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RESEARCH ARTICLE

Active control of coupling and its effect on near-field pressure fluctuations in supersonic rectangular twin jets

R. Leahy[1], A. Esfahani[1], N. Webb[1] and M. Samimy[1,*]

[1]Gas Dynamics and Turbulence Laboratory, Aerospace Research Center, The Ohio State University, Columbus, Ohio 43235, USA
*Corresponding author. E-mail: samimy.1@osu.edu

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Abstract
Supersonic rectangular twin jets (SRTJ) are of interest for current and future generations of tactical aircraft. However, the adverse effects of screech-loop coupling have previously been documented to significantly increase the near-field (NF) pressure fluctuations. These high-amplitude pressure fluctuations have the potential to fatigue and damage nearby aft components of the aircraft. Previous studies have documented that the NF pressure fluctuation level depends on the coupling of the jets: in-phase coupling along the twin jets' minor axes produces stronger NF pressure fluctuations than that of out-of-phase coupling. The objective of this work is to further investigate the effects of coupling modes on NF pressure fluctuations in SRTJ and to mitigate the adverse effects of coupling using active flow control. Localized arc filament plasma actuators are employed to alter the SRTJs' coupling mode by leveraging natural flow instabilities with minimal power input. A NF microphone array is used for simultaneous coupling and NF pressure fluctuation measurements. Schlieren imaging and spectral proper orthogonal decomposition are used to assess the effects of control on the flow field. The effect of excitation at various frequencies and actuation patterns on coupling and NF pressure fluctuations in different flow regimes are explored and discussed.

Impact Statement
The design requirements for tactical aircraft are becoming increasingly complex, and their propulsion system must adapt to operational requirements that include thrust vectoring and reversing, integration into the fuselage and increased entrainment and mixing. Supersonic rectangular twin jets (SRTJ) promise to fulfil these requirements of tactical aircraft. However, due to the nature of closely spaced supersonic twin jets and the formation of acoustic feedback loops, coupling and screech have the potential to increase the unsteady near-field (NF) pressure fluctuations. The increased NF pressure fluctuations can induce structural damage to aft components of the aircraft. Localized arc filament plasma actuators (LAFPAs) provide a means to harness the jets' natural flow physics for controlling the flow and pressure fields of these jets. This work experimentally demonstrates the application of LAFPAs to significantly reduce the NF pressure fluctuation in SRTJ, while improving the understanding of the physics of the processes involved.

1. Introduction

When two or more jets are closely spaced, their flow and acoustic fields can couple, generating elevated near-field (NF) pressure fluctuations. In applications, this can result in higher acoustic/sonic fatigue to the aft components of an aircraft, which increases the maintenance requirements and limits the working life of structural components around the nozzles. These detrimental effects have led to conservative designs and thus undesirable added weight (Rudder & Plumblee, 1975). Prime examples of damage due to coupling are the B1-A and the F15-E test programs, where damage to the nozzle flaps was observed, primarily in the internozzle region (area between the two nozzles) (Berndt, 1984; Walker, 1990). Larger spacing between the jets results in decreased aeroacoustic interactions and therefore weakened or eliminated coupling (Raman & Taghavi, 1998; Zilz & Wlezien, 1990); however, closely spaced jets are desirable from a systems perspective for the reduced airframe stresses and concomitant weight. Thus, the development of active flow control methods to mitigate aeroacoustic coupling of supersonic twin jets, as well as the associated NF pressure fluctuations, would enable desirable system designs by allowing the reduction of spacing between the jet exhausts. To effectively implement such active flow control for the mitigation of supersonic twin jet coupling, it is crucial that the physics of screech and coupling be thoroughly understood.

Powell's (1953) original screech feedback model has been adapted and modified (Panda, 1999; Tam, Seiner, & Yu, 1986) since its conception, but the original concept of the loop has remained the same. Large-scale structures (LSS), often termed instability waves or wave packets, are generated through excitation of the Kelvin–Helmholtz (K-H) instability by natural perturbations in the flow at the nozzle exit in the shear layer of the jet. The interaction of LSS and shock cells of a non-ideally expanded jet generates broadband shock-associated noise (BBSAN) (Tam et al., 1986). A portion of the BBSAN then travels upstream, outside of the jet core, and perturbs the shear layer at the nozzle exit, where it is most receptive to the K-H instability (Barone & Lele, 2005). These perturbations then generate additional LSS at the nozzle exit. If the timing is right, this loop can become self-sustaining, creating a high-amplitude tonal resonance known as screech. Recent literature has pointed to 'guided jet modes' (Bogey, 2021; Edgington-Mitchell et al., 2018; Tam & Hu, 1989; Wu, Lele, & Jeun, 2021; Zaman, Fagan, & Upadhyay, 2022), rather than BBSAN, being the upstream propagating mechanism that closes the loop. Nevertheless, the upstream velocities of these guided waves and BBSAN are similar and therefore do not significantly alter the timing criterion of screech.

The primary focus of this work, twin jets' coupling, is directly related to the screech feedback mechanism. When the screech frequency and nozzle spacing are such that upstream propagating feedback waves from one jet arrive at its own nozzle exit plane in phase with the feedback waves from the other jet, coupling of the twin jets' screech loops is established. Therefore, it is the organization and development of LSS which are ultimately responsible for coupling and the detrimental effects mentioned previously (elevated NF pressure fluctuations). Berndt (1984) noted that laboratory-scale experiments correlated with hardware damage due to dynamic pressure in the full-scale test program, thus giving motivation to understand screech and coupling in laboratory-scale experiments. Previous work on low aspect ratio ($AR = 2$) supersonic rectangular twin jets (SRTJ) has shown that the screech mode tends to be flapping along the minor axis and the coupling modes can be in-phase or out-of-phase (generally for underexpanded and overexpanded regimes, respectively) (Samimy, Webb, Esfahani, & Leahy, 2023). In addition, work at the Gas Dynamics and Turbulence Laboratory (GDTL) has utilized active control via localized arc filament plasma actuators (LAFPAs) to control the organization and timing of LSS in jet flows (Kearney-Fischer, Kim, & Samimy, 2011; Kim, Kearney-Fischer, Samimy, & Gogineni, 2011; Samimy, Kim, Kastner, Adamovich, & Utkin, 2007). Localized arc filament plasma actuators have provided the means to not only control the development and organization of LSS to understand their effects on complex flow and acoustics physics, but also to manipulate LSS for optimal outcomes in application (suppressing far-field noise and NF pressure fluctuations). An extensive baseline and excited flow investigation has been conducted in low aspect ratio, sharp-throated, converging–diverging SRTJ and its findings have been documented in Samimy et al. (2023). This manuscript further details SRTJ baseline coupling, as well as the effects of excitation on coupling and NF pressure fluctuations.

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1.1. Supersonic rectangular twin jets coupling

Several previous studies have investigated the NF pressure in SRTJ (Karnam et al., 2021; Raman & Taghavi, 1998; Seiner, Manning, & Ponton, 1987; Walker, 1990; Zilz & Wlezien, 1990), but there have been a limited number of studies where the NF pressure levels were correlated with the twin jets' coupling modes (Seiner et al., 1987; Walker, 1990; Zilz & Wlezien, 1990). Table 1 highlights the experiments which have characterized the relationship between coupling mode and NF pressure in SRTJ. Included are specifics on nozzle geometry (i.e. aspect ratio (AR), and spacing (s) based on nozzle height (h) or width (w)) and the range of Mach numbers investigated, as well as notable findings from these studies. Seiner et al. (1987) conducted the first of them, which briefly investigated the dynamic pressures of the internozzle region of SRTJ. This work identified the flapping mode of SRTJ to be the dominant mode and noted that this mode had the highest plume resonance (screech) amplitude when the jets operated at an M_j far away from the M_d (M_j is the fully expanded Mach number and M_d is the design Mach number). They also noted that, in comparison with a single rectangular jet, the SRTJ had considerably higher NF pressure fluctuation levels in the underexpanded regime, allowing them to conclude that, in this flow regime, the jets were coupled. Zilz and Wlezien (1990) for the first time documented the coupling modes seen in SRTJ: in-phase (IP) and an out-of-phase (OOP) coupling along SRTJ minor and major axes. They found that coupling along the major axis (lateral coupling) occurred at aspect ratios closer to unity, while larger aspect ratios were susceptible to coupling along the minor axis. It is important to note that all these investigations assessed the NF pressure at different coupling modes that occur at different Mach numbers (i.e. no one-to-one comparison of coupling modes was made at the same M_j). In our recent work in low AR supersonic SRTJ ($AR = 2$), (Esfahani, Webb, & Samimy, 2021; Samimy et al., 2023), which is also the focus in this paper, we have observed IP and OOP coupling along the SRTJ minor axis to be dominant, and therefore we will only refer to these coupling modes as IP and OOP. Zilz and Wlezien (1990) notably reported that OOP coupling mode along minor axis revealed a lower NF pressure level by evaluating the overall sound pressure level (OASPL) levels in the internozzle region of the jet. This work also found that the pressure levels directly over one of the twin jets do not fluctuate or shift significantly with an IP to OOP coupling mode as in the internozzle region.

