subsonic (Yugulis et al. 2014) and supersonic cavity flows (Webb and Samimy 2016); and shock wave and boundary layer interaction (Webb et al. 2013). Eight LAFPAs are distributed around the nozzle exit that provide perturbations to the jet shear layer near the nozzle exit at various azimuthal modes (m=0–3 and m=±1, ±2, ±4) and different Strouhal numbers.

Acoustic drivers, which have been used extensively in the literature, have simple sinusoidal actuation signals. They are, however, limited to low-speed and low Reynolds number flows due to amplitude limitation (Kibens 1979). LAFPAs are high-frequency and high-amplitude devices but with non-sinusoidal actuation signals (Utkin et al. 2007; Samimy et al. 2007), which generate actuation signals at the specified Strouhal number as well as at its harmonics with decreasing amplitude. We had postulated that even when the specified Strouhal number actuation is around the jet preferred mode, we excite the jet shear layer instabilities by higher harmonics of the excitation Strouhal number. After several merging/pairing processes, the flow ends up with structures at the jet column mode Strouhal number. Our most recent work (Crawley et al. 2016) clearly demonstrates this process and shows that the initial jet shear layer is potentially excited by the 3rd or 4th harmonic of the excitation Strouhal number. After three or four stages of vortex pairings, similar to the works of Ho and Huerre (1984) and Kibens (1979) in low-speed flows, the structure passage Strouhal number around the end of jet potential core is reduced to the value of the excitation Strouhal number.

1.2 Objectives

As discussed, varying upstream flow perturbations generated in different jet facilities could potentially cause the observed wide variation of jet preferred mode Strouhal number. Active flow control via LAFPAs provides a unique way to explore and shed some light on this issue. In the present work, jet shear layers are excited over a series of excitation Strouhal numbers and azimuthal modes (axisymmetric, helical, and flapping). The variation of the jet preferred mode Strouhal number is investigated by imaging the flow-field modification and measuring pressure-field amplification.

2 Technical approach

2.1 Facility and instrumentation

The experiments were conducted at the Gas Dynamics and Turbulence Laboratory (GDTL) within the Aerospace Research Center at the Ohio State University.
The jet anechoic chamber facility (Hahn 2011) is a 6.2 × 5.6 × 3.4 m³ room covered with fiberglass wedges designed to have a cutoff frequency of 160 Hz. Figure 1 shows a schematic of the anechoic chamber. The air supply for the high-speed jets comes from three five-stage reciprocating compressors (up to 16 MPa). Air is then filtered, dried, and stored in two cylindrical tanks (43 m³ total in volume). The nozzle is mounted on the end of the plenum. In the current study, a twin-jet nozzle with a nozzle separation distance of 2 exit diameters is used. They are bi-conical converging–diverging nozzles, with a design Mach number of 1.23 and nozzle exit diameter (D) of 19.05 mm (0.75 in.). For the measurements of the single jet of the twin-jet nozzles, the nozzle farthest from the microphone array is capped and completely blocked during the experiments. The fully expanded jet operating condition is primarily examined, which occurs at a jet Mach number ($M_j$) of 1.23 with Reynolds number around 800,000. Additional jet operating conditions are also examined for broader study and documented in Cluts et al. (2016). All the experiments were conducted with a jet total temperature ratio of 1.

The far-field microphone array in the anechoic chamber is shown in Fig. 1. There are 11 B&K 4939 microphones pointing toward the center of the nozzle exit and corresponding to polar angles ranging from 30° to 120° measured from the jet downstream axis. For the twin-jet measurements, the microphone positions are measured from the midpoint between the centerline of the twin-jet nozzles. The individual microphone distances range from 95 to 145 inches (127–193D).

