Exploring Physics and Control of Twin Supersonic Circular Jets

Ching-Wen Kuo, Jordan Cluts, and Mo Samimy
The Ohio State University, Columbus, Ohio 43235

DOJ: 10.2514/1.2054377

The closely spaced twin-jet configuration often seen in military aircraft is distinct from the single jet in both the flowfield and acoustic field. The twin-jet plumes interact with each other weakly or strongly, depending upon the distance between the two jets, the jet operating flow regime, and the Mach number. In this study, the interaction mechanisms and coupling of a supersonic twin jet exhausting from biconical converging–diverging nozzles with design Mach number of 1.23 at a separation distance of two nozzle exit diameters are investigated using near-field pressure measurements and phase-locked flow visualization. Across a series of jet operating Mach numbers, the twin-jet plumes feature three major jet azimuthal modes: axisymmetric, helical, and flapping. The jet flapping mode is strongly augmented in the twin-jet configuration compared to the single-jet case. Along the twin-jet plane, which is also the plane of the jet flapping direction, jet plumes with coherent flow structures are observed to move up and down. Because of the nature of the jet flapping motion, the near-field pressure fluctuations are markedly amplified at low Strouhal numbers, particularly along the twin-jet plane for further downstream locations where the coherent structures are developed and large. Localized arc filament plasma actuators are implemented as an active flow control tool on both nozzles, just upstream of nozzle exit, to explore the coupling mechanisms. The results show that decoupling and coupling of twin-jet plumes can both be achieved, depending on the jet operating condition and the excitation parameters employed.

I. Introduction

A TWIN-JET configuration (that is, two jets issuing roughly parallel to one another and at a relatively small distance from one another) is currently present in a variety of military aircraft, such as the F/A-18 and F-15. These twin-jet configurations cause the jets to interact and behave differently from a single jet in terms of noise directivity and jet plume development. For example, such interaction has led to nozzle damage of the F-15 and B-1 aircraft. During the development of the B-1A aircraft in the 1980s, the prototype aircraft faced durability issues of the structural components of the engine nozzle. In particular, the external flaps of the trailing edge of the engine nozzle were found damaged. In wind-tunnel tests conducted at NASA Langley Research Center with a 6%-scale B-1 propulsion model with a jet exit Mach number of 0.9, Berndt [1] found that there was a discrete tone appearing in the near-field pressure spectra in nearly all of the sensors installed in the region between the twin-jet nozzles. He determined that a discrete tone with strong magnitude was detrimental if the frequency was close enough to the natural frequency of a structural component. This caused so-called sonic fatigue [2] (or acoustic fatigue), which could lead to structural failure.

To prevent the structural failure of the external flap of the engine nozzle by avoiding the discrete tone forming in the engine surroundings, the upgraded B-1B aircraft had a fairing and vane between the engine nacelles. The purpose of the fairing and vane was to aerodynamically direct the freestream from below the engine into the internozzle region.

In twin-jet plumes, there are three major flow regions [3]: converging, merging, and combining. The converging region [4] begins at the nozzle exit and ends around 5 to 15 nozzle exit diameters downstream, depending on the jet Mach number and the nozzle separation distance. In the converging region, the twin-jet plumes begin to bend toward each other and eventually merge into an elliptical jet plume (merging region) [5]. Due to the inward bending of twin-jet plumes, particularly in the underevaporated jet regime, the shock cell structures are altered as well. Further downstream, the twin-jet plumes transform into a nearly circular jet plume and the position of maximum jet velocity shifts from the individual jet centerline axes to the centerline of the merged plume (combined region). After the twin-jet merging region, the twin-jet spreading angle is found [6] to be less than that of a single circular jet.

The region immediately between the nozzles is of particular interest due to the presence of aircraft structures as well as the complex flow phenomena that can occur there. Between the twin-jet plumes, before they merge, a small region of reversed flow can occur. With appropriate aerodynamic design and considerations on the inner fairing [7] of the twin-jet nozzle afterbody, the merging point of the twin-jet plumes could be shifted downstream with less nozzle afterbody drag. The dynamic pressure loading on the engine nacelle could also be reduced to avoid structural fatigue. As long as the aerodynamic interaction of the twin-jet plumes is interrupted, the coupling of the jets and accompanying sonic fatigue can be reduced or eliminated.

From military aircraft to the latest concepts for future commercial aircraft [8], many aircraft will be designed with highly integrated engines including multiple jets separated by one to six nozzle diameters: some close enough for jet interaction effects to occur. Noise concerns have long been an issue on aircraft, especially for...
high-powered military aircraft during takeoff from an aircraft carrier. In the twin-jet configuration, the noise directivity of twin jets is not azimuthally symmetric like a single jet. To estimate the noise due to the coupling of the twin jet, the noise level of the single jet plus 3 dB is used, which is equivalent to the noise emitted from two identical but without any interaction single jets. As a result of the converging and interacting twin-jet plumes, noise amplification is observed on a plane normal to the twin-jet plane, as compared to the single jets plus 3 dB. In the twin-jet plane, and particularly for downstream polar angles, however, there is a noise benefit (up to 3 dB noise reduction) compared to the noise level of two incoherent single jets. This noise reduction, known as acoustic shielding, is due to the acoustic refraction and reflection in the inner region of twin-jet plumes. Kantola [9] conducted a thorough experimental study of the far-field noise characteristics of twin jets and provided the analysis of the onset frequency of acoustic shielding and the half-angle of the cone of acoustic shielding. The effect of acoustic shielding varies with twin-jet nozzle spacing. To investigate the acoustic shielding effect of twin-jet engine designs, there have been full-scale engine tests [10] to evaluate the far-field noise benefit during aircraft takeoff. As aircraft engine design evolves, the latest twin-jet study involves the acoustic properties near a hybrid wing-body shield [11] and the noise impact of twin rectangular jets [12]. Because of the broad range of twin-jet spacing, nozzle geometries, and jet Mach numbers, the noise directivity and characteristic of twin jets are complex and varied.

In the supersonic jet regime, there is a tonal noise component called screech [13]. Screech appears as a discrete tone (and often with its harmonics) in the acoustic spectrum and often is accompanied by broadband noise amplification. Screech tones are formed during off-design nozzle operation when acoustic waves, generated by interaction of the shock waves and naturally occurring large-scale structures in the shear layer of the jet, travel upstream around the jet plume. These upstream traveling waves interact with the receptive region of the plume, reinforcing the generation of large-scale structures in the jet. There are multiple modes of screech tone (axisymmetric, helical, and flapping), depending on jet Mach numbers [14]. At certain jet Mach numbers with a dominant screech mode, the acoustic waves traveling upstream around the twin jet could couple the twin-jet plumes and significantly augment noise levels.

Seiner et al. [15] investigated the high dynamic pressure loading associated with twin-jet plume interaction in model-scale and full-scale F-15 engine nozzles [16]. The interaction and oscillation patterns [17] of twin-jet plumes are correlated to various jet azimuthal modes in jets with screech. The flapping mode is found [18] to be the most prevalent in coupled twin-jet plumes and causes twin-jet plumes to flap laterally along the twin-jet plane. With appropriate flow control devices [19], suppression of the screech and decoupling of the twin-jet plumes interaction can occur. By decoupling, the amplitude of screech tones is significantly reduced. Additionally, the coherent large-scale flow structures in the twin-jet plumes are significantly fragmented [20].