Shortly after, Walker (1990) used Zilz and Wlezien (1990) findings to infer an IP vs OOP coupling when viewing the OASPL of the jets, but did not characterize the coupling with a phase between the two. Raman and Taghavi (1998) performed a comprehensive study on coupling and NF pressure fluctuation levels in high AR SRTJ. Their configuration used an $AR = 5$ and the work was able to confirm the findings of Zilz and Wlezien (1990), explicitly that OOP coupling leads to decreased NF pressure fluctuations in the internozzle region. The most recent known study reporting coupling and NF pressure levels was performed by Karnam et al. (2021). In this brief study the jets used had an $AR = 2$, and were coupled OOP at an overexpanded nozzle pressure ratio (NPR) = 3.0. Instead of comparing internozzle pressure fluctuations at different M_j/NPRs, the authors compared the pressure fluctuations of microphones directly over top of each of the twin jets with an internozzle microphone. The authors noted significant (~10 dB) decrease in OASPL in the internozzle region compared with overtop of the jets, thus confirming Zilz and Wlezien's finding.

All previous works mentioned investigate the NF pressure fluctuations without the use of control, except for Seiner et al. (1987) and Walker (1990). These studies used a passive control technique by attaching a tab to the nozzle exit to disrupt coupling. Both have shown limited success in achieving decoupling and reducing NF pressure levels. Although there have been extensive works to control circular twin jets and characterize the NF pressure field (e.g. recent experiments performed at the GDTL Kuo, Cluts, & Samimy, 2017b), to the authors' knowledge there has been no body of work to utilize active control to characterize SRTJ NF pressure fluctuations in conjunction with coupling.

In this work, active flow control is implemented with the use of localized arc filament plasma actuators (LAFPAs). Localized arc filament plasma actuators were developed at the GDTL and have been used as a method of controlling the organization and timing of LSS forming in shear flows (Samimy, Kim, Kearney-Fischer, & Sinha, 2010; Samimy, Webb, & Crawley, 2018). They have demonstrated significant

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Table 1. *Previous notable studies on NF pressure and coupling of SRTJ.*

References	Nozzles design and aspect ratio	Nozzle spacing	Range of M_j	Coupling and NF pressure findings
Seiner et al. (1987)	C-D, rectangular, $M_d = 1.41$ $AR = 2.62$	$s/h = 3.74$	1.18–1.90	Revealed screech amplitude was increased significantly from single to SRTJ configurations, suggesting coupling between the jets
Zilz and Wlezien (1990)	C-D, rectangular $M_d = 1.25, 1.45$ $AR = 1.15, 2.86$	$s/w = 1.55$–3.2	1.26–1.55	11 dB OASPL reduction when coupling changed from IP to OOP at different M_j values
Walker (1990)	C-D, rectangular $M_d = 1.40$ $AR = 3.71$	$s/w = 2.50$–3.7	1.1–1.7	Inferred OOP to IP coupling from OASPL levels
Raman and Taghavi (1998)	Converging nozzles $AR = 5$	$s/h = 5.5, 9, 15$	1.0–1.6	11 dB screech amplitude reduction when coupling changed from IP to OOP at different M_j values
Karnam et al. (2021)	C-D, rectangular $M_d = 1.50$ $AR = 2.0$	$s/D_e = 2.25$	1.36	10 dB lower internozzle OASPL relative to levels registered overtop of twin jets when coupled OOP

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control authority in a wide variety of flows: subsonic and supersonic jets at various flow conditions and configurations (Kearney-Fischer et al., 2011; Kim et al., 2011; Kuo et al., 2017b; Samimy et al., 2007) and subsonic and supersonic cavity flows (Webb & Samimy, 2017; Yugulis, Hansford, Gregory, & Samimy, 2013). More information on the control mechanism of LAFPAs can be found in a review article by Samimy, Webb, and Esfahani (2019).

As discussed above, LSS play a crucial role in the screech and the coupling feedback process and are responsible for the extraction of energy from the mean flow to drive the screech feedback loop (Edgington-Mitchell, 2019). Thus, the LAFPAs' ability to alter LSS timing, organization, coherence, etc. allows them to effectively control the screech and coupling processes. Recent work in our laboratory (GDTL) has characterized the LAFPAs control authority and effects on the near field as well as far field across a wide range of NPRs to show their effectiveness while understanding the underlying physics in all flow regimes (Samimy et al., 2023). The current work is aimed at investigating the effects of coupling on NF pressure fluctuations using active control by LAFPAs. This study is an expansion of previous literature to further document the relationship between supersonic SRTJ coupling modes and the corresponding NF pressure fluctuations and provide a physical interpretation of the results. As stated earlier, all previous works characterized the coupling with NF pressure at different Mach numbers. The novelty of this investigation is employing the LAFPAs to alter the coupling mode at a constant M_j and independently observe the effect of coupling on NF pressure fluctuations. This work also presents the NF pressure streamwise development (in the irrotational hydrodynamic field), the effects of varying LAFPA excitation frequency and actuation patterns on the coupling and NF pressure. Data have been collected on overexpanded, design Mach, and underexpanded regimes ($M_j = 1.35$, 1.50, 1.65, respectively), but the focus of this paper is on $M_j = 1.35$. However, similarity and differences of the results with the other two cases are briefly discussed.

2. Experimental methodology

2.1. Facility and instrumentation

All the rectangular twin jets experiments were conducted in the GDTL's anechoic test facility at Ohio State University's Aerospace Research Center. The twin jets (shown in figure 1) consist of two rectangular nozzles of aspect ratio 2. The nozzle width is 0.95 inches (24.1 mm), and the adjacent nozzle lips are spaced 0.758 inches (19.25 mm) apart, which is 1 area-based equivalent diameter. The nozzles are bi-conical with a sharp throat (i.e. military-style). The design Mach number (M_d) is 1.5. The twin jets assembly is installed within a 6.2 m by 5.6 m by 3.4 m anechoic chamber. The flow is driven by dried, high-pressure air from two large (36 m^3 total capacity) pressure vessels with a maximum pressure of approximately 2300 psi (16 MPa). The stagnation pressure of the flow is set by a computer-controlled valve, which can be adjusted to maintain the desired NPR. For this work, the NPR was varied from 2.97 to 6.20 ($M_j = 1.35$ to 1.85). This allowed the LAFPAs' control authority to be examined in the overexpanded, design and underexpanded operating regimes.

Near-field acoustic and hydrodynamic pressure measurements were carried out using an azimuthal and a linear microphone array. The azimuthal array consists of 4 Brüel and Kjær 4939 ¼ in. microphones, shown in figure 2(*a*); these microphones were positioned at an axial location of $x/D_e = 0$ (nozzles' exit plane) and radially (measured from the twin jets' major axis) at $r/D_e = 2$ (for microphones 1 and 2) and $r/D_e = 4$ (for microphones 3 and 4). Microphones 3 and 4 were placed so measurements of the coherence and phase of the jets with respect to each other could be made. It should be noted that the sole purpose of these two microphones was to obtain data on the coupling mode of twin jets along the minor axis as previous coupling experiments have shown the minor axis coupling to have dominance over the lateral coupling mode (i.e. along the major axis) (Esfahani et al., 2021). Microphones 1 and 2 were used to measure NF pressure fluctuations in the internozzle region ($z/D_e = 0$) as well as over one of the jets ($z/D_e = 1.125$). These azimuthal microphones' locations are closely related to that of NF pressure measurements in previous literature (Raman & Taghavi, 1998; Zilz & Wlezien, 1990).