The near-field microphone array in the anechoic chamber is shown in Fig. 2; it consists of a linear array of 12 B&K 4939 microphones. The array is angled at 10 degrees with respect to the downstream jet axis, in order to approximately match the spreading angle of the twin-jet plumes and to keep the array just outside of the jet shear layer. The first microphone is located 1D above the nozzle lipline and 1.5D downstream of the nozzle exit as measured to the center of the microphone tip. Subsequent microphones lie 1.3D from one another as measured along the array. The microphone array is always located along the twin-jet plane as shown in Fig. 2. The near-field microphone locations relative to the midpoint of twin-jet nozzle are depicted in Fig. 3.

Schlieren images of the jet plumes are acquired using a Z-type schlieren system. Two parabolic mirrors 8 inches in diameter with a focal length of 6 ft are used for light collimation. A high-power LED light source (model HPLS-36 from Lightspeed Technologies) with interchangeable LED head (model white 5500 K) is used with an external trigger signal to pulse the light at the desired frequency. A vertical knife edge is mounted for horizontal (axial plane) refractions in the twin-jet plumes. A CMOS camera (1280×960 pixels) with a Nikon 55-mm lens is used to capture the flow images. The resulting spatial resolution is 127 pixels per
nozzle diameter with available viewing range of 8D wide by around 4D tall for the twin-jet plumes. A flash duration of 1 μs is used, which is sufficiently short to study the instantaneous flow features of the jet plumes.

In the baseline jet cases, a B&K 4939 microphone is located on the twin-jet plane 2D away from the inner nozzle lip. This microphone is used to capture the dominant frequency, the screech tone, as the trigger signal for the light source and camera. The microphone signal is bandpass filtered by a signal-conditioning filter manufactured by Kemo (model Bench Master 21 M) around the fundamental frequency of the screech tone. The signal is then processed by an Agilent 33521A arbitrary waveform generator. The Agilent creates a 10 Hz square wave triggered by the rising edge of the roughly sinusoidal filtered signal. The square wave is then fed into a waveform delay generator manufactured by Berkeley Nucleonics (model 565) as the reference timing for the trigger signal. In the waveform delay generator, the delays of both the camera shutter and the flash are accounted for independently with respect to the original trigger signal. In the excited jet cases, instead of the microphone signal, the trigger signal comes from the dedicated LAFP excitation control computer. Under either condition, phase-locked schlieren images are taken. Typically, 200 instantaneous images are acquired and then post-processed in MATLAB to find the images with the highest correlation. The thirty images with the highest correlation are contrast-stretched and averaged. The phase-averaged image filters out the fine-scale turbulence and improves the visualization of coherent flow structures. The phase-averaging also allows clear identification of the interaction mechanisms of the twin-jet plumes.

2.2 Data acquisition

Both near-field pressure and far-field acoustic signals measured by the microphones are conditioned by B&K Nexus 2690 conditioning amplifiers with a built-in bandpass filter from 20 Hz to 100 kHz. The signals are connected to National Instruments PXI-6133 A/D boards and recorded by LabView software. Microphone calibration is performed with a B&K acoustic calibrator, model 4231, and the microphone calibration constants are recorded to provide the conversion from measured voltage to pressure. The sampling frequency is set at 200 kHz, and 819,200 data points were collected for each case. The collected data points are split into 8192 data points per segment. The resultant frequency bandwidth is 24.4 Hz. The Fast Fourier Transform is used to calculate power spectral density for each segment and the averaged values are obtained from these segments. The calculated power spectral density is then converted to sound pressure level (SPL) in decibels. The resultant spectra are non-dimensionalized to SPL per unit Strouhal number. The Strouhal number is defined as $St = fD/c$, where $f_c$ is the characteristic frequency of the jet defined as $f_c = U_j/D_j$; $U_j$ is the jet velocity and $D_j$ is the nozzle exit diameter. The far-field spectra are then propagated to the observer distance of 80 nozzle exit diameters (using spherical propagation assumption). The repeatability of acoustic measurements is within ±1 dB on a daily basis and the accuracy of experimental data is validated by comparing to existing literature (Seiner et al. 1988; Bozak and Henderson 2011).

