Active Flow Control of Supersonic Twin-Jet Plumes

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ABSTRACT

This paper describes an experimental investigation of supersonic twin-jet interaction and its control. The natural flow behavior of twin-jet plumes is observed with nozzles separated center-to-center by two nozzle exit diameters. Phase-locked flow visualization is utilized to study the interaction mechanism and their effect on near-field pressure fluctuations is assessed using a microphone array. Localized arc filament plasma actuators (LAFPAs) are implemented to provide the upstream perturbation for active flow control of twin-jet plumes. In the natural twin-jet, the significant twin-jet interaction is observed with jet flapping mode being dominant on the twin-jet plane. It is shown that by using LAFPAs, decoupling and coupling of twin-jet plumes can both be achieved. It is also shown that the twin-jet plumes can be perturbed to feature different flow behaviors and interaction patterns.

Keywords: Flow control, Twin jets, Flapping mode, Jet noise

I. INTRODUCTION

Upstream flow perturbation has been shown to affect the evolution and development of flow structures convecting downstream. The well-organized flow structures are observed in jet plumes [1]. Various dominant jet azimuthal modes are shown to result in different development of jet plumes [2][3]. With various levels of perturbation, the jet flow features respond at different levels in the flow field and pressure field [4]. Several researchers have used various techniques to perturb the jet flow at different flow conditions. McLaughlin et al [5] used glow discharge excitation to study the flow response in the supersonic jets and its impact on the noise emission. Zaman & Hussain [6] excited the shear layer instability mode with an acoustic driver to suppress the turbulence with the elimination of coherent flow structures. Once the evolution of the flow cascade is disturbed, the flow behavior and development are different from the unexcited jets.

In the high-speed flow regime, active flow control was not feasible due to the increase of flow speed and highly energetic turbulence. A unique and powerful device, called localized arc filament plasma actuators (LAFPAs), was developed at the Gas Dynamics and Turbulence Laboratory (GDTL) of the Ohio State University. LAFPAs are capable of performing active flow control in high-speed and high Reynolds number flows [7]. In both subsonic and supersonic single jets, LAFPAs have been shown to improve the jet spreading rate, modify the near-field pressure fluctuation, and suppress the far-field acoustic radiation. Meanwhile, LAFPAs are able to affect the spatial behavior of jet plumes with different jet azimuthal modes. This makes it a suitable candidate for active flow control on twin-jet plumes.

In the twin-jet configuration, due to the existence of the secondary jet, it is not azimuthally symmetric in either the near-field pressure fluctuations or far-field noise directivity. The individual jet plumes next to each other interact and eventually merge into one stream downstream. Depending on the nozzle separation distance and jet condition, there is weak and strong twin-jet interaction. Seiner et al [8] showed that when the strong twin-jet coupling is present, the jet flapping behavior is observed in the flow field accompanying a strong tonal resonance. This strong tonal resonance and the energetic flow interaction result in the amplified dynamic pressure loading, which is detrimental to the aircraft after-body structure. Some passive flow control devices were developed to suppress the twin-jet flow
interaction [9][10]. However, the physical mechanisms of twin-jet coupling are not fully studied yet.

In the single jet regime, the active flow control has been investigated with LAFPAs. In the twin-jet configuration, LAFPAs would be able to provide the spatial perturbation to eliminate the unfavorable twin-jet flow interaction. These would expand the capability of active flow control from single jet to twin-jet regime. The objective of this paper is to first explore the natural behaviors of twin-jet plumes operating at different jet conditions. Based on the observation of natural twin-jet plumes, LAFPAs would then provide varying spatial perturbations to counteract the natural flow interaction. Via active flow control, one would expect to perturb the jet plumes to feature disparate flow behaviors and interaction patterns promptly as the jet condition varies.

II. 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 (OSU). The jet anechoic chamber facility [11] is a 6.2 m x 5.6 m x 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 with the far-field microphone array. The air supply for 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 m$^3$ total in volume). The nozzle is mounted on the end of the plenum. A twin-jet nozzle, shown in Figure 2, is used for study with bi-conical converging-diverging inner contour designed for a Mach number of 1.23. The nozzle exit diameter ($D$) is 19.05 mm with center-to-center nozzle separation distance of $2D$.