As in the twin circular jets, there are multiple screech modes in twin rectangular jets with high-aspect-ratio nozzles. Due to the changes in nozzle geometry, the resulting coupling phenomena [21] in twin rectangular jets is markedly different from twin circular jets. Raman et al. [22, 23] have extensively studied the resonance mode of twin rectangular jets with a nozzle aspect ratio of five and twin-jet spacing ranging from 5.5 to 15, based on the minor jet axis of the rectangular nozzle. In twin circular jets [15], coupled plumes induce acoustic waves traveling upstream only along the twin-jet plane. On the contrary, in twin rectangular jets [24], twin-jet coupling induces acoustic waves primarily in the plane normal to the twin-jet plane. This causes different acoustic directivity due to coupling between circular and rectangular nozzle cases. It is evident that the nozzle geometry plays a crucial role in the coupling effect of twin-jet interaction. In this paper, the fundamental interest is to investigate the interaction mechanism of twin-jet plumes as well as an attempt to highlight the flapping mode, resulting in the strongest coupling for twin circular jets.

To achieve a better understanding of noise generation mechanism and noise mitigation, significant efforts have been put to the development of active jet control to alter the development of jet plumes. It is believed that, by actively controlling the noise generation mechanism, it is possible to alter the noise level, directivity, and frequency content. Over the past several years [25], a class of plasma actuators called arc filament plasma actuators (LAFPAs) has been developed and matured at the Gas Dynamics and Turbulence Laboratory of The Ohio State University. With eight plasma actuators distributed uniformly around the nozzle exit, LAFPAs have experimentally demonstrated jet mixing enhancement, generation of various azimuthal modes, and jet noise suppression; and they have been a significant tool in exploring the understanding of flow and acoustic physics. Based on these findings, this work aims to extend the control authority established in single jets to the twin-jet regime. Using active control provided by LAPFA excitation of twin jets, the primary objective of this paper is to investigate the natural phenomenon of twin-jet coupling and search for a control technique to affect the behavior of twin-jet interaction.

II. Technical Approach

A. 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 (OSU). The jet anechoic chamber facility [26] was a 6.2 × 5.6 × 3.4 m 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 high-speed jets came from three five-stage reciprocating compressors (up to 16 MPa). Air was then filtered, dried, and stored in two cylindrical tanks (43 m³ total in volume). The nozzle was mounted on the end of the plenum, and the facility could accommodate nozzles with exit diameters up to 5.080 cm (2 in.). In the twin-jet study, three twin-jet configurations were built with nozzle separation distances of two, three, and four nozzle exit diameters. This work focuses more on military application, where the nozzle separation distance is quite small. In the current paper, therefore, only experimental results from twin-jet nozzles with a nozzle separation distance of two nozzle exit diameters are shown. An example of a twin-jet nozzle is shown in Fig. 2. They are biconical converging–diverging nozzles, with a fully expanded Mach number of 1.23 and a nozzle exit diameter D of 1.905 cm (0.75 in.). The nozzle lip thickness is 0.76 cm (0.3 in.), and the ratio of nozzle lip thickness to nozzle exit diameter is 0.4, which is large compared to practical
applications. The reason for this compromise in nozzle geometry is the implementation of active flow control devices in the model scale nozzle. The potential effects of this thick nozzle lip on screech tone amplitude will be discussed later.

In the early stages of designing the twin-jet nozzle with various nozzle separation distances, two different nozzle geometries were considered: one with an s-duct similar to the design used at NASA [11, 27], and one with a straight duct connected to the upstream plenum. The s-duct geometry was considered in order to replicate the nozzle geometry used at NASA, allowing for comparisons of the results from the two facilities. The second design was considered as an alternative for ease of manufacturing. Numerical simulations were performed to aid in selecting one of the designs. The Reynolds-averaged Navier–Stokes (RANS) simulations with the $\kappa$-$\epsilon$ turbulence model and an implicit time-marching scheme were used for these simulations [28]. The selection criteria were 1) no flow separation within the ducts, and 2) uniform flow distribution at the nozzle exit plane. The results of RANS simulations indicated a minor decrease in the level of turbulent dissipation in the s-duct geometry. This indicated possible flow separation in the s-duct. The contours of the jet Mach number and pressure distribution at the nozzle exit plane for two geometries, however, did not present any distinct difference. It was concluded that the flow in the two geometries did not significantly differ from one another; hence, either of the geometries could be used for the current research. In the end, the geometry with a straight duct was selected for its simplicity and ease of manufacturing.

The far-field microphone array installed in the anechoic chamber is shown in Fig. 1. There are 11 B&K 4939 1/4 in. microphones pointing toward the center of the nozzle exit and corresponding to polar angles ranging from 30 to 120 deg measured from the jet downstream axis. For the twin-jet study, 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 in. (127D to 193D). For the measurements of the single-jet mode of the twin-jet nozzles, the nozzle farthest from the microphone array is blocked during the experiments.

The near-field microphone array installed in the anechoic chamber is shown in Fig. 3; it consists of a linear array of 12 B&K 4939 1/4 in. microphones. The array is angled at 10 deg with respect to the downstream jet axis, in order to approximately match the spreading angle of the twin jet and to keep the array outside of the jet mixing layer. The first microphone is located 1D above the nozzle lip line and 1.5D downstream of the nozzle exit, as measured to the center of the microphone tip, as shown in Fig. 4 where the array is at an azimuthal angle of $\phi = 0$ deg relative to the twin-jet nozzle. Subsequent microphones lie 1D from one another as measured along the angled array. For the measurements from the single nozzle of the twin-jet nozzles, the farthest nozzle from the microphone array is blocked during the experiments. Varying azimuthal angles between the twin-jet nozzle and the array are obtained by rotating the nozzle assembly to different orientations. The near-field array is always stationary relative to the midpoint of the twin-jet nozzle for any given azimuthal angle. When the azimuthal angle is changed, the jets move relative to the stationary microphone array. The microphone locations relative to the fixed midpoint of the twin-jet nozzle are depicted in Fig. 4, which also shows the relative locations to the nearest jet centerline for the two azimuthal angles: $\phi = 0$ and 90 deg. This varying distance leads to changes in the pressure level measured by microphones at different azimuthal angles (or along various planes).

Schlieren images of jet plumes are acquired by using a Z-type schlieren system. Two parabolic mirrors, 8 in. in diameter with a focal length of 6 ft, are used for light collimation. A high-power light-emitting diode (LED) light source (model HPLS-36 from Lightspeed Technologies) with interchangeable LED heads (model white 5500 K) is used with an external trigger signal to pulse the light at 1 $\mu$s at the desired frequency. A vertical knife edge is mounted for horizontal (axial direction) refractions in the twin-jet plumes. A complementary metal-oxide-semiconductor camera (1280 x 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 an available viewing range of 8D wide by around 4D tall for twin-jet plumes. The flash
duration is $1 \, \mu s$, which is short enough to study the instantaneous flow features of the twin-jet plumes. In the baseline twin-jet schlieren imaging, a B&K 4939 1/4 in. 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 schrec 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 21M) around the fundamental frequency of the schlieren 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 twin-jet cases, instead of the microphone signal, the trigger signal comes from the dedicated computer for LAFPFA excitation. Under either condition, phase-locked schlieren images are acquired. Typically, 200 instantaneous images are acquired and then postprocessed in MATLAB to find the images with the highest correlation. The 30 images with the highest correlation are contrast-stretched and averaged to produce clear and sharp images. This allows identification of the interaction mechanism of the twin-jet plumes.