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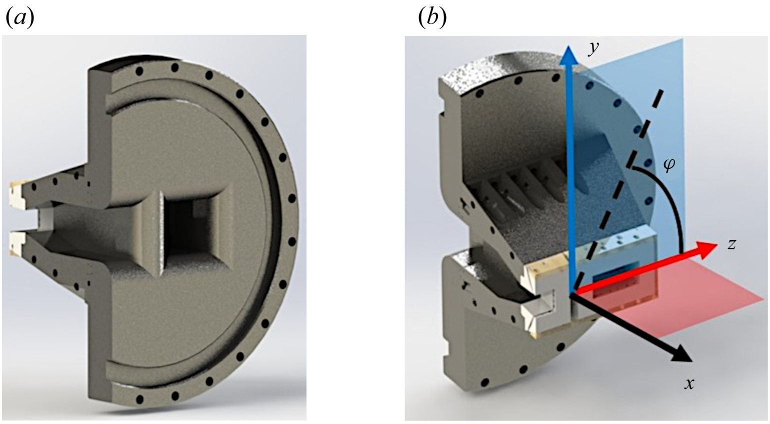

Figure 1. *The SRTJ assembly: (a) internal cutaway, (b) the coordinate system: minor axis (y), major axis (z), and azimuthal angle (φ).*

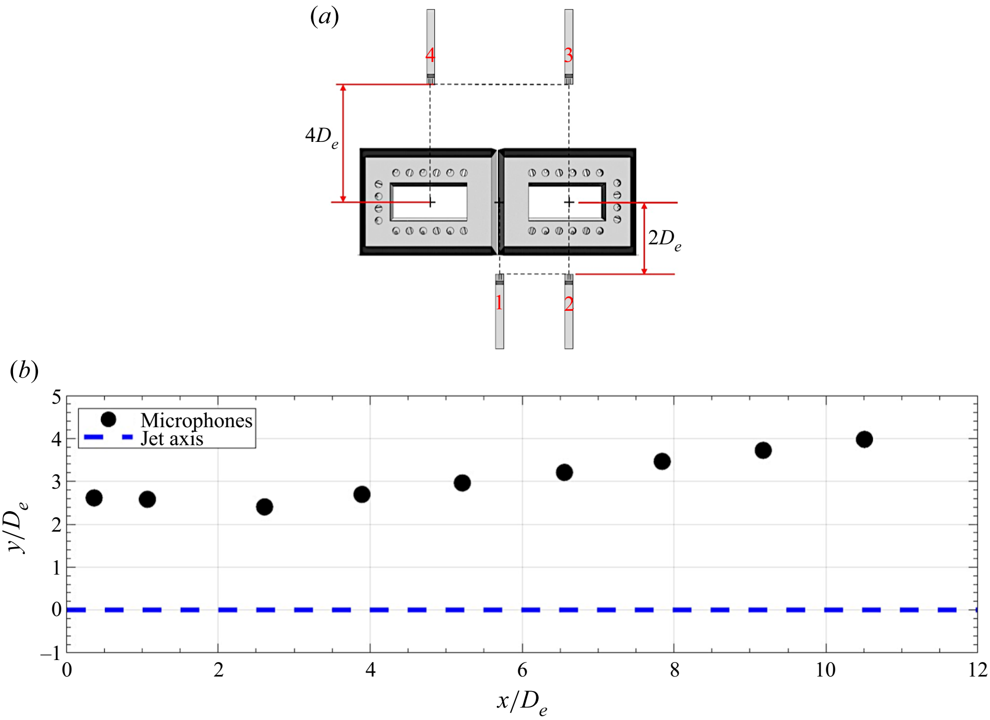

Figure 2. *Near-field microphone locations: (a) ($x/D_e = 0$) for azimuthal array microphones (1–4) and (b) ($z/D_e = 0$) for linear array microphones (5–13, in order of ascending x location).*

The NF linear microphone array (figure 2*b*) was utilized to capture streamwise variations of NF pressure levels; it consists of nine Brüel and Kjær 4939 ¼ in. microphones (5–13). All linear array microphones were located on the internozzle plane ($z/D_e = 0$) to not affect the screech feedback path. Figure 2(*b*) shows both *x* and *y* location of the microphone with respect to the jet centreline. The axial extent of the microphone placement was determined to ensure that shock cells number 3 to 5 were covered with high spatial resolution for different NPRs. Microphones 7–13 in figure 2 are angled at 10° with respect to the downstream jet axis. The array angle and positions on the radial direction or normal to the jet axis (y/D_e) were selected to ensure that the microphones were not within the flow field.

This was confirmed through examination of the shear layer spreading from instantaneous schlieren imaging (not shown).

Time-resolved schlieren imaging was utilized using a standard Z-type schlieren arrangement. The collimated light passed through both jets (i.e. parallel to the jets' major axis (z), figure 1b). A HPLS-36 high-powered, pulsed, LED light source from Lightspeed Technologies was used in continuous mode for illumination and the images were acquired at 59 091 frames per second with an 8 µs exposure by a Phantom v1210 high-speed camera. The knife-edge was oriented vertically to measure density gradients along the x-axis and 10 000 images with a window size of 512×320 pixels were acquired for each test condition. The results were post-processed using Ohio Supercomputer Center resources with a spectral proper orthogonal decomposition (SPOD) code developed by Schmidt and Colonius (2020).

2.2. Data acquisition and processing

All NF pressure measurements were taken simultaneously with the azimuthal and linear array microphones shown in figure 2. The sampling frequency was 200 kHz and 25 blocks of 32 768 samples were acquired for each data point, resulting in a frequency resolution of 6.10 Hz. Microphone signals were amplified and band-pass filtered between 20 Hz and 100 kHz, using a Nexus 2690 signal conditioner. Prior to acquiring a set of NF data, a few runs were conducted to ascertain what level of gain was needed to use the entire dynamic range without saturating the channels. Microphone calibrations were also performed at the selected gain, using a Brüel and Kjær model 4231 acoustic calibrator. The gain value for all experiments reported in this paper was set to 1 mV Pa^{-1}.

Microphones 3 and 4 (shown in figure 2a) were used to determine the strength and mode of the jets' coupling for the baseline and under various excitation conditions. The earlier work in our laboratory (Esfahani et al., 2021) motivated this placement of the microphones by documenting that coupling along the minor axis is more dominant than that along the major axis in this low *AR* SRTJ. This is in contrast with supersonic circular twin jets, in which the coupling is primarily along the shared major axis of the jets (Kuo, Cluts, & Samimy, 2017a). The Morlet-wavelet coherence magnitude and phase between microphones 3 and 4 were calculated. Then, the time-averaged coherence magnitude and phase were calculated (note coherence was set to zero when the coherence magnitude was below 0.7, but all points were used in calculating time-averaged coherence. In addition, the phase was not included in the average if coherence was below this threshold). These quantities were used to determine the jet coupling strength and mode (IP or OOP). This allowed the jets' response to the excitation using LAFPAs to be observed and the strength and mode of the jets' coupling under various excitation conditions to be determined. A fast Fourier transform code in MATLAB was used to calculate the spectra for each block of data and then averaged spectra were calculated from 25 blocks. The calculated power spectral density (PSD) was then converted to decibels referenced to 20 µPa.

Using the data from microphones 5 through 13 (figure 2b), the de-toned (smoothed) PSD was also computed by means of a moving median with a window size of 1 kHz to remove all sharp peaks associated with both the natural screech and excitation. The removal of the spectral peaks assisted in showing the effect of excitation on broadband characteristics of the data. Overall sound pressure level in decibels was determined by integrating the PSD as shown in (2.1), also used in previous literature (Brès, Ham, Nichols, & Lele, 2017). This calculation was performed for both raw and de-toned spectra, over the frequency domain with limits, f_{upper} and f_{lower}, corresponding to Strouhal numbers of 0.04 to 1.5. Strouhal number was calculated using the fully expanded jet equivalent diameter D_j (defined in Tam & Tanna, 1982) and fully expanded jet velocity, u_j: $St = fD_j/u_j$. Note that Tam & Tanna's definition of D_j is for round jets, but based upon conservation of mass. Therefore, the actual jet diameter employed here in the calculation of D_j is taken to be the area-based equivalent diameter of the rectangular jets under study

$$OASPL = 10\log_{10}\left(\int_{f_{lower}}^{f_{upper}} 10^{0.1PSD(f)}\,\mathrm{d}f\right). \tag{2.1}$$

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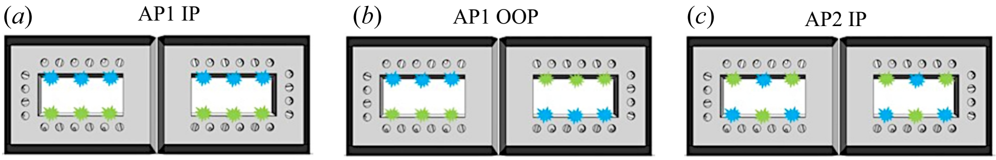

Figure 3. *Implemented actuation patterns, where (a) encourages IP coupling between twin jets, (b) encourages OOP coupling, and (c) encourages development of three-dimensional LSS.*

2.3. Plasma actuators

Localized arc filament plasma actuators provide high-amplitude and high bandwidth perturbations necessary for excitation of instabilities in supersonic shear layers. They have significant documented success controlling high-speed jet flows (e.g. Kearney-Fischer et al., 2011; Kim et al., 2011; Samimy et al., 2007). A high voltage is applied across the two electrodes of each actuator, which induces the breakdown of the air in the gap between the electrodes, producing a thermal perturbation for the excitation of the instability in the jet's shear layers (Samimy et al., 2018).