The phase-averaged schlieren images are processed via MATLAB to identify the streamwise locations of coherent flow structures. From the flow images, a horizontal slice of pixels is extracted and plotted to identify the locations of peak intensity which are the streamwise locations of coherent flow structures. The accuracy of identifying the peak intensity location is approximately ±0.02D (or ±2 pixels) with the spatial resolution of 127 pixels per nozzle diameter. In each jet plume between the top and bottom jet shear layer, five horizontal slices of pixels are used to calculate the averaged streamwise locations of the structures. Only flow images of jet plumes excited with the axisymmetric mode are used with this processing to provide the estimated streamwise locations of coherent toroidal flow structures. The uncertainty of the averaged streamwise location of the structures is less than ±0.1D.

2.3 Brief description of localized arc filament plasma actuators (LAFPAs)

Jet excitation is performed by LAFPAs, which are high-frequency and high-amplitude devices used for flow control. Originally developed at the GDTL for the purpose of controlling and studying high-speed and high Reynolds number flows, each actuator consists of two 1-mm Tungsten electrodes. These electrodes are arranged such that their tips are approximately 3 mm apart from one another on the inner surface of the nozzle just upstream (1 mm) of the nozzle exit. A plasma generator, controlled by a dedicated computer, then generates a high voltage and ramps it up to 7 kV, at which point air breakdown between the electrodes occurs and an arc forms across the gap of the electrodes. This arc causes localized heating of the flow leading to perturbations for excitation of jet shear layer instabilities. The current maximum frequency is limited to 20 kHz by the power supply’s cooling system. The power supply is currently being upgraded to increase the frequency to about 60 kHz. The excitation Strouhal number is defined as $St_{DF} = f_e D_j/U_j$, where $f_e$ is the forcing/excitation frequency. Because the characteristic length scale of a jet is the nozzle exit diameter, the excitation Strouhal number is designated as $St_{DF}$ where the subscript letter D refers to the characteristic length scale and F means the forcing (or excitation) Strouhal number.
As discussed earlier in Sect. 1.1, when the excitation Strouhal is around the jet preferred mode, the jet shear layer instability is excited by the higher harmonics of the excitation Strouhal number, but the structures go through 3 to 4 pairings and end with structures at the excitation Strouhal number (Crawley et al. 2016). The merging/pairing process is quite similar to those observed in the low-speed and low Reynolds number jets (Ho and Huerre 1984; Kibens 1979).

A total of eight actuators are evenly spaced around each nozzle just upstream of the exit. Since there is no preferred rotation direction and a helical mode could take either direction, the clockwise direction at the nozzle exit is designated as the positive rotation direction for helical modes during excitation. This excitation configuration allows for several different azimuthal modes to be generated. In the current paper, the experimental results mainly show the excitation from three most commonly used azimuthal modes: axisymmetric mode (m = 0), helical mode (m = 1), and flapping mode (m = ±1). For sinusoidal actuation, the flapping mode results from superposition of m = 1 and m = −1. In the current work, the actuation is not sinusoidal, but we can still mimic the flapping mode (Samimy et al. 2007). In comparison to the single jet case with two parameters of frequency and azimuthal mode, the twin-jet has actuators for both nozzles (a total of 16 actuators), introducing two additional parameters of phase angle (ϕ) and direction of azimuthal mode, which can be independently controlled for each nozzle. This opens a range of possible control schemes to be explored in the future. In the current paper, the excitation parameters are identical for each twin-jet nozzle, except for the phase between the two jets, as discussed in Sect. 3.3. For further information on LAFPAs, see Samimy et al. (2007) or Utkin et al. (2007).

3 Results and discussion

3.1 Effect of excitation on the near-field pressure fluctuations

Near-field pressure fluctuations were measured to evaluate the effect of excitation around the jet preferred mode Strouhal number on the jet. The pressure and the actuator trigger signal were simultaneously acquired to allow phase-averaging. Figure 4 presents the examples of the phase-averaged pressure obtained from the $M_j$ 0.9 jet excited with axisymmetric mode at two excitation Strouhal numbers: impulse and periodic excitation regimes. The trigger signal is plotted along with the measured pressure to identify the actuation cycle (shown with small triangle symbols) for phase-averaging, as shown in Fig. 4. The phase-averaged pressure is plotted on top of the measured time-resolved pressure. Sinha et al. (2012) showed that in low Strouhal number excitation, there is an impulse response in the pressure fluctuations (Fig. 4a) and when the excitation Strouhal number is increased, the response becomes periodic (Fig. 4b).