B. 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 the equivalent pressure. The sampling frequency is set at 200 kHz, and 819,200 data points are collected. The collected data points are split into 8192 data points per segment. The resultants frequency bandwidth is 24.4 Hz. The fast Fourier transform is calculated in each segment, and the averaged values are obtained from these segments. The calculated power spectral density is then converted to decibels. The resultant spectra are nondimensionalized to sound pressure level (SPL) per unit Strouhal number. The Strouhal number is defined as $St = f D / U$, where $f$ is the characteristic frequency of the jet defined as $f_c = U / D_1$; $U$ is the jet velocity; and $D_1$ is the fully expanded diameter of the jet. The far-field spectra are then propagated to the observer distance of 80 nozzle exit diameters (using spherical propagation assumption) as a standard format in this paper. The repeatability of acoustic measurements is within $\pm 1 \, \text{dB}$ on a daily basis, and the accuracy of experimental data is validated by comparing to existing literature [15,16].

C. Experimental Operating Conditions

Four jet operating conditions were examined: the Mach numbers $M_f$ of 1.15, 1.23, 1.3, and 1.4. Initially, a series of jet Mach numbers from 1.05 to 1.5 with intervals of 0.05 were tested. After a detailed analysis of the acoustic measurements, those four jet Mach numbers were selected to reflect the different flow behaviors observed in the twin-jet plumes. All the experiments were conducted with a jet total temperature ratio of one and acquired primarily at two azimuthal angles ($\phi = 0$ and 90 deg) along the twin-jet plane and the plane normal to the twin-jet plane, respectively. Acoustic measurements and schlieren visualization were both taken in the baseline twin-jet and excited twin-jet cases.

Excitation of the twin jet is performed by LAFPAs: high-frequency and high-amplitude devices used for flow control. Originally developed at the GDTL for the purpose of controlling and studying single jets, 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 input signal 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 instabilities. These pulses can be controlled accurately at rates up to 20 kHz. Each individual twin-jet nozzle has a total of eight actuators evenly spaced around the nozzle just upstream of the exit. This configuration allows for several different azimuthal modes to be generated. These modes range from the axisymmetric mode ($m = 0$) up to helical modes ($m = 3$), as well as mixed modes such as the flapping mode ($m = \pm 1$). 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 the phase angle and direction of the helical 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 unless mentioned specifically.

III. Results and Discussion

The closely spaced, nearly parallel twin-jet configuration is commonly seen in military aircraft. In such an arrangement, jet plume interaction can occur weakly or strongly, depending upon the jets operating conditions. The focus of this paper is to investigate and provide a better understanding of the interaction mechanism of twin-jet plumes using plasma actuators as a flow diagnostic tool. Section III.A briefly presents and discusses the far-field noise directivity of twin-jet plumes and highlights the role of screech tones in the twin-jet plume interaction. Section III.B presents flow images of the twin-jet plumes for various jet Mach numbers. These images well depict the flow behavior in the inner region of the plumes. The near-field pressure fluctuations are examined to study the disparate levels of flow dynamics induced by the twin-jet plumes under various jet azimuthal modes. The results of single-jet excitation by LAFPAs, acting as a flow diagnostic tool, are discussed in Sec. III.C. The effects of excitation parameters (including Strouhal number and excitation mode) are investigated and summarized in Sec. III.D. With fundamental understanding of the natural features of supersonic twin-jet plumes, Sec. III.E demonstrates active control capability on twin-jet plumes. Both the decoupling and coupling of twin-jet plumes are presented and discussed. Among three major azimuthal modes (axisymmetric, helical, and flapping) of the jet plumes, the flapping mode, inducing a flapping motion of the coupled twin jet, is found to be the most critical one and responsible for the strong twin-jet coupling.

A. Acoustic Far-Field Characteristics of Supersonic Twin Jet

There is significant noise directivity of a twin jet in azimuthal angles, in addition to polar angles in single jets. This is due to acoustic shielding along the twin-jet plane and noise amplification along the plane normal to the twin-jet plane. Figure 5 shows the far-field spectral comparisons between single jets and twin jets at two azimuthal angles for two representative polar angles. There are four groups of spectral comparisons for different jet Mach numbers in each plot. At a shallow polar angle of 30 deg, the difference in spectral levels of the twin jet at two different azimuthal angles is very small for frequencies below the peak Strouhal number. Consequently, the spectral difference between the twin jet and single jet in the low Strouhal number region is identical for both azimuthal angles. For frequencies above the peak Strouhal number, the spectral level shows significant variation between the two azimuthal angles, and the spectral trend across azimuthal angles is consistent for various jet Mach numbers. At $\phi = 0$ deg, the spectral level of the twin jet and single jet is quite similar for high Strouhal numbers. This is interpreted to be the effect of acoustic shielding. On the other hand, at $\phi = 90$ deg, the spectral level of the twin jet strongly differs from the single jet in the high-Strouhal-number region. The level of spectral difference depends on the jet Mach number, and it is expected to depend on the nozzle separation distance [27] and jet temperature.
ratio \[9\]. This difference is due to the effect of twin-jet interaction observed along the plane of \(\phi = 90\) deg. As the observer polar angle increases to 90 deg, the acoustic shielding effect eventually vanishes (Fig. 5b). The spectra are nearly alike for twin jets at various azimuthal angles, and there are consistent spectral differences between single jets and twin jets. There is only a minor azimuthal effect \[27\] on the broadband shock-associated noise (BBSAN), where the BBSAN is slightly higher at \(\phi = 0\) deg than \(\phi = 90\) deg.