The near-field microphone array installed in the anechoic chamber is shown in Figure 3 where the array is at an azimuthal angle $\phi = 0^\circ$ relative to the twin-jet plane; 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 away from the jet shear layer. The first microphone is located 1$D$ above the nozzle lipline and 1.5$D$ downstream of the nozzle exit as measured to the center of the microphone tip. Subsequent microphones lie 1.3$D$ from one another as measured along the angled array. Various azimuthal angles (30°, 60°, or 90°) 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 twin-jet nozzle for any given azimuthal angle. Measured near-field pressure signals are processed with identical routines for the analysis [12]. 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 [13], [14].

Schlieren images of jet plumes are acquired by using a Z-type Schlieren system. In the baseline twin-jet Schlieren imaging, 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. In the excited twin-jet cases, instead of the microphone signal, the trigger signal comes from the dedicated computer used to control the excitation. Under either condition, 200 instantaneous phase-locked Schlieren images are taken, and then post-processed in MATLAB for the images with the highest correlation. The thirty 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.
2.2 Localized Arc Filament Plasma Actuators (LAFPAs)

Upstream flow perturbation is performed by LAFPAs which are a high frequency and high amplitude device designed for active 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 [15]. 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 and leads to the perturbation of jet shear layer instabilities. These upstream perturbations are controlled accurately at rates up to 20 kHz in this study. Each individual twin-jet nozzle has a total of 8 actuators evenly spaced around the nozzle just upstream of the exit. The azimuthal angle between each actuator is 45 degrees. The incremental degree of azimuthal angle of consecutively firing actuator is then given by $m^*(360/N_a)$ where $N_a$ is equal to 8 in the current setup. This configuration allows for several different azimuthal modes to be generated. These modes range from axisymmetric mode ($m = 0$) up to helical modes ($m = 3$) as well as mixed modes such as the flapping mode ($m = \pm 1$). Figure 4 presents the schematic of the firing of individual actuator for three representative azimuthal modes. For the axisymmetric mode, all eight actuators are fired simultaneously at the excitation frequency. There is no phase difference among all actuators since the value of $m^*(360/N_a)$ equals to zero. For the helical mode ($m = 3$), the phase angle between firing actuators is 135 degrees with the leading actuator starting from the top (#1). The actuation sequence is actuators #1, #4, and #7 (hereafter #147) in the first cycle then continues as #258, #361, and #472. As for the mixed mode, flapping mode ($m = \pm 1$), two sets of three actuators on the opposite sides are grouped and fire consecutively with 180 degrees phase difference, e.g. #812 and #456 with vertical flapping direction. The mathematical expression of actuation for all azimuthal modes is shown in Ref. [7] and the plain description of each azimuthal mode is provided in Ref. [16]. 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 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.

![Figure 4](image)

Figure 4  Schematic of individual actuator excitation for various azimuthal mode configurations where various colors represent different actuation phase. (a) Axisymmetric mode ($m = 0$), (b) Helical mode ($m = 3$), and (c) Flapping mode ($m = \pm 1$)

### III. RESULTS AND DISCUSSIONS

#### 3.1 Flow Field of Supersonic Twin-Jet

The nature of the flow field of twin-jet plumes is observed via the Schlieren imaging technique. Figure 5 presents the phase-averaged Schlieren images of twin-jet plumes taken along the twin-jet plane at four different jet Mach numbers. These four cases were selected to represent the dominant flow behavior observed in the twin-jet plumes as the jet operating conditions vary. At a jet Mach number of 1.15 (Figure 5a), the twin-jet plumes feature toroidal flow structures appearing at similar streamwise locations in both jet plumes. This flow behavior is attributed to the axisymmetric mode [17]. The twin-jet plumes stay relatively unaffected by each other even beyond the jet potential core. In the next jet Mach number of 1.25 (Figure 5b), the twin-jet plumes exhibit helical (cork screw type) flow structures in both jet plumes and seem to weakly interact out of phase from each other beyond $x/D = 3$. This flow behavior is attributed to the helical mode [18]. The last dominant flow behavior (or azimuthal mode) is observed in Figure 5c and Figure 5d where the twin-jet plumes interact...
symmetrically relative to the centerline of twin-jet plane. The jet flapping mode [19] distorts and displaces the jet plumes (and shock cells) up and down repetitively along the twin-jet plane. The interaction level of the twin-jet coupling gradually amplifies as the observed streamwise position shifts downstream. Also, as the jet Mach number increases from 1.35 to 1.45, the length of shock cells grows and the wavelength of the jet flapping mode increases as well. From the Schlieren images of baseline twin-jet plumes, the presence of the second jet in the twin-jet configuration results in the different levels of twin-jet interaction.