To further explore the trends present in the jet response, the ratio between the period of the pressure waveform (shown by the small circles in Fig. 4) and the period of the trigger signals (the triangle symbols) is plotted in Fig. 5 versus the excitation Strouhal number. A low value of this ratio indicates an impulse jet response, but the response becomes periodic as the ratio approaches 1. The ratio increases with the excitation Strouhal number and saturates after a Strouhal number of 0.1, which agrees with the results of Sinha et al. (2012). The excitation with varying Strouhal numbers is, therefore, divided into the impulse perturbation and the periodic perturbation. Figure 6 presents a comparison of the near-field pressure spectra, measured in the $M_j$ 0.9 jet excited with axisymmetric mode at
Strouhal numbers of 0.02, 0.15, and 0.35. In each excitation case, the spectrum from the excited jet is plotted on top of that of the baseline jet. At the lowest Strouhal number (impulse) excitation, there is no statistically significant pressure amplification aside from the tonal noise appearing at the excitation Strouhal number and its harmonics. The periodic perturbation cases (Strouhal numbers of 0.15 and 0.35) show significant pressure amplification across a wide range of Strouhal numbers in addition to the tonal noise mentioned above. The maximum pressure amplification is observed with the excitation Strouhal number of 0.35 (Crawley et al. 2015). This example illustrates the difference between the impulse and periodic perturbations. The results also agree with the results in the literature on the low-end of the jet preferred mode Strouhal number range, where the upstream flow perturbations begin to effectively modulate the jet shear layer and the jet plume.

3.2 Effect of excitation on the coherent flow structures in the jet

Jet flow images were acquired via schlieren to evaluate the effect of excitation around the jet preferred mode Strouhal number. The flow images were phase-locked to the trigger signal of the actuators to provide phase-averaged flow images at various phases. Figure 7 presents the schlieren images of the baseline $M_j = 1.23$ jet and the excited jet with axisymmetric mode excitation at four representative excitation Strouhal numbers from 0.1 to 0.8. A low supersonic jet was used for flow imaging to increase the density gradient and image contrast. However, the difference in the compressibility level, typically evaluated using convective Mach number, between the two jets is relatively small and the results are expected to be similar based on our previous work in high subsonic and low supersonic jets (Samimy et al. 2007, 2012). The excited jet cases feature two flow images with a phase difference of 180 degrees. The effect of excitation on the appearance of coherent flow structures is clear when compared to the unexcited case. Excitation with a low Strouhal number of 0.1 (Fig. 7b) results in one dominant large-scale structure developing and convecting downstream in the jet plume. When the excitation Strouhal number is raised to 0.3, consecutive large-scale structures develop in the jet plume as shown in Fig. 7c. These coherent flow structures grow and decay/disintegrate as they convect downstream (Crawley et al. 2016). As the excitation Strouhal number continues to increase, the development and subsequent disintegration of coherent flow structures gradually shift upstream in the jet. Additionally, the spacing between them is decreased (Fig. 7d, e).

The axial positions of observed coherent flow structures are extracted, as discussed in Sect. 2.2, and summarized in Fig. 8. Two symbols represent the two axial positions at two different phases (0° and 180°). In the case of excitation Strouhal number of 0.1, the coherent flow structures are widely spaced in the jet plumes with no chance for any interactions between them; therefore, this case is characterized as the impulse response to the excitation (see Fig. 4a). As the excitation Strouhal number increases, the structures get closer to each other and increase the possibility of interaction; therefore, this case is referred to as the periodic response to the excitation (see Fig. 4b). The streamwise location and distance between the observed coherent flow structures vary widely as the excitation Strouhal number is changed. The observed axial positions, however, progressively move upstream with reduced structure spacing.