Figure 1 shows a model of the current SRTJ nozzles. These nozzles have thicker lips to accommodate the plasma actuators, distributed around the nozzles' perimeters. Shown in figure 3, there are six actuators (three on the top, three on the bottom) on each nozzle. Each actuator consists of two, 1 mm diameter tungsten electrodes that are spaced 3 mm apart centre to centre, one of which is grounded, the other is connected to an in-house-built, high-voltage pulse generator. The electrodes are located within a groove that is 1.0 mm wide and 0.5 mm deep, approximately 1 mm upstream of the nozzle exit. The tips of the electrodes are nearly flush with the nozzle surface. Each actuator channel is individually computer controlled, allowing a wide variety of excitation conditions. Three main excitation parameters were implemented: excitation pattern, relative phase of excitation between the two jets and the excitation frequency.

Excitation patterns (spatial organization of actuators to fire) were determined based on the LAFPAs' ability to alter the SRTJ natural coupling mode (i.e. to suppress or enhance it). Samimy et al. (2023) confirmed that the screech mode of these low *AR* jets is a flapping or antisymmetric mode along the minor axes, like that identified in low *AR* jets by Zilz and Wlezien (1990). The coupling modes, as reviewed earlier, are directly tied to the screech loops of each of the twin jets. To mimic the natural flapping of the jets, actuation pattern 1 (AP1), shown in figure 3(*a*,*b*), was used. In AP1, all three actuators on each nozzle lip were fired simultaneously and 180° OOP with those on the opposing lip of the same nozzle. The phase of actuation between the two jets was set either to 0° (figure 3(*a*), to encourage IP coupling) or 180° (figure 3(*b*), to encourage OOP coupling). Again, it is important to state that one of the main objectives of the current work is to investigate how the two (IP and OOP) coupling modes affect NF pressure fluctuations at the same M_j. Actuation pattern 2 (AP2) shown in figure 3(*c*), was utilized to promote the generation of three-dimensional LSS in the flow. This excitation pattern encourages three-dimensional development of LSS, which are less coherent and more disorganized than that of the naturally occurring LSS and those produced by AP1 excitation. The AP2 LAFPA excitation mimics that of excitation performed in circular jets (Kuo et al., 2017b), where higher azimuthal modes (e.g. helical mode, $m = 3$) produced lower NF pressure fluctuations than those of the baseline levels due to three-dimensional LSS. The AP2's effect on far-field (FF) noise as well as coupling in SRTJ has been documented in Samimy et al. (2023). A recent simulation work using higher Strouhal number (*St*) excitation (∼1) with a three-dimensional pattern in a single rectangular jet shows significant reduction in the FF noise (Prasad & Unnikrishnan, 2023). The associated NF pressure fluctuations of AP1 and AP2 will be discussed in the results to follow.

The excitation frequencies (pulse repetition) imposed by LAFPAs are of importance as they govern the organization (i.e. timing) and spatial development of LSS. Frequencies at which the LAFPAs were used in this work are as follows:

- Screech frequency ($St_e = St_s$).
- Above screech frequency ($St_e > St_s$).

Most of the excitation frequencies presented are within the jet column mode (i.e. the jets' 'preferred mode', $St = 0.2$–0.60) where the actuators have shown a strong effect on controlling the development of LSS and subsequent screech and coupling loops. These jet column frequencies used to excite the jets were chosen based on an empirical closure model developed and validated at the GDTL (Webb, Esfahani, Yoder, Leahy, & Samimy, 2022). Excitation frequencies below the natural screech frequency were deemed undesirable as previous campaigns demonstrated that these lower frequencies increased NF pressure fluctuations and FF acoustic levels and did not reveal any interesting physics or beneficial control effects. Thus, lower frequency cases were omitted from this work.

For the selection of excitation frequencies above the screech frequency, the developed empirical closure model provided a means of predicting how the twin jets will respond to excitation at a particular frequency and coupling mode within the jet column mode. The model postulates that LSS propagating downstream interact with the shock cells and produce upstream travelling acoustic waves that form an interference pattern at the nozzle lip. The screech loop is created when the frequency and perturbation phase of the feedback waves match with those of the production of LSS. Similarly, the coupling mode (IP/OOP) of the jets is found using the net perturbation amplitude and phase at the nozzle lip. This model is similar to that of Norum (1983), but uses the empirical shock cell spacing model developed in the GDTL, and has been extended to SRTJ for both overexpanded and underexpanded jets. With this model, excitation parameters for the LAFPAs can be selected for a specific desired coupling mode at excitation frequency to either reinforce or suppress the preferred (or natural) coupling mode. More on this can be found in Webb, Esfahani, Yoder, et al. (2022).

3. Results

3.1. Baseline

The NF measurements were used to determine the coupling and screech modes and to relate them to the NF pressure fluctuations. Results in this baseline section present the coupling modes over different flow regimes. The NF pressure fluctuations from these baseline M_j values will be compared with the excitation cases that follow.

The NF measurements utilized an azimuthal array (figure 2*a*) to assess the coupling and screech modes. It is not shown here, but previous unheated SRTJ work has shown that the primary screech mode is flapping (or antisymmetric) along the minor axis (Samimy et al., 2023). Figure 4 highlights the trends of time-averaged coherence and phase as well as the variation of phase at a given NPR for understanding of SRTJ coupling across a wide range of NPRs. These are wavelet-based time-averaged coherence (magnitude) of the coupling in black as well as the absolute value of the time-averaged phase of the coupling at the natural screech frequency (St_s). Microphones 3 and 4 (figure 2*a*) register the acoustic feedback of each jet and therefore the coherence and phase between these two provide insight into the coupling of the screech loops. It is important again to note that SRTJ coupling of screech loops is intertwined with the screech feedback process, i.e. coupling takes place at the frequency at which the resonance peak (screech) is located. Note that the SRTJ coupling (as well as screech tonal amplitude) is dependent on the experimental conditions (ambient temperature, jet stagnation temperature, ambient relative humidity, etc.) which affect the resonant feedback loops. Consequently, some variability has been observed in the coupling modes and screech amplitudes in this extended research program, similar to that which Powell notes in his results (Powell, 1953). More detailed information on this observation is documented in Esfahani (2022).

Three main observations of the coupling modes over the range of NPRs were made: (i) coupling is strong at highly over- and underexpanded cases, while it is weakened near the fully expanded design condition; (ii) the dominant coupling mode is OOP and IP (figure 4) at over- and underexpanded operating conditions, respectively; (iii) intermittent coupling is seen from overexpanded to

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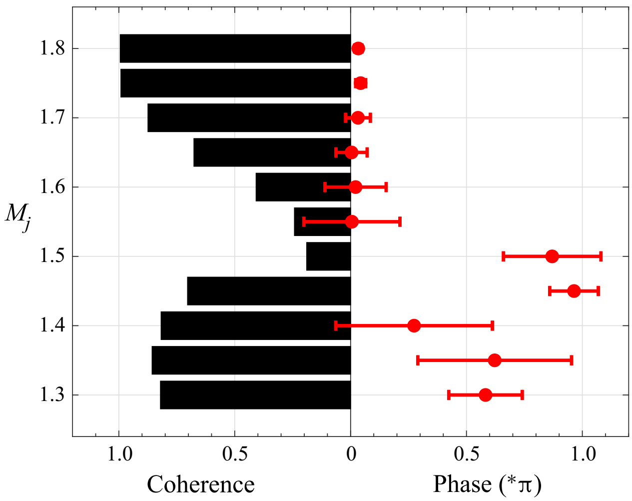

Figure 4. *Baseline wavelet-based time-averaged coherence and phase at the natural screech frequency (St_s).*

weak underexpanded flow regimes. The first point regarding the strength of coupling is denoted by the black bars that signify the coherence level between the acoustic signals (at St_s) of microphones 3 and 4. The coupling at the screech frequency is moderately strong at the lower M_j values (overexpanded regime), denoted by coherence ∼0.7 or higher, then weakens near the fully expanded design M_j and, finally, strengthens in the underexpanded regime shown by the coherence of the signals increasing to 1. This observation makes sense when considering the physics at hand: at M_j values far away from the design condition ($M_j = M_d = 1.50$), the non-ideally expanded jet has a stronger shock train (both in the over- and underexpanded regimes than the ideally expanded condition), that allows stronger interactions with the convecting LSS, resulting in enhanced BBSAN and thus stronger screech and coupling. Screech and coupling are present at the design Mach number ($M_d = 1.50$) because a secondary shock train, due to the sharp throated nozzle, is always present. This confirms the results of Seiner et al. (1987), who found that when operating at NPRs far from M_d, the screech amplitudes are strengthened due to the strong shock cells downstream of the jet.