Figure 5  Phase-averaged Schlieren images of baseline twin-jet plumes along the twin-jet plane. (a) $M_j = 1.15$, (b) $M_j = 1.25$, (c) $M_j = 1.35$, and (d) $M_j = 1.45$. Phase locking is based on the dominant screech tone.

Among the various dominant azimuthal modes, jet flapping mode is found from the prior flow-field measurements [16] to incur the highest jet spreading rate as well as the most amplified jet plumes. This potentially makes the jet boundary of the inner twin-jet region much closer thereby promoting jet plume interaction. The higher azimuthal modes (e.g. $m = 3$) result in smaller scale of coherent flow structures with less significant near-field pressure fluctuations. Jet flapping mode, however, is implicitly shown to feature the strongest near-field hydrodynamic pressure fluctuations. This near-field perturbation could potentially affect the adjacent jet and achieve the phase synchronization of the jet plumes [20]. Due to these reasons, jet flapping mode is seen to effectively couple twin-jet plumes and promote coherent large-scale turbulent structures in the baseline twin-jet plumes.

### 3.2 Coupling of Twin-Jet Plumes

As described previously, there are weak and strong twin-jet interactions. To best demonstrate the capability of LAFPAs, the first excitation case presents the coupling of twin-jet plumes operating at a jet Mach number of 1.23. This jet Mach number is selected because of its weak plume interaction. The Schlieren images of twin-jet plumes with and without the excitation are shown in Figure 6. The excitation parameters are flapping mode with flapping direction along the twin-jet plane at an excitation Strouhal number ($St_{DF}$) of 0.3; these parameters are selected for its maximum effect in terms of the modification of the flow field. In the baseline case (Figure 6a), the twin-jet plumes exhibit helical (cork screw type) flow structures in both jet plumes and seem to weakly interact out of phase as seen in Figure 5b. In the excitation case (Figure 6b), there is a significant change in the flow field of the twin-jet plumes due to the upstream perturbation of the jet flapping mode. The natural helical flow structures are replaced by the flow structures which displace up and down laterally along the twin-jet plane. Because of the identical excitation parameters implemented on both jets, the twin-jet plumes interact asymmetrically relative to the centerline of twin-jet plane. The pattern of flapping mode is different from the one observed in the natural twin-jet plumes.

A linear microphone array was installed in the near field of twin-jet plumes to identify the level of twin-jet interaction for further analysis. To support the evidence of flow field modification observed in Figure 6, Figure 7 presents the corresponding near-field pressure contour measured along twin-jet plane. The experimental results of pressure contours are plotted with the normalized axial distance ($x/D$) versus Strouhal number ($St$). The gradient of pressure level and spatial/spectral key area is clearly presented on the contour with two primary features. First, a relatively small area (mainly affected by the shock noise) is located in the upstream region around $x/D$ of 5 and $St$ of 1. Then, the major feature is the pocket of intense pressure level appearing particularly in the jet.
downstream region at low Strouhal numbers. By comparing the excitation case (Figure 7b) to the baseline (Figure 7a), the near-field pressure level is significantly amplified at downstream locations where the large-scale flow structures interact and contribute high level pressure fluctuation. The coupling of twin-jet is prominently induced via LAFPAs. The pressure near field of twin-jet plumes is considerably augmented and the flow field of twin-jet plumes is substantially modified.