![Fig. 5 Ratio of time period between the phase-averaged pressure waveform and the trigger signal as a function of excitation Strouhal number](image1)

![Fig. 6 Near-field pressure spectra measured at x/D=3 from the $M_j = 0.9$ jet excited with axisymmetric mode at various excitation Strouhal numbers](image2)
as the excitation Strouhal number increases. The observation holds for either one of the two phases shown in Fig. 8. In the case of the excitation Strouhal number of 0.8, the observed structures are much smaller, closer to each other, and decay upstream of the end of potential core (Fig. 7e). With this earlier decay of the coherent structures, they lose their dominance in the jet plume, which implies an upper limit on the jet preferred mode Strouhal number. Further analysis will show the impact of upstream shifted flow structures on far-field acoustic spectra.

Figure 9 shows the averaged structure spacing ($\lambda/D$), normalized by the nozzle exit diameter as a function of the excitation Strouhal number. The results are curve-fitted to the equation $\lambda/D = 0.67/St_{DF}$. This curve is also compared with an equation previously derived using PIV measurements to locate the coherent structures (Samimy et al. 2012). Both curves show an inverse relationship between
structure spacing and excitation Strouhal number and closely match one another, even though one is obtained using quantitative and another qualitative data. Convective velocity of the structures can be obtained using this calculated wavelength and the excitation Strouhal number. The convective velocity normalized by the jet exit velocity is 0.67, which falls well into the range of the values obtained via other optical techniques (Kearney-Fischer et al. 2011; Kuo et al. 2012a). From this empirical relationship, the structure spacing is determined to be between 3D to 1D for the jet preferred mode Strouhal numbers of 0.2–0.6.

The effect of excitation near the jet preferred mode Strouhal number is examined with helical and flapping mode excitation as well. Figure 10 presents the schlieren images of the $M_j$ 1.23 jet excited with two azimuthal modes at excitation Strouhal numbers of 0.3, 0.5, and 0.8. The streamwise region of the coherent flow structures and the structure spacings still correspond well with the excitation Strouhal number, similar to the results with axisymmetric mode excitation shown in Fig. 7. Among the three azimuthal excitation modes, the flapping mode incurs the most significant impact on the flow field including the highest jet spreading rate (Kim and Samimy 2009) and the substantial distortion of jet plumes (Gaitonde and Samimy 2011).

The effect of excitation at various azimuthal modes is further studied with far-field acoustic measurements. Figure 11a shows representative far-field spectral comparisons of the $M_j$ 1.23 jet for baseline and various excited cases with flapping mode excitation at a polar angle of 60°. Figure 11b shows the difference of the sound pressure level between excitation cases and the baseline case. It has been known in the literature that dynamics of large-scale structures in the jet shear layer make significant contributions to the peak far-field noise, primarily at shallow angles to the jet axis (Tam 1995). While more far-field spectral comparisons at other polar angles can be found in Cluts et al. (2016), the 60° polar angle is selected in Fig. 11 due to the clear and significant effects of various excitations. In the baseline spectrum, the screech tone peak is around Strouhal number of 0.55. In the spectra of the various excitation Strouhal number cases, the natural screech tone disappears and is replaced by the excitation tone and its harmonics. Depending on the value of the excitation Strouhal number and the azimuthal mode, there are varying levels of noise amplification and shifting of the peak Strouhal number. At the excitation Strouhal number of 0.3, maximum amplification is observed. This maximum amplification occurs in the flapping mode excitation in comparison to the other modes, shown in Fig. 11b. As the excitation Strouhal number increases, the peak Strouhal number and noise amplification shift toward higher Strouhal numbers. From the flow-field results, the coherent flow structures in the jet shear layer gradually move towards the nozzle exit. The higher frequency noise components are shown to emit from streamwise locations nearer to the nozzle exit (Kuo et al. 2012a).
On the contrary, the low frequency noise radiates from farther downstream around the end of the jet potential core. This clearly illustrates the connection between the high-frequency noise amplification and the upstream shift of the coherent flow structures.