After a brief review of the noise directivity of twin jets, it is useful to have a simpler way to describe the noise emission level of the twin jet. A conventional method to accomplish this is to estimate the noise level of a twin jet using the sum of the noise level of two incoherent but identical single jets, assuming there is no interaction between the two jets. These summed noise levels are equivalent to the sound pressure level of a single jet operating at the same jet operating condition plus 3 dB. Using this method, it is more plausible to evaluate the effects of shielding and amplification by subtracting the estimated noise level of the twin jet (the single jet + 3 dB) from the measured twin-jet noise level. Consequently, if there are negative values of sound pressure level, it represents a shielding effect. Similarly, if there are positive values of sound pressure level, it indicates the twin-jet interaction induces amplification. The example results of circumferential noise directivity between the overall sound pressure level (OASPL) of twin jet and the OASPL of a single jet plus 3 dB are shown in Fig. 6 for two representative jet Mach numbers. The effect of acoustic shielding is clearly observed at \(\phi = 0\) deg, especially at low polar angles. The acoustic shielding phenomenon degrades as the polar angle increases to 90 deg and the azimuthal angle shifts from 0 to 90 deg. These trends are consistent for the two different jet Mach numbers, though the variations of \(\Delta\)OASPL are more significant in the \(M_j = 1.3\) case than \(M_j = 1.23\). In Sec. III.B, it will be shown that there is strong twin-jet coupling at \(M_j = 1.3\).
When the twin-jet nozzle spacing is around 1.4, the flapping mode of the twin jet is between 1.2 and 1.5, the flapping mode of twin jets and single jets have the same screech tone modes for various Mach numbers, except for the \( M_j \) 1.4 case. In the screeching \( M_j \) 1.4 single jet, the jet plumes are dominated by the helical mode (mode C); in contrast, in the screeching \( M_j \) 1.4 twin jet, the plumes are dominated by the flapping mode (mode B). Due to this change, the flowfield is significantly modified. In Sec. III.B, the schlieren images confirm this flowfield modification from single-jet to twin-jet plumes. In addition to observing the variations of the screech modes, Seiner et al. [15] showed that the flapping mode results in the strongest coupling of the twin-jet plumes. They drew this conclusion from the analysis of schlieren images and screech tone amplitudes. In the current study, various azimuthal modes of twin-jet plumes will also be discussed using schlieren images. Additionally, near-field pressure measurements will be presented to evaluate the level of twin-jet interaction for different jet azimuthal modes. These results will further verify the dominant jet azimuthal mode responsible for the twin-jet coupling.

Since the jet characteristics are significantly affected by various screech modes, it is meaningful to use the level of screech tones as an indicator of twin-jet plume interaction. There is a relationship among screech magnitude, jet Mach number, and twin-jet nozzle spacing. Screech tones can appear in both under- and overexpanded single- and twin-jet regimes exhausting from contoured nozzle or supersonic noncontoured nozzles (such as biconical nozzles of the present work), due to the presence of shock cells. In evaluating the level of twin-jet plume interaction, the amplitude of the screech tones could be a good indicator. The magnitude, mode, and often the Strouhal number of the screech tones from twin jets are therefore compared to that of a single jet to evaluate the nature and degree of amplification or suppression of twin-jet plume interaction. In both the single-jet and twin-jet configurations, Seiner et al. [15] recorded the dominant screech tone across a wide range of jet Mach numbers. Figure 7 replicates the data from Seiner et al. [15] and presents representative data acquired in our study at OSU for jet Mach numbers of 1.15, 1.23, 1.3, and 1.4. The screech tones are grouped together and identified as A, B, and C to represent the axisymmetric, flapping, and helical modes, respectively. In both single jets and twin jets, operating at different Mach numbers, the fundamental wavelength of the screech tones measured at OSU compares well with Seiner et al.’s data. Twin jets and single jets have the same screech tone modes for various Mach numbers, except for the \( M_j \) 1.4 case. In the screeching \( M_j \) 1.4 single jet, the jet plumes are dominated by the helical mode (mode C); in contrast, in the screeching \( M_j \) 1.4 twin jet, the plumes are dominated by the flapping mode (mode B). Due to this change, the flowfield is significantly modified. In Sec. III.B, the schlieren images confirm this flowfield modification from single-jet to twin-jet plumes. In addition to observing the variations of the screech modes, Seiner et al. [15] showed that the flapping mode results in the strongest coupling of the twin-jet plumes. They drew this conclusion from the analysis of schlieren images and screech tone amplitudes. In the current study, various azimuthal modes of twin-jet plumes will also be discussed using schlieren images. Additionally, near-field pressure measurements will be presented to evaluate the level of twin-jet interaction for different jet azimuthal modes. These results will further verify the dominant jet azimuthal mode responsible for the twin-jet coupling.

In the current study, the ratio of the nozzle lip to nozzle exit diameter is large due to the implementation of the active flow control device. It was believed that this would potentially impact the amplitude but not the mode of frequency of the screech tones. To look into this issue, Fig. 7 is provided, which compares the screech mode and wavelength between thin lip nozzle results in the literature and thick lip nozzle results in the current work. The ratio of nozzle lip thickness to exit diameter is less than 0.06 for the nozzle of NASA Langley Research Center [15] and 0.4 for the current work. The agreement in the screech mode and the wavelength between the two results is quite good, considering the significant differences in the

**Fig. 7** Nondimensional fundamental wavelength \( (\lambda / D) \) of screech tones as a function of jet Mach number \( M_j \); a) single jet, and b) twin jet.

**Fig. 8** Schematic of the relationship among screech magnitude, jet Mach number, and twin-jet nozzle spacing, replicated from the work of Wlezien [29].
nozzles; the NASA nozzle was a simple straight pipe, and the nozzle in the current work is a biconical converging–diverging nozzle. Meanwhile, the level of screech tone in terms of jet Mach number was discussed in [15]. Although there is a potential impact on the absolute level of the screech tones with the thick nozzle lip, the trend of screech tone level relative to jet Mach number from the current work is very similar.

B. Flowfield and Irrotational Near-Field Characteristics of Supersonic Twin Jet

A schlieren imaging technique was used to investigate the flow behavior of twin-jet plumes and their interactions. In a screeching jet, screech tones are discrete high-amplitude tones, which correlate with the flow behavior of the twin-jet plumes. Thus, a microphone located near the nozzle exit was used to measure the screech frequency and amplitude, and it provided a triggering signal for phase-locking and phase-averaging of schlieren images. Figure 9 presents the phase-averaged schlieren images of twin-jet plumes operating at various jet Mach numbers. This should highlight the dominant flow behavior of twin-jet plumes induced by the screech tone, which was used for phase-locking. The toroidal flow structures appearing in both jet plumes at a similar axial position seem to weakly interact with each other. As the jet Mach number increases to 1.23 (Fig. 9b), the twin-jet plumes change to the helical mode. The helical (cork screw type) flow structures are observed in both jets and seem to weakly interact out of phase from each other in the inner region of twin-jet plumes. Again, the twin-jet plumes remain relatively unaffected and there is no significant twin-jet interaction.

As the jet Mach number rises to 1.3 (Fig. 9c), the twin-jet plumes start to exhibit intense interaction induced by the flapping mode along the twin-jet plane. Repetitive sinusoidal motions are observed from both jets that noticeably move the jet (and thus the flow structures) back and forth. In the inner region of the twin-jet plumes, the distinct twin-jet coupling is observed at the same phase in both jets. While comparing the flow behavior across two different image planes, the twin-jet plumes exhibit the coupling phenomenon primarily along the twin-jet plane, which is the direction of the flapping motion. This interaction mechanism reveals the preferred mode of natural twin-jet coupling. Looking at a different Mach number case with a flapping motion and coupling behavior, at a jet Mach number of 1.4 (Fig. 9d) and with stretched shock cells, the first clear in-phase flow structures appear slightly after \( x/D = 4 \) in comparison with the jet at a Mach number of 1.3, which interacts

![Fig. 9 Phase-averaged schlieren images of baseline twin-jet plumes on the twin-jet plane on top and normal to the twin-jet plane on bottom: a) \( M_j = 1.15 \), b) \( M_j = 1.23 \), c) \( M_j = 1.3 \), and d) \( M_j = 1.4 \). Phase locking is based on the dominant screech tone.](http://arc.aiaa.org/doi/abs/10.2514/1.J054977)
before $x/D = 4$. Twin-jet plumes heavily interact with each other with in-phase symmetric flapping motion relative to the geometric centerline of twin-jet nozzle. Again, the twin-jet coupling is physically limited to along the twin-jet plane.