3.3 Decoupling of Twin-Jet Plumes

With the encouraging demonstration of twin-jet coupling via LAFPAs, the next excitation case presents the decoupling of twin-jet plumes operating at jet Mach number of 1.3. This jet Mach number is selected because of its noticeable twin-jet interaction. Figure 8 shows the Schlieren images of twin-jet plumes with and without excitation. The excitation parameters are helical mode \( (m = 3) \) at excitation Strouhal number \( (St_{DF}) \) of 0.5; these parameters are selected for its optimal suppression on the near-field pressure level. In the baseline case (Figure 8a), the twin-jet plumes interact symmetrically relative to the centerline of twin-jet plane as seen previously. This strong twin-jet coupling is detrimental and unfavorable. By implementing the active flow control device (LAFPAs), in the excitation case (Figure 8b), the energetic flow dynamics are thoroughly reduced and the twin-jet plumes stay relatively unaffected by each other particularly in the jet downstream region. The decoupling effect of active flow control on twin-jet plumes is evident.

Figure 9 presents the corresponding near-field pressure contour measured along twin-jet plane. In the baseline case (Figure 9a), due to the strong twin-jet interaction, the measured near-field pressure level is significantly higher than the other baseline case shown in Figure 7a. The pattern of near-field pressure amplification is similar in Figure 9a and Figure 7b; this potentially reveals that the upstream flow perturbation is able to effectively influence the flow dynamics and structure evolution in the same way as the baseline jets. In the excitation case (Figure 9b), because the twin-jet plumes stay relatively unaffected by each other, the near-field pressure level is noticeably decreased by comparing to its baseline case. This model-scale experimental demonstration illustrates the potential of active flow control, which could also be implemented on the twin rectangular jets [21] or jet-surface interaction conditions [22].
Figure 8  Phase-averaged Schlieren images of twin-jet plumes at $M_j = 1.3$. (a) Baseline case, (b) Excited case with helical mode ($m = 3$) at $St_{DF}$ of 0.5

Figure 9  Near-field pressure contour of $M_j = 1.3$ twin-jet measured along the twin-jet plane. (a) Baseline case, (b) Excited case with helical mode ($m = 3$) at $St_{DF}$ of 0.5

Figure 10 discusses the azimuthal impact of pressure near field. The difference of overall sound pressure level (OASPL) between the excited and baseline case are plotted with the normalized axial distance ($x/D$) versus azimuthal angle ($\phi$). Recall from Figure 8, the symmetrical flow interaction of baseline twin-jet becomes gradually apparent after $x/D = 3$. On the contrary, the excited twin-jet plumes stay relatively unaffected by each other particularly in the jet downstream region. Meanwhile, the energetic flow dynamics events are shifted upstream due to the flow perturbation. Based on the observation of flow field modification, there are two opposite trends recognized in Figure 10a. After $x/D \approx 7$, there is noticeable pressure reduction on the twin-jet plane ($\phi = 0^\circ$) because the nature of jet flapping mode mainly appears along the twin-jet plane. The reduction level gradually diminishes as the azimuthal angle increases to 90 degrees, which is the plane normal to the twin-jet plane. Before $x/D \approx 7$, instead of pressure reduction, there is pressure amplification observed mostly at an azimuthal angle of 90 degrees. In a similar fashion, the amplification level gradually decreases with the azimuthal angle. The upstream pressure amplification is attributed to the additional energetic flow dynamic events induced by the flow perturbation. In a detailed analysis, Figure 10b presents the representative spectra at different streamwise locations with various azimuthal angles. At $x/D = 12$ of twin-jet plane ($\phi = 0^\circ$), the significant pressure reduction is clearly observed mainly below $St$ of 0.1. On the other hand, at $x/D = 3$ with $\phi = 90^\circ$, the peak frequency of shock noise component in the excited case is shifted toward higher frequency than the baseline and the magnitude of shock noise is amplified. The upstream pressure amplification is primarily contributed by shock noise amplification. The upstream flow perturbation rearranges the evolution of coherent flow structures and alters the interaction between the flow structures and shock cells.
3.4 Active Flow Control on Twin-Jet Plumes