The contour of far-field sound pressure level variations caused by flapping mode excitation of the jet at various Strouhal numbers is shown in Fig. 12. The area of significant variations of sound pressure level is approximately between excitation Strouhal numbers of 0.2–0.6 (with the level of variation higher than 3 dB) and centered around an excitation Strouhal number of 0.3. As the excitation Strouhal number is increased to 0.8, the level of variation is significantly decreased.

### 3.3 Further discussion of the effect of excitation

Jet shear layer is highly susceptible to perturbations within a certain range of Strouhal numbers as illustrated in the excited single jet experiments. While all the perturbations were within the nozzle (just upstream of the nozzle exit), perturbations could stem from the upstream flow, within or upstream of the nozzle, or downstream and outside the nozzle. We will demonstrate the latter using a twin-jet in the present work. The presence of the second jet within the pressure and acoustic fields of the first jet in a twin-jet configuration could subject both jets to excitation from one another and cause interaction and coupling of the jets. The level of twin-jet coupling, if both subjected to the same upstream conditions or excited at the same Strouhal number, is shown to depend primarily on the azimuthal mode excitation of that jet shear layer, as demonstrated by our group (Kuo et al. 2017) and others (Raman and Taghavi 1998).

Figure 13 presents the schlieren images of twin-jet plumes without excitation (baseline) at various jet Mach numbers with a 2D center-to-center separation distance between the two nozzles, where D is the nozzle exit diameter. The images were taken on the twin-jet plane where the twin-jet coupling primarily takes place. At the lowest jet Mach number case with $M_j = 1.15$ (Fig. 13a), the twin-jet plume is dominated by the axisymmetric mode. The coherent toroidal flow structures are clearly observed in both jets at very similar streamwise locations. In the second case with $M_j = 1.23$ (Fig. 13b), the plumes are dominated by the helical mode and seem to interact out of phase with one another. In the last case with $M_j = 1.3$ (Fig. 13c), the twin-jet plumes are strongly modulated by the flapping mode.
The appearance of coherent flow structures at very similar streamwise locations and phase-locking of the structures indicate distinct coupling of the two jets. Additionally, the acoustic measurements of the twin-jet plumes show that the most significant pressure amplification occurs when the flapping mode is present (Cluts et al. 2016).

To explore the effects of downstream of the nozzle excitation of a jet, a series of schlieren images were taken in the $M_j$ 1.3 single-jet and twin-jet excited with axisymmetric mode excitation. The jet at this jet Mach number exhibits a baseline dominant flapping mode (Fig. 13c). The excitation is able to excite the jet shear layer, significantly altering the baseline flow behavior. Figure 14a, b shows the single jet excited at Strouhal number of 0.3 with axisymmetric mode and twin-jet both jets excited at Strouhal number of 0.3 with axisymmetric mode at the same phase. For each jet plume, the coherent toroidal flow structures are clearly observed at similar streamwise locations. The excited twin-jet plumes now behave more like the axisymmetric mode than the flapping mode of the baseline. Figure 14c illustrates twin-jets, still excited at Strouhal number of 0.3, but there is a phase difference of 180° between the excitation of the two jets. The coherent toroidal flow structures are still observed, but they are smaller and moved further upstream in the jet shear layer, in comparison with those in Fig. 14b. This is clearly caused by the phase shifting in the actuation of the two jets and thus the effects of excitation from the neighboring jet on one another. As shown in Fig. 15, the structure spacing is halved, which is as if the jets were excited...
at a Strouhal number of 0.6, but at the same phase. As another example, Fig. 14d presents the twin-jet excited at a Strouhal number of 0.15 with a phase difference of 180 degrees between the two jets. The coherent toroidal flow structures are observed at nearly identical locations and spacing to those in Fig. 14b. Again, this is caused by the excitation from the neighboring jet, and the resultant twin-jet plumes behave like the jet were excited at a Strouhal number of 0.3 but the same phase.