In the case of a single-jet plume, as shown in Fig. 10, one of the twin-jet nozzles is blocked. Beside the similar shock cell length compared to the twin-jet cases, the dominant azimuthal mode is not easily noticeable. At a jet Mach number of 1.15, the toroidal flow structures are barely observed. In the other single nozzle jet Mach number cases, the dominant azimuthal modes (helical and flapping modes) may not have a certain preferred directivity to be captured by the flow visualization. By comparing the flow images of twin-jet and single-jet plumes, it is clear that the flapping mode is significantly amplified in the twin-jet configuration.

In addition to flow visualization of the twin-jet plumes interaction, for further analysis of flow dynamics induced by weak or strong twin-jet interaction, the near-field linear microphone array was used. The irrotational near-field pressure fluctuations around the twin-jet plumes and the single-jet plume were both measured for comparison. The near-field experiments specifically focused on two jet Mach numbers.
numbers, $M_j = 1.23$ and 1.3, as these two conditions featured different dominant azimuthal modes. The experimental results are presented in the form of SPL contours with Strouhal number ($St$) versus normalized axial distance ($x/D$). Figure 11 presents the SPL contours with the linear array located along the twin-jet plane. The microphone array is located above the twin-jet nozzle, as shown in Fig. 3 with microphone locations (for the $\phi = 0$ deg plane) given in Fig. 4. Single-jet results are shown in Figs. 11a and 11b, and twin-jet results are shown in Figs. 11c and 11d. Overall, there are two primary features appearing in the contours. In the upstream region around an $x/D$ of five and Strouhal number of one, there is a relatively small region mainly attributable to the presence of BBSAN. Similar results were also observed by Savarese et al. [30]. The other salient feature appears in the jet downstream region, where significant near-field pressure amplification is observed at low Strouhal numbers.

The effect of the jet Mach number in Fig. 11 can be seen by comparing the contours of $M_j = 1.3$ and $M_j = 1.23$ for the single jet. The former shows higher amplitude than the latter. Comparing the twin jet relative to the single jet, Fig. 11 shows that the SPL level is strongly dependent on the jet Mach number and a good indicator of the level of twin-jet coupling. For the $M_j = 1.23$ cases, the SPL contour of the twin jet is very similar to that of the single jet, confirming the relatively weak jet plume interaction as observed in the schlieren images. In the $M_j = 1.3$ case, the jet plumes feature a strongly interacting flapping mode; hence, there is significant change in the amplitude of the SPL contours. This amplification specifically appears at further downstream positions and at low Strouhal numbers ($St < 0.1$), where the irrotational near-field pressure component [31] dominates. These results favorably compare with the flow visualization results where the twin-jet coupling is observed to occur at axial positions of $4D$ to $8D$. Because of the nature of the flapping motion for the twin jet, the twin-jet plumes mainly exhibit their near-field impact along the twin-jet plane, which is also the plane of the flapping motion. To highlight the azimuthal difference of near-field pressure, Fig. 12 presents the near-field spectral contour along the plane normal to the twin-jet plane, with microphone locations (for the $\phi = 90$ deg plane) given in Fig. 4. On this plane, which is normal to the flapping plane, the absolute sound pressure level is lower than the counterpart in Fig. 11, which could partially also be due to the microphone array being slightly farther away from the jet shear layer of the twin-jet plumes. Besides the comparatively low SPL, there is no significant change observed in the SPL contours between the single-jet and twin-jet cases. These results depict the near-field characteristics of twin-jet plumes, which are in agreement with the flow visualization results.

Depending mostly on the interaction mechanism, twin-jet plumes interact weakly or strongly. The flapping mode has been experimentally observed to be the most effective interaction mechanism and induced the most intense twin-jet coupling. With the flapping motion, the coupled twin-jet plumes feature amplification in the near-field pressure fluctuations primarily on the plane of the flapping motion, which coincide with the twin-jet plane. Seiner et al. [15] were first to demonstrate that the flapping mode incurs the strongest twin-jet interaction, especially along the twin-jet plane. The current study demonstrates that this interaction and coupling cause significant amplification at low frequency along the twin-jet plane. With this information, evaluating the near-field pressure amplification at low Strouhal numbers along the twin-jet plane could help to identify which jet operating condition could potentially incur strong twin-jet coupling.

A way to directly view the effect of the twin-jet interaction is to take the differences between the contours of Fig. 11. In particular, comparing the single- and twin-jet contours for a given Mach number will highlight the strong or weak interaction of the jet. Figure 13 displays these contours of the near-field spectral difference ($\Delta$SPL) between the twin jet and single jet along the twin-jet plane at four jet Mach numbers. In the first case, which is the $M_j = 1.15$ jet (with the

![Fig. 12 Comparisons of baseline SPL contour along the plane normal to the twin-jet plane for single jet at a) $M_j = 1.23$, b) $M_j = 1.3$ and twin jet at c) $M_j = 1.23$, d) $M_j = 1.3$.](image-url)
dominant axisymmetric mode), the ΔSPL contour barely indicates twin-jet interaction, as the difference in SPL is slightly less than 3 dB, indicating a simple doubling of acoustic power. In the $M_j 1.23$ jet (with the dominant helical mode), the ΔSPL contour shows minor near-field pressure suppression where the twin-jet plumes feature weak interaction. It is possible that the twin-jet plumes bend inward toward each other, resulting in this minor near-field suppression due to the increased distance between the microphone array and the shear layer [5]. For the $M_j 1.3$ jet (with the dominant flapping motion), as discussed previously, the additional low-frequency amplification prominently indicates the existence of the strong twin-jet coupling. As for the last case of the $M_j 1.4$ jet (also with the dominant flapping mode), the impact of flapping motion incurs significant near-field pressure amplification, especially in the low frequencies at further downstream positions. Up to 6 dB increases clearly indicate the existence of strong twin-jet coupling. With the most amplification appearing below a Strouhal number of 0.1, the twin-jet plume interaction intensely amplifies the near-field hydrodynamic pressure components. In the irrotational near field, the pressure fluctuations could be decomposed into the hydrodynamic and acoustic components [32]. The hydrodynamic pressure component particularly dominates in the low Strouhal numbers. Evidently, the impact of twin-jet coupling can be easily gauged along the twin-jet plane in the near field of twin-jet plumes.

C. Active Control by Localized Arc Filament Plasma Actuators

Previous work in the GDTL using active control via LAFPAs in single jets has shown their capability to improve jet spreading [33], excite various azimuthal modes [34], and significantly affect jet noise [35]. In a brief recapitulation of the capabilities of LAFPAs, Fig. 14 presents the phase-averaged jet flow structures in an excited jet from the particle image velocimetry (PIV) measurements [36] and the corresponding near-field pressure fluctuation contours [37]. These results are phase-averaged based on the triggering signal of the LAFPAs and then phase-matched for the results shown in the figure. From the PIV data, the phase-averaged Galilean streamlines and superimposed normalized $Q$ criterion are combined to identify the coherent flow structures in the excited jet. As shown in Fig. 14, at two phases within one excitation period, the jet flow structures grow in scale as they convect downstream, and they eventually break up near the end of the potential core. The signature of these structures is similarly observed in the near-field pressure fluctuation contours (levels in pascals). Although the coherent flow structures convect downstream, their signature is clearly shown in the irrotational near-field pressure fluctuations. In the twin jet, the coherent flow structures in the two jet plumes could interact and produce strong twin-jet coupling with significant near-field pressure amplification.