The second observation is that the phase of the coupling of the jets has a specific trend over the different flow regimes. At the overexpanded conditions, the jets couple OOP (∼π rad) with large phase variations, while the underexpanded jets couple IP (∼0) with little to no phase variations. The phase of coupling agrees with the null space hypothesis of Raman and Taghavi (1998) as well as the predictions of the in-house developed feedback closure model (Webb, Esfahani, Leahy, & Samimy, 2022). Specifically, the null space is characterized as the region at the nozzle exit plane over which the feedback waves from a single jet have a phase variation of less than 10°. Raman and Taghavi hypothesized that, if these 'null spaces' between the two jets overlap, then the coupling mode the jets will naturally select is IP. Otherwise, the jets will couple OOP if at all. When applying this to the wide range of NPRs, as observed in the spectral content, the frequency of the screech tone is decreased with increased M_j due to the elongation of the shock train downstream of the jet (see Samimy et al., 2023). Consequently, the upstream acoustic waves impinging at the nozzle exit plane have longer wavelengths and a with larger radius of curvature at higher M_j values, thus a larger null space region and a greater tendency to couple IP.

The third observation of the coupling is the large phase variation (red bars) trend of overexpanded cases. Work is currently underway to further characterize the intermittency observed in overexpanded cases. Variations in coupling strength and phase in underexpanded round twin jets have been explored in detail in a recent publication by Wong et al. (2023).

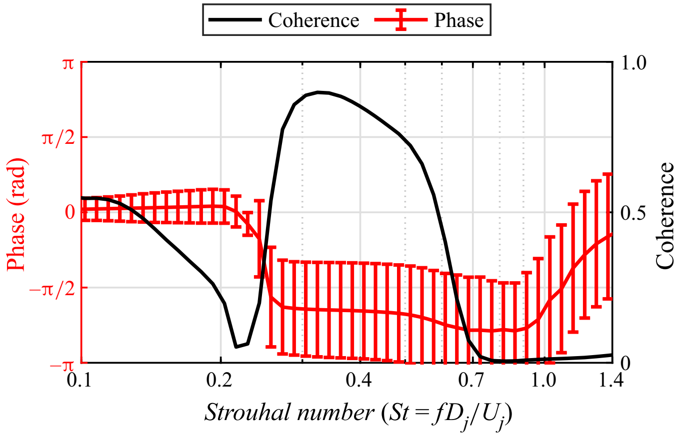

Figure 5. *Baseline results for time-averaged coherence and phase for the overexpanded case* ($M_j = 1.35$).

To gain a better insight of the baseline coupling and the effects of excitation, one M_j (1.35, NPR = 2.97) case will be analysed in depth, as the other M_j values have shown similar trends. Figure 5 highlights this overexpanded NPR's time-averaged wavelet coherence and phase. The coherence (black curve) of the signals from microphones 3 and 4 is broad and close to one at the natural screech frequency $St_s = 0.40$, denoting strongly coupled jets. The red curve shows an OOP signal at this natural screech frequency; however, it has a large phase variation as denoted by the bars. These large bars point to the fact there are considerable variations in phase during the measurement record (over 30 000 screech periods). A potential reason for these phase variations is the tendency of SRTJ at this M_j (or NPR) to couple IP or OOP, as will be further discussed below.

Because of the low spectral resolution of the wavelet technique, Fourier-based coherence and phase were used to confirm that the coupling occurs at precisely the natural screech frequency. The disadvantage of the Fourier method is that it does not accurately represent statistically non-stationary events (e.g. intermittent coupling), unlike the wavelet technique, and, due to the random phase calculated at uncorrelated frequencies, produces noisier plots with decreased clarity. Therefore, only wavelet coherence and phase results will be presented here.

3.2. Excitation: NF pressure fluctuations at the nozzle exit plane

As described earlier, the three main parameters of excitation (excitation frequency, actuation pattern and relative phase) were varied, and all three have significant effects. Each combination of these parameters targets a different physical phenomenon in the jet flow for specific outcomes in the coupling and NF pressure fluctuations. This section goes into depth on the characterization of excitation effects on coupling and NF pressure fluctuations utilizing azimuthal array at the nozzle exit plane (figure 2*a*) and the streamwise linear array (figure 2*b*). The coupling of screech loops was assessed using the same method as the baseline (coherence and phase of microphones 3 and 4), and the NF pressure fluctuations were characterized by calculated OASPL (microphone 1). It should be noted that microphones 1 and 2 show the interference between the feedback waves of the two jets. Since microphone 1 is located on the minor axis of SRTJ, IP coupling generates constructive and OOP coupling destructive interreferences, and thus higher and lower OASPL, respectively. In screeching SRTJ, whether coupled IP or OOP, the OASPL at microphone 2's location is expected to be high. However, the assessment of the effects of coupling in microphone 2's location, in fact in any location other than on the minor axis of SRTJ (due to the absence of simplifying symmetry), is not straightforward. Therefore, only the results from microphone 1 will be presented and discussed in the rest of the paper. Because similar general trends have been seen in all regimes, the overexpanded case $M_j = 1.35$ will be presented and discussed in detail and then the similarity and differences of the results with the design and underexpanded flow regimes ($M_j = 1.50$ and 1.65, respectively) will be briefly discussed.

The combined effects of two of the three main parameters of excitation, actuation frequency and relative phase, were investigated, and results are shown in figure 6 for two frequencies within the jet column mode (0.2–0.6). Note that all the cases shown in figure 6 utilize the AP1 firing pattern (figure 3). The top two rows (*a* and *e*, *b* and *f*) are excited cases at the natural screech frequency ($St_e = St_s = 0.40$). The top row displays the results for an IP excitation pattern and the second row for an OOP excitation pattern (figure 3). The coherence and phase show drastic changes from the SRTJ baseline coupling (figure 5), where the natural tendency was shown to be intermittently OOP coupled. Now the SRTJ are strongly coupled (high coherence at St_s), and the coupling is more consistent in time (decreased red bars on phase). The relative phase of two cases (IP, OOP) shows that the SRTJ are receptive to either coupling phase, hence the intermittent phase of the baseline case (figure 5), and that the LAFPAs can couple the jets either IP or OOP.

The second column illustrates the changes in the NF OASPL (ΔOASPL) to assess the change in NF pressure fluctuations relative to that of the baseline. Solely observing excitation at St_s and comparing the effects of IP and OOP coupled cases, it is apparent that the coupling significantly influences the internozzle pressure fluctuations (microphone 1, figure 2*a*). The pressure difference shows an increase (relative to the baseline) of ∼4 dB for the IP coupled case and a decrease of ∼8 dB for the OOP coupled case, for a total difference of 12 dB. This significant pressure difference reaffirms the findings of Zilz and Wlezien (1990), and Raman and Taghavi (1998); i.e. that OOP coupled cases show dramatically lower pressure fluctuations in comparison with IP coupled ones. However, to the authors' knowledge this is the first time NF pressure fluctuations has been directly related to coupling mode at the same M_j/NPR. A physics-based interpretation of these results assists in understanding this phenomenon. The IP and OOP coupled pressure fluctuation levels are a direct reflection of the acoustic feedback waves' interference. In the internozzle region, OOP cases result in destructive feedback of acoustic waves, thus resulting in lower pressure levels. The opposite is true for IP cases: the acoustic waves interfere constructively, resulting in higher NF pressure fluctuations.

