Control of Coupling in Twin Rectangular Supersonic Jets

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Coupling in the closely spaced twin jets employed in advanced tactical aircraft can lead to significant increases in near-field pressure fluctuations, which might result in structural fatigue and failure, and increased far-field noise. The benefits that can be obtained through integrating non-axisymmetric geometries in the latest generation of tactical aircraft have justified the renewed interest in gaining a better understanding of coupling and screech dynamics in such geometries. The simultaneous presence of two feedback loops, namely screech and coupling, in closely spaced coupled jets render the dynamics involved in these processes quite complex. The results of active flow control experiments aimed at better understanding the complex dynamics of the screech and coupling processes in closely spaced, low AR, twin rectangular supersonic jets with a design Mach number of 1.5 are presented in this paper. Experiments were conducted at an overexpanded Mach number of 1.35. The baseline jets at this Mach number demonstrate a tendency to intermittently couple in-phase. The screech mode of the individual jets was anti-symmetric. Two active control experiments, aimed at exploring the effects of altering the screech and coupling loops, are presented and the results are discussed. In the first experiment, the excitation frequency and relative phase between the adjacent jets were matched to the natural screech frequency of the jets and their coupling tendency but the jets were forced to adopt a symmetric screech mode. The results showed that organizing the shedding of large-scale structures (LSS) through excitation results in strengthening of the screech loop, which in turn enhances coupling. In the second experiment, the excitation was set to match the jets' natural screech frequency and mode but to oppose the coupling preference of the baseline jets. Results showed that such an excitation pattern leads to decoupling of the jets. This is likely due to the disruption of the time of arrival of acoustic feedback waves by out-of-phase shedding of LSS in the shear layers of adjacent jets. Consequently, it appears that altering the feedback time of arrival in the coupling loop - through altering the relative excitation phase of the jets - is effective in decoupling the jets. More work is needed to establish a comprehensive framework for controlling the jets over various fully expanded jet Mach numbers and the effects of control on near-field pressure and far-field acoustics.

I. Nomenclature

AR	=	nozzle aspect ratio
D_e	=	area-based equivalent nozzle diameter
f_s	=	screech frequency
f_e	=	excitation frequency
LSS	=	large-scale structures
M_d	=	design Mach number
M_j	=	fully expanded jet Mach number
NPR	=	nozzle pressure ratio
SPL	=	sound pressure level (in dB)

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SPOD = spectral proper orthogonal decomposition
St = screech Strouhal number, fD_e/u_j
St_e = excitation Strouhal number, fD_e/u_j
φ = azimuthal angle
Φ_c = relative phase between large-scale structures in adjacent jets
Φ_{sl} = relative phase between large-scale structures shed from the top and bottom shear layers of each jet

II. Introduction

The potential benefits of propulsion/airframe integration via employing non-axisymmetric nozzles has led to a renewed interest in their utilization in the latest generation of aircraft designs. Additional requirements on the exhaust system such as minimizing drag, thrust reversing, thrust vectoring in pitch, yaw and roll, and improved flow mixing have also been imposed due to the need for greater operational performance [1]. Integration of aft body and exhaust nozzles in an aircraft can severely affect drag and weight and since the aft body of an aircraft is not typically axisymmetric, integrating axisymmetric nozzles with the airframe introduces additional drag [2]. As a result, non-axisymmetric nozzles are an attractive option for minimizing drag as well as reducing weight.

Studies have shown that the plume spreading rate of a rectangular nozzle can be significantly higher than an equivalent axisymmetric nozzle [3,4]. It is also easier to implement a thrust vectoring system (as well as a thrust reversing system) in a two-dimensional nozzle as the nozzle walls can simply be deflected to change the thrust direction. Furthermore, a 4-flap, two-dimensional nozzle system can be lighter than an equivalent axisymmetric design [1]. Aircraft with high- and low-aspect-ratio (*AR*) rectangular nozzles have already been operational for years and recent interest in developing manned and unmanned platforms with non-axisymmetric nozzles integrated into the airframe (e.g., F/A-XX, MQ-25 and NGAD programs) underscores the need for further understanding and characterization of flow and radiated noise from such geometries. Another issue that needs to be considered when designing future aircraft with rectangular nozzles that improve propulsion/airframe integration is sonic/acoustic fatigue [5]. Due to widespread use of composites and special stealth coatings in the latest generation of high-performance military aircraft, structural components in the vicinity of the nozzles must be protected from the high levels of fluctuating pressures caused by coupling of the jets [6–10].