D. Effects of Excitation on Screeching Jet

The application of LAFPAs in both subsonic and fully expanded supersonic jets has been explored in the past at the GDTL. In the investigation of twin-jet plume interaction in the current work, LAFPAs are applied to a supersonic screeching jet. Due to the azimuthally asymmetric noise directivity of twin-jet plumes, first, a series of excited single-jet experiments were conducted, with the twin jet set up by blocking one of the nozzles, just to examine the effect of LAFPAs on a supersonic screeching jet. Screech is known to amplify the broadband noise and modulate the intensity and peak frequency of broadband shock-associated noise [38,39]. It is believed that the fundamental frequency of screech tones correlates with the evolution of large-scale flow structures in the jet plumes. By manipulating large-scale structures in the jet via LAFPAs, the relationship between the screech mode, the
amplification level of broadband noise, and the evolution of the jet plumes is explored. LAFPAs have been shown to provide perturbations to excite the jet shear layer instability, to generate large-scale flow structures\textsuperscript{[33,40]}, and to modulate the level of near-field hydrodynamic pressure fluctuations\textsuperscript{[41]}. These structures evolve as they convect downstream in the jet shear layer, but their evolution and scale vary depending on the excitation frequency and azimuthal mode. By altering the excitation Strouhal number $St_{DF}$, the impact on the level of the screech tone and broadband spectrum will be discussed.

Figures 15–17 show schlieren images for three excited jets and far-field spectra measured from the baseline single jet and the jet excited at three representative azimuthal modes. The far-field spectra shown are a representative case taken at a polar angle of 60 deg measured from the downstream jet axis. The $M_j$ 1.23 jet was excited with axisymmetric ($m = 0$), helical ($m = 1$), and flapping ($m = \pm 1$) modes to promote various jet azimuthal modes and structures. For each excited mode, LAFPAs were operated at the assigned excitation mode with three excitation Strouhal numbers from below to above the fundamental Strouhal number of screech tone, which was a Strouhal number of 0.55 in the $M_j$ 1.23 jet. In the first excited case with the axisymmetric mode, the distinguishable toroidal flow structures were easily observed in the schlieren images. The toroidal flow structures started to form at $1.5D$ for $St_{DF}$ of 0.3 and at $0.5D$ for $St_{DF}$ of 0.8, and they gradually grew in scale while convecting downstream. As the excited Strouhal number rose from 0.3 to 0.8, the evolution region of coherent toroidal flow structures moved further upstream and disintegrated and broke down earlier and more quickly in the streamwise direction. These disparate flow dynamics resulted in different impacts on the far-field noise emission. For the excitation Strouhal numbers ($St_{DF} \sim 0.3$ and $0.5$) lower than the fundamental screech tone in Fig. 15b, the excitation noticeably incurred broadband amplification compared to the baseline case. This broadband amplification was the consequence of the extensive evolution region of the coherent flow structures. At the higher excited Strouhal number, the coherent flow structures appeared in the upstream region mostly responsible for the high-frequency noise emission. Hence, the excitation with $St_{DF} \sim 0.8$ only generated high-frequency amplification compared to other excitation cases. In the other two excited modes with helical and flapping modes, aside from the different induced flow structures, all aforementioned phenomena were consistently observed in the schlieren images and far-field

![Fig. 15](image_url)
spectra. With appropriate excitation, the natural screech tone disappeared from the spectra and was replaced by the induced discrete tones (peaking at the excited Strouhal number $S_{DF}$ and its harmonics). The natural screech feedback loop and screech tone generation mechanisms were interrupted and taken over by the LAFPAs. The periodic LAFPA excitation reproduced the screech tone mechanism in the flow field and acoustic field. These results revealed the close connection between the screech tone and the dominant flow structure. Since the coherent flow structures were correlated to the formation of the screech tone, the strength and scale of the flow structures were responsible for the amplitude of broadband amplification and discrete tones. Among three excited modes, the flapping mode ($m = 0.0006$) caused the largest broadband noise amplification compared to the cases induced by axisymmetric and helical modes. Among the three excitation Strouhal numbers, $S_{DF}$ of 0.3, which was the closest to the jet preferred mode (jet column mode) frequency, generated the most coherent large-scale structures and the highest amplification of the peak far-field noise.

The excitation is also able to disrupt the strong interaction naturally present under certain conditions. Among the three selected excited modes ($m = 0, 1, \text{ and } \pm 1$), the flapping mode incurs the most distinguishable flow structures and most amplified noise emission. To suppress the naturally well-ordered structures, higher excitation modes (in this case, $m = 3$), are used. The $M_{j} 1.3$ jet is selected to demonstrate the reduction of far-field noise using different excitation modes because of its naturally strong flapping mode. Figure 18 shows schlieren images and far-field spectra measured from the baseline single jet and the jet excited at three azimuthal modes: axisymmetric ($m = 0$) and helical ($m = 1$ and 3) modes. Since the fundamental Strouhal number of the screech tone is 0.35 in the $M_{j} 1.3$ jet, the excitation Strouhal number is set to 0.8, which is significantly higher. From the flow visualization, the three excited modes all show a similar trend where the coherent flow structures grow and decay rapidly by $x/D$. However, the higher excited helical mode ($m = 3$) seems to induce weaker and smaller (not easily distinguishable) flow structures compared to the other two cases. The benefit of this is the lowest level

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Fig. 16 Schlieren images of a single jet at $M_{j} 1.23$: a) helical mode ($m = 1$) at $S_{DF}$ of 0.3, 0.5, and 0.8 from top to bottom; and b) far-field spectra.

Fig. 17 Schlieren images of a single jet at $M_{j} 1.23$: a) flapping mode ($m = \pm 1$) at $S_{DF}$ of 0.3, 0.5, and 0.8 from top to bottom; and b) far-field spectra.
Fig. 18  Schlieren images of a single jet at $M_j 1.3$: a) images for three azimuthal modes ($m = 0, 1, 3$ from top to bottom) at $St_{DF}$ of 0.8; and b) far-field spectra.

Fig. 19  Phase-averaged schlieren images of twin-jet plumes (on the twin-jet plane on top and normal to the twin-jet plane on bottom) at $M_j 1.3$ excited at $St_{DF}$ of 0.3: a) axisymmetric mode ($m = 0$), b) helical mode ($m = 1$), c) flapping mode ($m = \pm 1$), and d) helical mode ($m = 3$).
of broadband noise emission shown in the far-field spectra and the spectral comparisons of $\Delta S_{\text{PL}}$ between the baseline case and individual excitation cases. This example clearly illustrates the effects of the selection of excited modes for jet noise suppression. These findings will guide the exploration of the decoupling and coupling of twin-jet plumes.