The bottom two rows of figure 6 show the coupling and the change in pressure fluctuations still exciting the jets with AP1, but now the frequency has been increased to $St_e = 0.48$, above the natural screech frequency. Note that this frequency is still within the jet column mode ($St \sim 0.2$–0.6) where the jet is expected to respond strongly (Kuo et al., 2017a). Observing solely the time-averaged coherence and phase (figure 6*c*,*d*), the excited results show the ability to weaken the natural coupling loop. The black coherence curve is not as broad as when excited at the natural screech frequency, denoting that the coupling is not as strong as when excited at its natural screech frequency. Physically, the smaller, yet coherent LSS, encouraged by the higher St_e, extract significant energy from the mean flow, reducing the available energy for the natural feedback loop, consequently resulting in both weaker screech and coupling at St_s. To confirm this, the PSD of microphone 1 for this higher excitation IP case ($St_e = 0.48$, AP1 IP) is shown in figure 7. The baseline natural screech (black curve) contains a large base across frequencies ($St \sim 0.39$–0.42), reflecting the feedback variability which is expected in a natural resonance loop (Kearney-Fischer et al., 2011; Samimy et al., 2023). When excited at the precise frequency of $St = 0.48$, the peak is extremely narrow, confirming that there is no established screech loop (with the variability of a natural feedback process) at St_e. The high-amplitude and sharp peak at $St_e = 0.48$ is known to exist in acoustic field of excited cases at St_e as well as its harmonics (Kearney-Fischer et al., 2011). The SPOD results of this exact M_j at a slightly higher excitation frequency ($St_e = 0.57$), were shown in Samimy et al. (2023), demonstrated this phenomenon of less coherent LSS at St_s and more coherent LSS at St_e; SPOD energy modes of even higher St_e will be presented and discussed later.

The changes in the coupling phase at St_s (figure 6*c*,*d*) which follows the excitation phase are quite interesting and not intuitive. This is driven by three phenomena: (i) the primary one is the receptivity of the baseline SRTJ (figure 5) to both IP (figure 6*a*) and OOP (figure 6*b*) coupling, (ii) the secondary one

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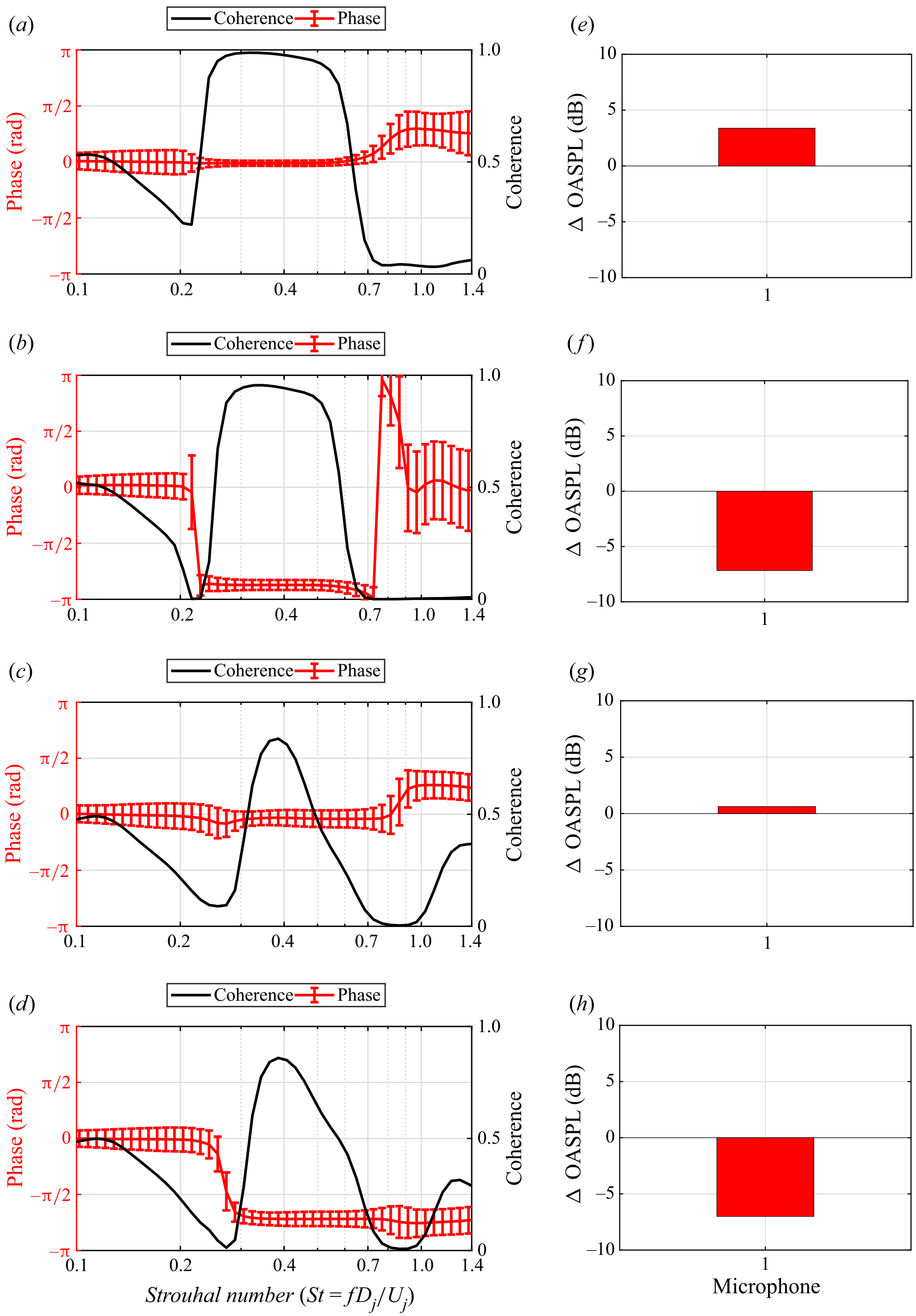

Figure 6. *Effect of frequency and actuation pattern on SRTJ coupling (a–d) and NF pressure fluctuations (e–h) for* $M_j = 1.35$*, AP1:* $St_e = St_s = 0.40$ *(a,e) IP, (b,f) OOP and* $St_e = 0.48$ *(c,g) IP, (d,h) OOP.*

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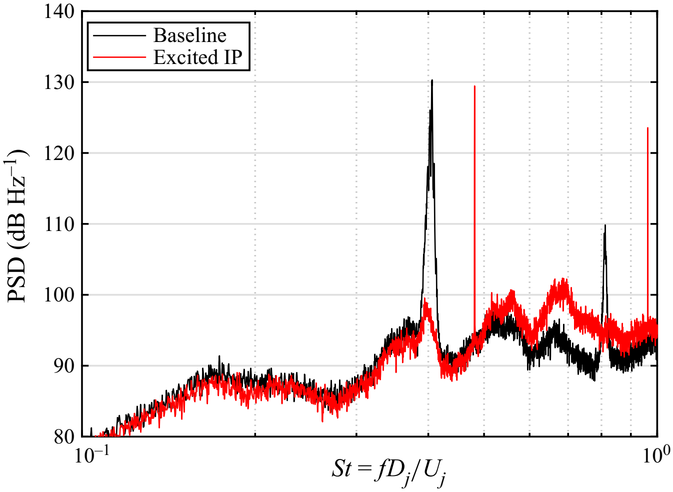

Figure 7. Power spectral density of microphone 3 data for $M_j = 1.35$ baseline (black) and AP1 IP at $St_e = 0.48$ (red).

is extraction of significant amount of energy from the mean flow by the LSS at $St_e = 0.48$ and (iii) the tertiary one is the excitation pattern at St_e (IP or OOP), which in conjunction with 2 helps the primary screech loop in deciding the phase of the coupling at St_s.

The first row of figure 8 presents coherence and phase (a) and ΔOASPL (c) for the IP excited case, but the LAFPAs fire at a much higher frequency ($St_e = 0.72$), outside of the jet column mode. The OOP case is not shown because the same trends as in the IP excitation case were seen. The phase is nearly unchanged from the baseline (figure 5), as the natural screech and coupling have been weakened but not eliminated. The weakening of the coupling and screech amplitude at St_s, has also resulted in approximately 2.5 dB OASPL at microphone 1 location. The explanation for this weaker coupling of SRTJ stems from the understanding that this higher frequency is now outside of the jet column mode. Like that of the $St_e = 0.48$ case, these spatially smaller LSS extract significant energy from the mean flow, reducing the available energy for the natural feedback loop at St_s.