Since understanding the dynamics of coupling and screech is crucial in implementing active control for twin jets, a brief overview of previous studies aimed at characterizing coupling and screech mode of twin rectangular jets is presented here. Research efforts to study coupling in supersonic jets were initiated in the early 1980s due to the necessity of understanding the coupling process in twin circular jets. Early studies showed that high levels of fluctuating pressures caused by coupling of the jets [6,7,9,11] often lead to sonic fatigue and failure of structural elements in the vicinity of the jets. The well-documented failures of nozzle flaps on the B-1A bomber and F-15E strike aircraft during the test program [6,8] spurred the early efforts, from early 80s to early 90s, to better understand the coupling mechanisms in twin circular jets. The dynamics of coupling in twin circular jets has been studied extensively in the intervening years culminating in recent publications that have examined the topic in great detail [12,13].

Despite the need for better understanding and characterization of the flow in twin rectangular geometries, it is surprising that only a handful of studies have been directed at this topic over the past three decades. The earliest work on the coupling between two low *AR* rectangular jets was reported by Zilz and Wlezien [14]. The authors identified the four possible coupling modes between low *AR* rectangular jets arranged side-by-side along their major axes: normal symmetric (in-phase coupling in the vertical plane), normal asymmetric (out-of-phase coupling in the vertical plane), lateral symmetric and lateral anti-symmetric (out-of-phase and in-phase coupling in the horizontal plane, respectively). They also noted that symmetric coupling modes generate higher sound pressure levels (*SPL*) and stronger near-field pressure fluctuations whereas anti-symmetric modes led to a reduction in *SPL* in the jets' plane of symmetry. Zilz and Wlezien reported that anti-symmetric (out-of-phase) coupling modes are present in closely spaced, underexpanded jets. Another notable finding of their study was the fact that higher spreading rates in rectangular jets can lead to rapid merging of the plumes and result in screech suppression. Following their work, Zeierman et al [15] studied the spreading rates of plumes in two adjacent rectangular nozzles with an aspect ratio of 3. They found that operating twin nozzles above their design Mach number does not alter the spreading rate compared to a single rectangular nozzle. However, when operated at a highly overexpanded condition, there is a significant increase in plume diffusion rate due to the addition of the second jet.

Raman and Taghavi [16] performed a comprehensive study of coupling between high *AR* twin rectangular jets. The aspect ratio in their work was 5, and the work itself is an extension of their earlier study of coupling between a linear array of four jets [17]. In their work, while looking at mixing and noise benefits, Raman and Taghavi [17] synchronized the four jets to achieve higher plume spreading rates. In their follow-up study [16], Raman and Taghavi confirmed the findings of Zilz and Wlezien [14], namely that out-of-phase coupling of the jets minimizes the near-field pressure fluctuation levels (at $\varphi = 90°$) and in-phase coupling maximizes them. Two more recent studies by Bozak [18] and Bozak and Wernet [19] were aimed at developing an empirical model for prediction of noise in twin circular and rectangular nozzles. They also studied flow velocity in the inter-nozzle region with PIV and noted that the addition of forward-flight effects led to the creation of a low velocity region between the two nozzles which, in turn, led to higher turbulent kinetic energy levels for the jet and an increase in the far-field sound pressure level (*SPL*) [19]. Almost all of the previous studies, with the works of Zilz and Wlezien [14] and Bozak [18] being an exception, have been directed towards investigating high *AR* nozzles with significant inter-nozzle spacings, a combination which may not be of interest for airframe/propulsion integration in the latest generation of tactical manned and unmanned aircraft. A thorough understanding of coupling modes in closely spaced, low *AR* twin rectangular jets is needed to implement active flow control strategies that would disrupt the underlying mechanisms of coupling. The works published recently on this subject [20–22] have focused primarily on the details of the flow and acoustic fields but have not investigated coupling between the jets across the wide range of NPRs likely present in application. Our SciTech 2021 paper [23], focused more on investigating the coupling modes of a twin rectangular nozzle geometry over a wide-range of fully-expanded Mach numbers (M_js) or nozzle pressure ratios (NPRs).

Another issue that has been a source of confusion due to the terminology used in the literature is the screech mode of each individual jet in twin rectangular jets. All the early reports of screech modes in rectangular jets [24–26] were based on results obtained using high aspect ratio ($AR > 3$) converging nozzles. Gutmark et al. [24] reported the existence of a symmetric mode (shown in Fig. 1a) in the slightly underexpanded regime ($1.0 < M_j < 1.08$) and an anti-symmetric (flapping) mode (Fig. 1b) at higher Mach numbers. Shih et al. [25], however, observed the presence of, and rapid switching between, symmetric and anti-symmetric modes for $1.1 < M_j < 1.2$ and a strong symmetric mode between $M_j = 1.30$ and 1.50. Following Shih et al.'s report, Raman and Rice published the results of their investigation of a high *AR*, underexpanded jet with a Mach number of $M_j = 1.44$ [26]. They reported the existence of an anti-symmetric mode at the screech frequency and a symmetric mode at the harmonic of screech for the same Mach number. The only study published on the screech mode of low *AR*, rectangular jets since early 90's is the numerical work of Gojon et al. [27] where the authors have reported the existence of anti-symmetric modes in underexpanded and overexpanded regimes for a jet issuing from an $AR = 2$, military-style nozzle. Our previous results [23] show that the screech mode of each individual jet, across a wide range of Mach numbers, is always anti-symmetric for our low *AR* nozzles. As will be shown in the results section, however, it is possible to force a jet that naturally has an anti-symmetric screech mode to adopt a symmetric mode.