As seen in Figure 8a, the twin-jet plumes interact symmetrically in the baseline case. However, in Figure 6b the twin-jet plumes interact asymmetrically in the excited case. Though Tam and Seiner [23] show that kinematically both symmetrical and asymmetrical flapping modes could be sustained in the twin-jet plumes, the symmetrical flapping mode is generally observed in the baseline twin-jet plumes with close nozzle separation distance (e.g. 2D). The natural behavior and phase synchronization of jet plumes induced by the asymmetrical flapping mode would need further studied potentially with wider nozzle separation distance. By using LAFFPs, the synchronization of symmetrical and asymmetrical flapping modes can both be manipulated and observed in the current twin-jet nozzle setup. Figure 11a shows the Schlieren images of twin-jet plumes featuring two flapping modes. In the symmetrical flapping mode, the pattern of flow structures in each jet is mirrored relative to the centerline of the twin-jet plane. On the contrary, in the asymmetrical flapping mode, the pattern of flow structures is identical in both jets. Figure 11b presents the difference of the near-field pressure contour between the twin-jet plumes with symmetric and asymmetric flapping modes. The twin-jet plumes with asymmetric flapping mode feature slightly higher pressure levels in the far downstream region than the symmetric one. Overall, the difference in pressure level is not distinct enough to distinguish these two modes.

Figure 10  Experimental results of $M_j = 1.3$ twin-jet with baseline and excited cases with helical mode ($m = 3$) at $St_C$ of 0.5. (a) Near-field ΔOASPL contour along various axial distances and azimuthal angles between excited case and baseline case, (b) Near-field spectral comparisons of representative baseline and excited cases

Figure 11  Experimental results of $M_j = 1.3$ twin-jet with flapping mode ($m = \pm 1$) excitation at $St_C$ of 0.3. (a) Schlieren images of twin-jet with the symmetric flapping mode on top and asymmetric flapping mode on bottom, (b) Difference of near-field pressure level along twin-jet plane between the twin-jet plumes with symmetric and asymmetric flapping modes
In the nature of strong twin-jet interaction, twin-jet plumes interact symmetrically in the baseline case. With active flow control, the asymmetrical flapping mode is observed in the twin-jet plumes. Additionally, the natural direction of jet flapping mode is mainly on the twin-jet plane. By using LAFPAs, the jet flapping direction can be manipulated as well. Figure 12 shows schlieren images of twin-jet plumes featuring two different flapping directions. In the Figure 12a, as seen in the previous figures, the jet flapping mode is mainly observed on the twin-jet plane. The streamwise locations of crests and troughs of the flow structures with flapping behavior are highlighted on the plane normal to the twin-jet plane. In the Figure 12b, the jet flapping mode mainly contributes to the plane normal to the twin-jet plane. On the twin-jet plane, the twin-jet plumes stay relatively unaffected by each other. The streamwise locations and pattern of the flow structures with the flapping mode is almost identical in Figure 12a and Figure 12b. The capability of active flow control on twin-jet plumes is fully demonstrated through these representative cases.

Figure 12 Phase-averaged Schlieren images (along the twin-jet plane on top and normal to the twin-jet plane on bottom) of twin-jet plumes at \( M_j = 1.3 \) with flapping mode \((m = \pm 1)\) excitation at \( St_{DF} \) of 0.3. (a) Flapping direction along twin-jet plane, (b) Flapping direction normal to twin-jet plane

**IV. CONCLUSIONS**

In the twin-jet configuration, due to the presence of the secondary jet, the acoustic and flow fields of twin-jet are no longer axisymmetric, as they are in a single jet. In the baseline twin-jet plumes, there are weak and strong twin-jet interactions depending on the jet azimuthal modes. The symmetrical jet flapping mode results in the most significant twin-jet coupling and near-field pressure amplification on the twin-jet plane. Expanding the implementation of LAFPAs from single jet to the twin-jet configuration, the active flow control shows promising results. From the demonstration of excitation cases, the decoupling and coupling of twin-jet plumes are both achieved and the corresponding impacts in the flow field and near-field pressure levels are discussed. Beyond the observed natural azimuthal modes, via the active flow control, the twin-jet plumes can be perturbed to feature different flow behaviors and interaction patterns.

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