The SPOD mode shapes shown in figure 8 confirm that LSS are present at both the natural screech frequency ($St_m = St_s$) (figure 8*b*) and the excitation frequency ($St_m = St_e$) (figure 8*d*). The $St_m = 0.40$ mode shape (figure 8*b*) exhibits the signature of coherent structures in the shear layer of the flow and the jets natural flapping (antisymmetric mode), while $St_m = 0.72$ (figure 8*d*) shows coherent structures that would not naturally exist in this case and are generated in the flow in response to excitation. The wavelengths of the lobes agree with the frequency of excitation, given an estimated convection velocity of $U_c/U_j \sim 0.7$. This flow field imaging technique strongly supports the LAFPAs' ability to alter the organization and timing of LSS' development within the SRTJ's shear layers. For more results on SPOD analysis of these jets and LAFPAs' effects on them, including the baseline mode shape (without excitation), the reader is referred to Samimy et al. (2023) and Webb, Esfahani, Leahy, et al. (2022).

3.3. Excitation: pressure fluctuations in the SRTJ hydrodynamic field

For two of the three excited cases presented earlier, NF pressure fluctuations were measured at the SRTJ hydrodynamic field utilizing the NF linear array to give insight into the streamwise development of LSS and the induced pressure fluctuations in the irrotational hydrodynamic field. The results at $St_e = St_s = 0.40$ are displayed in figure 9*a*,*c*, and at $St_e = 0.72$ are highlighted in figure 9*b*,*d*. The raw OASPL of the baseline, IP and OOP coupling cases are shown in the left column, while the right column shows the detoned OASPL. Comparing IP and OOP coupling with the baseline results at the $St_e = St_s$ case (top row),

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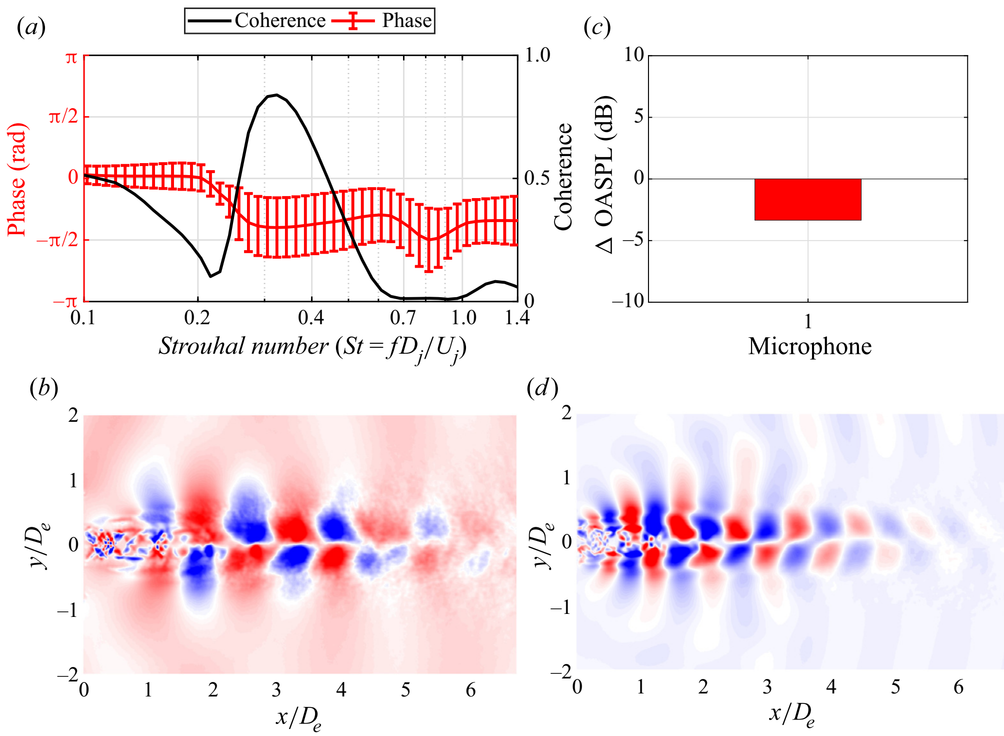

Figure 8. *Effects of excitation outside the jet column mode for $M_j = 1.35$, AP1 IP at $St_e = 0.72$: coherence and phase (a), ΔOASPL at microphone 1's location (c), SPOD mode 1 shapes at $St_m = 0.40$ (b) and at $St_m = 0.72$ (d).*

the raw OASPL in figure 9(*a*) shows a trend of significantly increased levels for the IP excited cases at all the downstream locations. Comparing the results for the baseline and OOP excited case, the OOP raw OASPL shows slightly decreased levels at lower x/D_e locations (<1.5), then higher level from $x/D_e = 2$ to 5. Remembering that the linear array probe is on the jet symmetry (internozzle) plane, it can be said that the same acoustic interference effects (i.e. IP constructive, and OOP destructive) noted in earlier discussion are the reason for these OASPL trends. The results are also consistent with the physics of the flow, i.e. the jets are screeching and the LSS are more coherent in both IP and OOP coupling cases than the baseline case. The switch of the OASPL positions between OOP and baseline cases up to $x/D_e \sim 5$ is due the dominance of acoustic field near the nozzles' exit plane and hydrodynamic field further downstream. The de-toned OASPL, representing the integration of the broadband PSD for all three cases (figure 9*c*), illustrates a collapse in the data at all streamwise locations. This demonstrates that the interference is occurring in the tonal peaks (of screech and its harmonics) of the PSD. These de-toned OASPL also portray the similar development of LSS in the flow, which are tied to the development of hydrodynamic pressure in the streamwise direction of the jet (Sinha, Alkandry, Kearney-Fischer, Samimy, & Colonius, 2012). It is known that LSS (or wave packets) follow a pattern of initial growth (up to around $x/D_e = 4$), saturation (between around $x/D_e = 4$ to 7) and finally decay. These trends in the results are consistent with the results in the literature and the fundamental physics of the flow.

The OASPL of the high excitation frequency case (figure 9*b*,*d*) shows a collapse of the IP and OOP excited and baseline cases. These results are consistent with the results shown in figure 8 and related discussions. The employment of this higher excitation frequency develops smaller, closely spaced LSS that extract more energy from the mean flow, suppressing or weakening the natural screech and coupling. In addition, the smaller LSS develop further upstream and disintegrate at a faster rate and therefore do not interact with the shock cells to same extent, thus creating less coherent feedback waves.

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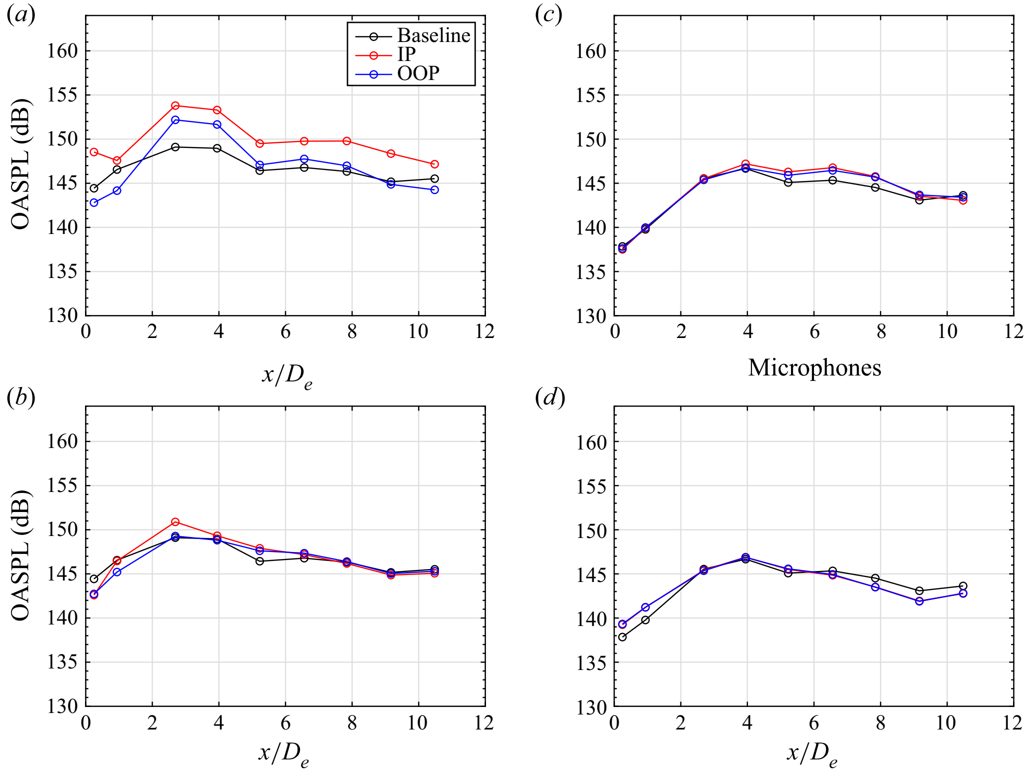

Figure 9. *Effect of excitation frequency and actuation pattern on streamwise variations of OASPL for* $M_j = 1.35$*:* $St_e = St_s = 0.40$ *for (a) raw and (c) de-toned OASPL,* $St_e = 0.72$ *for (b) raw and (d) de-toned OASPL.*

Overall, the main findings are that excitation frequencies within the jet column mode can have significant effects on the screech and coupling and therefore IP and OOP coupling plays a large role in the levels of internozzle pressure fluctuations. This is again because LSS are sufficiently large and coherent to drive the natural coupling loops. The other main finding of this investigation is that, when exciting at higher frequencies outside of the jet column mode, the baseline coupling remains, but is either significantly weakened or suppressed, resulting in reduced NF pressure fluctuations for either IP or OOP excitation.