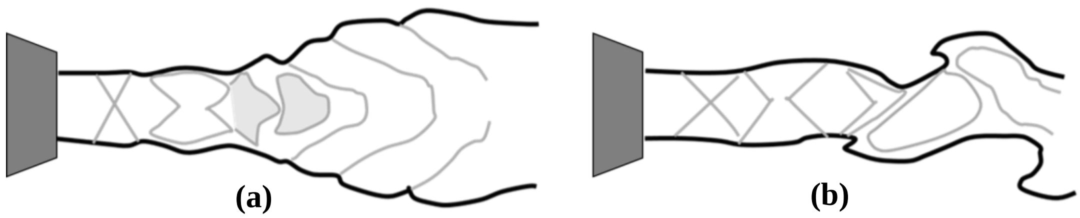


Fig. 1 Observed screech modes for single rectangular jets a) symmetric b) anti-symmetric (after [26,28])

The coupling mode of twin jets and the screech mode of the individual jets are intimately intertwined in coupled twin jets as two feedback loops simultaneously exist in such configurations: the screech loop and the coupling loop. Downstream convecting structures in the shear layer of one of the jets (jet A) interact with its shock cells and generate acoustic waves. The upstream travelling acoustic waves from one of the shock cells often establish a feedback loop. These waves perturb the jet A's shear layer at the nozzle lip where it is most receptive and generate new large-scale structures (LSS). The feedback loop is established when the phase of the LSS generated by the upstream travelling acoustic waves matches that of the structures required to generate them. Additionally, the waves that established the screech loop also perturb the shear layer of the other jet (jet B) at the nozzle lip. Again, if the naturally generated structures and the acoustic perturbations are in phase in jet B, this process leads to the coupling of the jets. Understanding these processes is crucial for implementing effective control in twin rectangular jets.

While some work on the physics and control of twin circular jets exists in the literature (e.g., recent work at the GDTL [29]), no attempt has been made, to the authors' knowledge, to control and decouple twin rectangular jets with active flow control techniques. The use of passive techniques, such as installing tabs in the nozzles, to decouple twin rectangular jets has resulted in very limited success as reported by Walker [8]. In this work, we are controlling the jets using an active technique, namely Localized Arc Filament Plasma Actuators (LAFPAs) developed at the Gas

Dynamics and Turbulence Laboratory (GDTL) [30,31]. These actuators exert control authority by producing periodic thermal perturbations using an arc discharge. The perturbations excite the Kelvin-Helmholtz instability in shear layers, and the amplified perturbations eventually roll up into flow structures in the shear layer. By modifying the frequency and relative timing of the LAFPAs' perturbations, the spatial organization and growth of flow structures can be controlled [32]. LSS are known to play a critical role in mixing and acoustics in jet flows [33]. Thus, the LAFPAs can, using only perturbation-level inputs at selected frequencies, exert significant control authority over jets and other flows with shear layers[33–37]. Given that the LSS/shock interactions are what drive the screech and coupling loops, LAFPAs, through their ability to affect the shedding of LSS, constitute a perfect control technique to manipulate these processes as was shown in GDTL's previous publications [29,38,39]. More details on the mechanism through which LAFPAs excite the flow can be found in a recent review article by Samimy et al.[40].

The broad objectives of the current work are to:

a. reduce near-field pressure fluctuations and
b. reduce far-field noise

via active control. As part of these broader objectives, we are seeking to decouple the jets and suppress/weaken screech as both contribute to the broader objectives of this work. If screech were suppressed or significantly weakened, the jets would decouple. However, it is possible to decouple the jets without suppressing screech. Achieving either would contribute to both objectives. Working towards our stated objectives, we designed a series of experiments to investigate how either of the two mentioned loops (i.e., screech and coupling) can be affected by LAFPAs. This paper examines the results of two such experiments at an overexpanded jet Mach number (M_j) of 1.35 to demonstrate the capabilities of the control as well as the mechanisms governing the control.