The axial positions of the observed coherent flow structures from Fig. 14 are extracted and plotted in Fig. 15a. In the cases of both the single- and twin-jet, each excited at a Strouhal number of 0.3 with the same phase, their averaged structure spacing is nearly identical, as shown in Fig. 15b, with a structure spacing around 2.2D. This structure spacing matches that of the twin-jet excited at half the Strouhal number (St_{DF} = 0.15) but with each jet 180 degrees out of phase, which is also shown in Fig. 15a for comparison. However, with the original excitation Strouhal number of 0.3 but with the 180 degree phase difference between the two jets the number of structures is doubled. The empirical curve of structure spacing versus excitation Strouhal number (shown in Fig. 9 for single jet, λ/D=0.67/St_{DF}) is plotted for comparison. The averaged structure spacing values for the two twin-jets excited with a phase difference of 180 degrees are estimated to be 1.1D (with excitation Strouhal number of 0.3) and 2.2D (with excitation Strouhal number of 0.15). These points are plotted on the empirical curve based on these measured structure spacings. These representative cases illustrate the potential effect of excitation from the neighboring jet and the likely interaction of multiple excitations. While such an external jet excitation is not believed to be the cause of variation in the jet preferred Strouhal number in the literature, these results were presented to show how sensitive these flows, which have natural instabilities, are to excitations of various types.

4 Conclusions

There has been controversy about the value of the jet column mode (or preferred mode) Strouhal number measured across various jet facilities. The current results indicate that potentially low-level natural perturbations in any facility could cause disparate evolution and development of flow structures convecting downstream and result in a different jet preferred mode Strouhal number. Overall, there is a wide range of Strouhal numbers where the jet shear layer could be perturbed and significant pressure variations observed as a result of the perturbations. From measurement of near-field pressure waveforms, excitation causes either impulse or periodic responses of the jet depending on the value of the excitation Strouhal number. In the low Strouhal number excitation with impulse perturbation, no significant statistical pressure variations are measured. Significant pressure amplification is measured when the excitation Strouhal number increases, resulting in periodic perturbation. The Strouhal number where the onset of periodic perturbation occurs agrees with the observed low-end value of the jet preferred mode Strouhal number. This is the point at which the upstream flow perturbations begin to effectively disturb and modulate the jet shear layer. From flow-field imaging, the impulse perturbation only causes one clear and dominant large-scale structure to develop and convect downstream in the jet plume. Conversely, the periodic perturbation results in a cascade of coherent flow structures that develop and convect downstream and thus change the statistical properties of the jet. While the

![Fig. 15](image)

Fig. 15 Relationship between excitation Strouhal number (St_{DF}) and structure spacing (λ/D): a Streamwise locations of coherent flow structures obtained from schlieren images. b Comparison of coherent structure spacing with the single jet results shown in Fig. 9.
excitation Strouhal number keeps increasing, the streamwise extent of the observed coherent flow structures shifts towards the nozzle exit, and disintegrate rapidly and further upstream. Once the Strouhal number is high enough the structures no longer significantly impact the entire plume and mark the high-end value of the jet preferred mode Strouhal number. The evolution and development of coherent flow structures are shown to contribute to the wide variation of the jet preferred mode Strouhal number.

In the twin-jet experiments, the twin-jet shear layers are separately perturbed to illustrate the impact of various perturbations and the mutual interaction of the jets. Twin-jet shear layers are excited at the same Strouhal number but with a phase difference of 180° between the two nozzles. Due to the mutual interaction, the resultant flow field of the twin-jet plumes has coherent structures as if both jet shear layers were excited at twice the Strouhal number. The twin-jet results illustrate the effect of excitation from both internal and external perturbations and the interaction of the twin-jet plumes.

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References

Hahn C (2011) Design and validation of the new jet facility and anechoic chamber. Thesis, The Ohio State University
Zaman K (1985) Effect of initial condition on supersonic jet noise. AIAA J 23(9):1370–1373