3.4. Excitation: effect of three-dimensionality

The last main excitation parameter is the influence of different actuation patterns on NF pressure fluctuations. As shown in figure 3 and explained earlier, AP2 was adopted to encourage the development of three-dimensional LSS. This actuation pattern does not reinforce the jets' natural screech mode (flapping), like that of AP1. In contrast to the inherently two-dimensional K-H instability, AP2 encourages three dimensionality to reduce coherence of the LSS that facilitate screech and coupling. Although the coupling of this excitation is not shown, this high frequency AP2 patterns effect on the coherence and phase is detailed in (Samimy et al., 2023). Figure 10 highlights NF OASPL of excited cases using AP2 at two different frequencies: (*a*) $St_e = St_s = 0.40$ (*b*) and $St_e = 0.72$. Excitation at natural screech (figure 10*a*) demonstrates that the OASPL are independent of relative phases. This is expected, as AP2 is not tied to the jets' natural coupling modes (IP and OOP) and promotes three-dimensionality. In comparison with AP1 at this frequency, AP2's excited levels are similar to those of the lowest excited levels in AP1 (OOP

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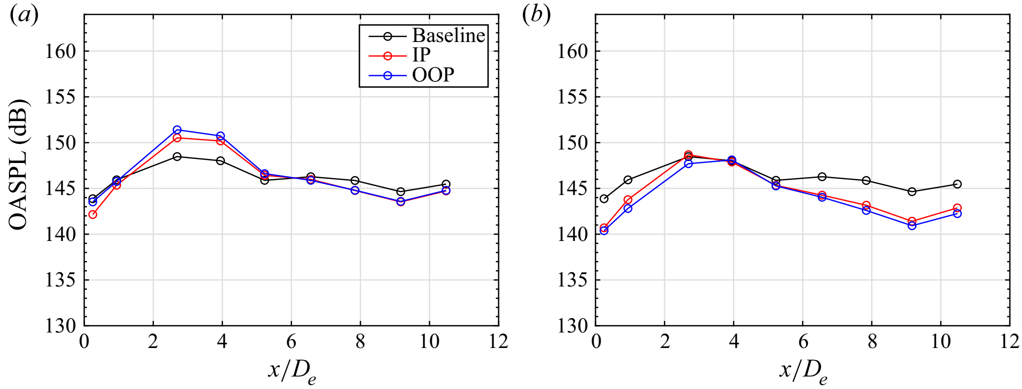

Figure 10. *Streamwise variations of OASPL of AP2 excitation for $M_j = 1.35$: (a) $St_e = St_s = 0.40$, (b) $St_e = 0.72$.*

case), with more of a decrease in OASPL at downstream locations. Focusing on the higher frequency case of AP2 (figure 10*b*), it is important to highlight that, other than near the peak OASPL locations, the excitation has reduced OASPL at every measured streamwise location. Although not shown, NF pressure fluctuations at the nozzle exit plane have seen significant decrease in OASPL in microphone 1 with high frequency AP2 excitation.

While most of the results presented in this paper are in the overexpanded regime, similar trends of IP and OOP effects on internozzle pressure fluctuations and the effects of control have been seen in overexpanded, underexpanded and design cases (Leahy, Esfahani, Webb, & Samimy, 2022). It is worth noting the observations of high frequency, AP2 excited cases in other flow regimes. In design and underexpanded regimes ($M_j = 1.50$ and 1.65, respectively), the high frequency (outside the jet column mode), AP2 excitation demonstrated similar trends in pressure fluctuations in streamwise direction (not shown). The main findings were: (i) relative phase of AP2 had little effect on OASPL like in $M_j = 1.35$, due to AP2 not targeting the natural flapping screech and coupling modes, (ii) excited cases showed similar downstream (past the peak OASPL) reduction in OASPL, (iii) the peak NF pressure fluctuations moved downstream with increasing M_j/NPR, agreeing with the understanding of the development of LSS; i.e. for higher M_j values (or NPRs) the shock train (and supersonic core) is elongated (Samimy et al., 2023), allowing LSS to grow to a larger size, before breaking down at the end of the supersonic core.

4. Conclusions

This work focuses on the physics and the effects of coupling on the NF pressure fluctuations in SRTJ. Previous studies have found that the unsteady NF pressure fluctuations due to the coupling of the flow and acoustic fields can damage aft components of the aircraft. The sharp-throated, converging–diverging twin jet nozzles used in this work have an aspect ratio of 2 and a design Mach number of 1.50. The area-based equivalent diameter is 0.758 in. (19.25 mm), and the lip-to-lip and centre-to-centre spacings of the nozzles are $1D_e$ and $2.25D_e$, respectively. The NF azimuthal and linear arrays of microphones were used to assess NF OASPL and to determine the coupling mode of the jets with a time-averaged wavelet-based coherence and phase. Active control via LAFPAs was utilized to manipulate LSS (or wave packets) in the jets' shear layers. The LAFPAs seed the flow with thermal perturbations within a band of frequencies where flow instabilities naturally amplify them. Various excitation Strouhal numbers ($St = fD_j/u_j$), both within and outside the jet column mode, as well as actuation patterns were employed for different outcomes. The frequencies chosen were guided by an in-house developed feedback closure model.

The LSS are the primary driving factor of jet screech. With the addition of another closely spaced jet, the two screech loops can couple, generating large unsteady NF pressure fluctuations. The coupling modes in the SRTJ investigated are IP and OOP along the minor axis of the jets. Previous literature has documented that the internozzle (jet symmetry plane) region's NF pressure fluctuation amplitude is dependent on the coupling of the jets; IP coupling produces stronger NF pressure fluctuations than OOP coupling. However, all the previous studies have observed this at different jet nozzle pressure ratios (or M_j values), where different coupling modes and strength can exist. To the authors' knowledge, this is the first time NF pressure fluctuations are assessed at different coupling modes with the same M_j.

The baseline coupling modes of SRTJ were investigated over a large jet operating range ($M_j = 1.30$ to 1.80, corresponding to nozzle pressure ratios from 2.77 to 5.75). The major findings of the baseline coupling are: (i) coupling is strong at highly over- and underexpanded cases, while it is weakened near the design condition; (ii) the dominant coupling mode is OOP and IP at over- and underexpanded operating conditions, respectively; (iii) intermittent coupling is often observed in OOP coupled cases, primarily in overexpanded M_j values.

The LAFPAs' control authority over coupling and NF pressure fluctuations is significant and was used for different effects at different frequencies and patterns of excitation. Some findings of the excited cases include: (i) exciting at the natural screech frequency can couple the jets either IP or OOP. The coupling strongly affects the internozzle NF pressure fluctuations due to either constructive (for IP) or destructive (for OOP) interference of the acoustic feedback waves; (ii) exciting at higher frequencies than the screech frequency but within the jet column mode, the LAFPAs are able to weaken the natural coupling loop, while simultaneously controlling the coupling mode; (iii) exciting at frequencies higher than the jet column mode proved to weaken the natural screech and coupling loops, due to the generation of smaller LSS, which take away energy from the natural screech loop. This resulted in lower NF pressure fluctuations in all regions of the jet; (iv) actuation patterns that encouraged three-dimensional development of LSS, weakened the natural coupling loop, thus reducing NF pressure fluctuations in all regions.

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Declaration of interests. The authors declare no conflict of interest.

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