### E. Twin-Jet Plume Control via Excitation

Supported by the visualizations of the interaction mechanisms of the twin-jet plumes and the understanding of effective excitation parameters for supersonic screeching jets, twin-jet plume control results are presented and discussed for decoupling and coupling via excitation. Figure 19 presents the phase-averaged schlieren images of twin-jet plumes excited at various modes. These images are taken by synchronizing the camera to the phase of the excitation signal and then averaging over 30 images. To exhibit twin-jet decoupling via excitation, the $M_{j} 1.3$ jet is examined because of its strong baseline coupling. Among the various excited Strouhal numbers, $St_{DF}$ of 0.3 is selected, as its schlieren images show clear modulation of the twin-jet plumes. In the first excited case with the axisymmetric mode ($m = 0$), the natural flapping mode is fully replaced by the axisymmetric mode in the plumes. In the images along two viewing planes, the coherent toroidal flow structures are clearly observed at the same streamwise position. Similarly, the coherent helical flow structures are seen in both imaging planes while the twin-jet plumes are under helical mode ($m = 1$) excitation. In the excited case with flapping mode ($m = \pm 1$), the excitation is configured to induce an identical flapping pattern in both jets. Such excitation results in a different (asymmetric) flapping pattern compared to the natural twin-jet behavior (symmetrical flapping) discussed earlier.

Again, the flapping mode only has significant impact along the plane of the flapping direction. In the last excited case with a helical mode ($m = 3$), the excitation completely overwhelms the strong natural twin-jet coupling and incurs the least twin-jet plume interaction among all four excited cases. These results illustrate the promising capabilities of flow control on twin-jet plumes. Next, a further analysis is provided to evaluate the near-field changes of pressure fluctuation induced by the excited twin-jet plumes.

The measurements are specifically acquired along the twin-jet plane to look into the behavior of twin-jet coupling. The experimental results of the excited twin-jet are presented as the SPL difference between the excited and baseline twin jets. This highlights the impact of the excitation on reinforcing or disrupting the twin-jet interaction. Figure 20 presents the $\Delta S_{\text{PL}}$ induced by the twin-jet plumes excited with $St_{DF}$ of 0.3, at four excited azimuthal modes for $M_{j} 1.3$. The small band around the region of a Strouhal number of one is attributed to the change of BBSAN. A potential explanation for this is the modification of the interaction between the shock cells and the dominant flow structures in the flow images shown and discussed earlier. In the low-frequency downstream portions of each plot, the $\Delta S_{\text{PL}}$ contours show the significant change in the irrotational near-field pressure caused by excitation. Aside from the flapping mode ($m = \pm 1$) excitation, the other excited modes ($m = 0, 1, 3$) all cause suppression of the near-field pressure fluctuation because the excitation changes the natural flow structures and the twin-jet interaction.

From the significant broadband reduction in SPL, it is clear that the flapping mode leads to strong twin-jet interaction at $M_{j} 1.3$, particularly along the flapping direction of the twin-jet plane. As for the comparisons of different levels of near-field pressure suppression given by various excited modes, the helical mode


$(m = 3)$ incurs the highest reduction up to 6 dB. This finding is consistent with the flow images where there is no noticeable flow interaction up to eight diameters downstream of the nozzle exit in the inner region of the plumes. Though the axisymmetric mode $(m = 0)$ results in coherent toroidal flow structures, due to the disruption of the natural twin-jet plumes, it still generates significant near-field pressure suppression comparable to the helical mode $(m = 3)$ excitation. Due to the nearly similar flow structures to the flapping mode case, the helical mode $(m = 1)$ induces the least reduction where the coherent helical flow structures are observed in both imaging planes shown previously. Since the flapping mode $(m = \pm 1)$ excitation reinforces the natural flapping behavior, the fluctuation level in the near field of the twin-jet plumes is strengthened. Summarizing the flow images and near-field pressure response, it can be stated that the ordering of the three azimuthal modes investigated from high to low in terms of the twin-jet interaction is as follows: flapping mode $(m = \pm 1)$, helical mode $(m = 1)$, and axisymmetric mode $(m = 0)$. In the baseline twin-jet plumes, therefore, the appearance of weak or strong twin-jet coupling depends on the azimuthal modes and interaction mechanism of the twin-jet plumes.

In the $M_j 1.3$ twin jet with strong coupling caused by the flapping mode, the decoupling of the twin-jet plumes is demonstrated across a series of excited modes. The optimal excitation parameters are a helical mode $(m = 3)$ with $St_{DF}$ of 0.5 for the best near-far-field pressure reduction [42,43] (not shown here). On the other hand, in the $M_j 1.23$ twin jet with weak coupling related to the helical mode, the coupling behavior of twin-jet plumes is modulated via LAFPAs. Figure 21 presents the phase-averaged schlieren images of the twin-jet plumes excited at various modes. Again, the excitation is configured to induce identical flow behavior in both jets. Among the various excited Strouhal numbers, $St_{DF}$ of 0.5 is selected for the highly amplified interaction of the plumes. During excitation with axisymmetric $(m = 0)$ and helical $(m = 1)$ modes, along both image planes, the coherent toroidal and helical flow structures are noticeably captured. In the last two excited cases, the induced flow structures are only clearly observed along the twin-jet plane, similar to those in Figs. 19c and 19d. The images normal to the twin-jet plane are therefore not shown. In all excited modes, the induced flow structures grow and decay rapidly within five diameters downstream of the nozzle exit and all are different from the baseline case. These show that the twin-jet plumes at $M_j 1.23$ are amplified and deliberately coupled by reinforcing the helical mode $(m = 1)$, or with any other helical mode (e.g., $m = 3$). Meanwhile, as discussed previously, the flapping mode typically incurs the most amplified twin-jet interaction along the twin-jet plane. It is expected that there will be significant changes in the near-field pressure response in the excited $M_j 1.23$ twin jet. Figure 22 presents the $\Delta SPL$ contour induced by the excited twin jet with $St_{DF}$ of 0.5 at four excited azimuthal modes for $M_j 1.23$. The measurements are acquired along the twin-jet plane to document the pressure fluctuation from the amplified twin-jet plumes observed in the flow images. First, there are similar changes around a Strouhal number of one related to BBSAN among all excited cases. The interpretation for this change is the modification of the dominant flow structures interacting with the shock cells. This shifts the peak of the shock noise component to higher Strouhal numbers while the coherent flow structures are observed further upstream than the baseline twin-jet case shown in the flow images. In addition to the BBSAN modifications, there are significant amplifications of the near-field pressure responses, particularly in the low Strouhal number region, but with disparate amplitudes depending on the excited azimuthal

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**Fig. 21** Phase-averaged schlieren images of twin-jet plumes at $M_j 1.23$ excited at $St_{DF}$ of 0.5: a) axisymmetric mode $(m = 0)$, b) helical mode $(m = 1)$, c) flapping mode $(m = \pm 1)$, and d) helical mode $(m = 3)$. 
mode. The amplified levels of the near-field pressure response reveal the coupling of the twin-jet plumes via excitation. Beginning with the lowest impact case with an axisymmetric mode ($m = 0$), there is only minor amplification up to 2 dB observed in the ΔSPL contour within five diameters downstream of the nozzle exit where the decaying of coherent flow structures are observed in the flow images. As for the helical mode ($m = 1$), due to the natural helical behavior of the twin-jet plumes at $M_j = 1.23$, the near-field pressure response is amplified to reflect the reinforcement of the helical mode. However, the level of amplification decreases as the excited helical mode changes from $m = 1$ to $m = 3$. This agrees with the comparison of stronger helical structures observed in Fig. 21b than those observed in Fig. 21d, where amplification is less strong due to the higher-order excitation mode. Lastly, the excitation with the flapping mode ($m = \pm 1$) results in the strongest amplification of the near-field pressure response of up to 6 dB. This reemphasizes that there are weak and strong twin-jet interactions and the flapping interacting mechanism incurs the most intense amplification of the twin-jet plumes.

IV. Conclusions

The closely spaced and nearly parallel twin-jet configuration is common in military aircraft. In such an arrangement, jet plume interaction can occur weakly or strongly, depending upon the jet operating regime. To explore the phenomenon of twin-jet interaction, screech-locked schlieren images of twin-jet plumes exhausting from biconical converging–diverging nozzles with a design Mach number of 1.23 are taken at various jet Mach numbers. Two image planes are taken: one on the twin-jet plane, and another one normal to the twin-jet plane. Four jet conditions are included to demonstrate various jet azimuthal modes (axisymmetric, helical, and flapping) and the associated screech modes. At a jet Mach number of 1.15, the twin-jet plumes exhibit the axisymmetric mode with toroidal flow structures clearly observed in both jet plumes at similar streamwise positions. However, there is no significant visual twin-jet interaction seen in the inner region of twin-jet plumes, and the plumes remain fairly unaffected by one another. As the jet Mach number increases to 1.23, the azimuthal mode of the twin-jet plumes changes from axisymmetric to helical. The (corkscrew) helical flow structures are observed in both jets and seem to weakly interact out of phase from each other in the inner region of the plumes. Again, the twin-jet plumes remain relatively unaffected by one another, and there is no significant twin-jet interaction observed. As the jet Mach number rises to 1.3 and 1.4, the twin-jet plumes greatly interact with each other via in-phase symmetrical flapping motion relative to the geometric centerline of the nozzles along the twin-jet plane. The repetitive sinusoidal motion is observed from both jets that noticeably moves the flow structures up and down. The strong twin-jet coupling is naturally established by the jet flapping motion primarily along the twin-jet plane, which is the direction of the flapping motion.

In comparing the flow behavior between the twin-jet and single-jet plumes, it is clear that the presence of a secondary jet amplifies the jet plumes’ lateral motion at certain jet Mach numbers where the azimuthal flapping mode is induced. To gauge the level of amplification, a near-field linear microphone array is used to record the irrotational near-field pressure fluctuations around the twin-jet plumes as well as the single-jet plume for comparison. In the cases of $M_j = 1.15$ and 1.23, the near-field pressure levels of the twin jet are roughly 3 dB higher than that of the single jet, indicating relatively weak plume interaction. However, in the cases of $M_j = 1.3$ and 1.4, where the jet plumes feature strong flapping motion, there is a significant increase in the amplitude of the SPL contour up to 6 dB in comparison with that of the single jet. This amplification mostly
appears at low Strouhal numbers ($St < 0.1$) where the hydrodynamic pressure component dominates. The significant hydrodynamic amplification reflects the strong twin-jet interaction observed in the flow images. Because of the nature of the jet flapping motion, the near-field pressure amplification occurs only along the twin-jet plane. In the past, twin-jet studies focused on the acoustic emission in the far field where there was acoustic shielding along the twin-jet plane and noise amplification in the plane normal to the twin-jet plane. This near-field impact, with different characteristics from the far-field acoustics, has not been fully investigated and reported until this work. This finding provides a guide to the identification of twin-jet coupling. Since the exact exit velocity and temperature ratio of the twin-jet plumes frequently varies for military aircraft, evaluating the near-field amplification at low Strouhal numbers along the twin-jet plane would help to identify those jet conditions that could incur strong twin-jet coupling.

LAPFAs, acting as a flow diagnostic tool, are implemented in the supersonic screeching jet. A series of excited single-jet experiments are conducted to explore the difference between various excited modes before it is used on the twin-jet. Three main azimuthal modes (axisymmetric, helical, and flapping) excitations are studied. In the excited jet, the natural screech tone is replaced by the discrete tone at the excitation Strouhal number and its harmonics. The periodic LAPFA excitation reproduces the screech tone mechanism in the flow field and acoustic field. For excitation Strouhal numbers lower than the fundamental screech tone of a supersonic screeching jet, the excitation causes noticeable broadband amplification compared to the baseline case. This broadband amplification is the consequence of the extensive evolution region of the coherent flow structures, and thus their interaction with shock cells. For excitation Strouhal numbers higher than the fundamental screech tone of the supersonic screeching jet, the excited coherent flow structures move further upward, grow, and decay rapidly. This limits the broadband amplification to the high-Strouhal-number region of the spectra. In each excited mode, the corresponding jet azimuthal mode is clearly captured in the flow images. Among the three different jet modes, the flapping mode (which features the up and down lateral motions) along the flapping direction has the most distinguishable flow structures and the most significant broadband noise amplification. On the other hand, in order to suppress the growth and size of jet flow structures, a higher azimuthal mode ($m = 3$) with a higher excitation Strouhal number was examined. This case exhibits smaller flow structures than other excited as well as baseline cases. Furthermore, more promising noise suppression is observed than other excited cases. These results should guide future exploration of decoupling and coupling of twin-jet plumes.

With the fundamental understanding of the interaction mechanisms of supersonic twin-jet plumes, there are weak and strong twin-jet coupling depending on the jet operating Mach number. In the case of strong twin-jet coupling, the twin-jet plumes can be effectively decoupled by disrupting the natural azimuthal mode. At $Mj = 1.3$ with strong twin-jet coupling dominated by the jet flapping motion, helical mode ($m = 3$) excitation completely overwhelms the dominant mode and alters the evolution of flow structures. From the near-field pressure measurements, the helical mode ($m = 3$) excitation results in an irrotational near-field pressure reduction up to 6 dB. Similarly, in the case of weak twin-jet coupling, the twin-jet plumes allow significant coupling, especially via jet flapping mode excitation. At $Mj = 1.23$ with weak twin-jet interaction attributed to the jet helical mode, flapping mode ($m = \pm 1$) excitation generates strong coherent flow structures and incurs significant jet flapping motion along the twin-jet plane. This results in significant amplification (up to 6 dB) of the near-field pressure fluctuations, especially for Strouhal numbers less than 0.1. With the demonstration of LAPFA excitation capabilities, the active flow control potential of twin-jet plumes is promising. The decoupling and coupling of twin-jet plumes are both achievable for various jet conditions and nozzle geometries. Across various excitation modes, the flapping mode is found to be the most critical one in terms of contributing to the twin-jet coupling.

Acknowledgements

The support of this research by the Office of Naval Research with Knox Millsaps is greatly appreciated. We also appreciate numerous discussions with Datta Gaitonde of The Ohio State University, Brenda Henderson of the NASA John H. Glenn Research Center, and John Spyropoulos of The U.S. Naval Air Systems Command. We also would like to thank Christopher Clifford and Michael Crawley for their assistance with experimental setup and data acquisition at the Gas Dynamics and Turbulence Laboratory.

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