III. Experimental Methodology

A. Nozzle Design

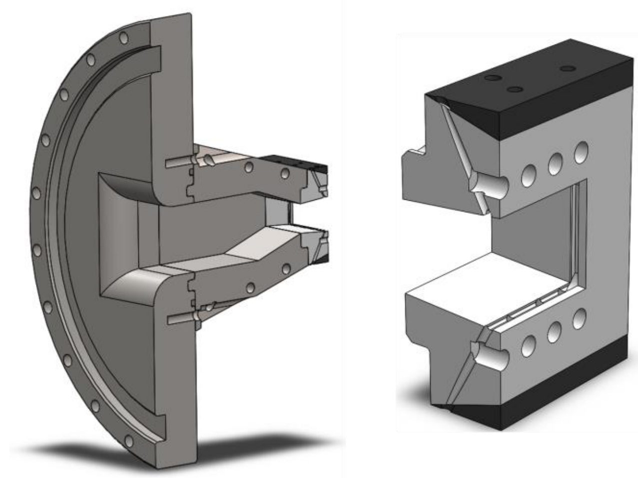
A new facility was designed and built at the GDTL to study flow physics and aeroacoustics of low *AR*, twin supersonic rectangular jets. The facility uses a pair of rectangular military-style, converging-diverging nozzles with a design Mach number of 1.5 (M_d = 1.5) and aspect ratio of 2 (*AR* = 2). From the outset, the facility was designed to be modular so that it would be possible to change nozzle spacing, design Mach number and actuator configuration by replacing specific parts with alternate versions.

In its current configuration, the center-to-center spacing between the nozzles is 1.708 in. (43.38 mm), which is equal to 2.25 equivalent exit diameters (2.25D_e) where D_e = 0.758 in. (19.25 mm) is the area-based nozzle exit equivalent diameter. The nozzle exit width (w) and height (h) are 0.95 in. (24.13 mm) and 0.475 in. (12.07 mm), respectively. The nozzle assembly cutaway can be seen in

Fig. 2a. It must be noted that the internal geometry of our twin jets nozzle assembly and its other parameters such as nozzle *AR* and center-to-center spacing are virtually identical to that of the twin rectangular jet facility tested at University of Cincinnati [41]. Through an extensive shake down campaign, we have determined that the ideally expanded Mach number is close to the design Mach number of M_d = 1.50

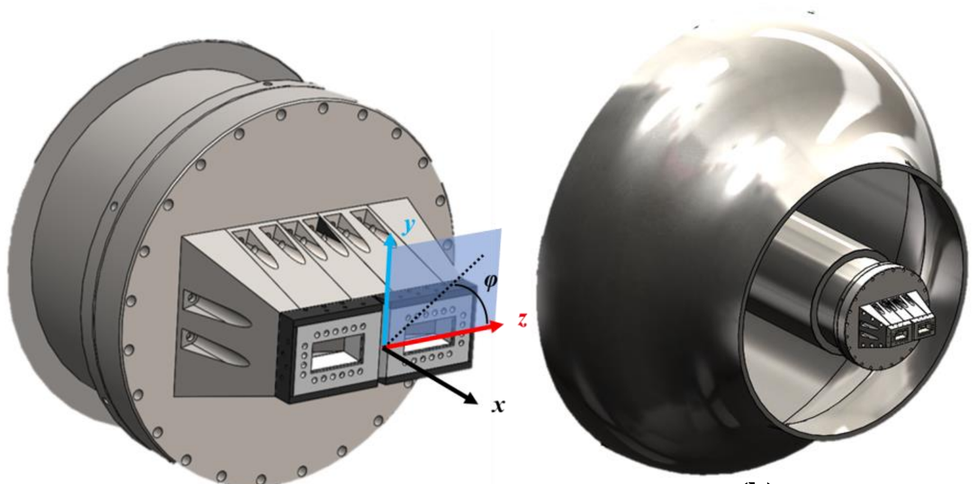
Boron nitride housings for LAFPAs, hereafter referred to as actuator blocks, are used to prevent arcing to the metal components. In order to shelter the arc discharge from the flow, 1 mm wide by 0.5 mm deep grooves were cut into the boron nitride block, approximately 1 mm upstream of the nozzle exit plane. The grooves house the 1 mm diameter tungsten electrodes of the actuators. Previous work [42] has shown that the existence of the groove does not affect the control authority of the actuators. Six actuators were placed along the major axis lips of the nozzle, three on top and three on the bottom, while two actuators were placed along the outer minor axis lip of the nozzle. The electrodes for each actuator are arranged such that their tips are approximately 3.5 mm apart. Each of the 8 actuators in a nozzle can be triggered independently to control various screech and coupling modes in the jets.

Fig. 2b shows a cutaway of the actuator block showing the electrode bores. The nozzle assembly (Fig.3a) is attached to a high-pressure air pipe via a circular mounting plate at the center of a co-flow duct (Fig.3b), used for simulating forward flight effects.



(a) **(b)**

Fig. 2. a) Nozzle assembly cutaway b) actuator block cutaway



(a) **(b)**

Fig. 3. a) Twin jets assembly showing minor axis, *y*, major axis, *z*, and azimuthal angle, φ b) twin jets facility installed inside the co-flow channel

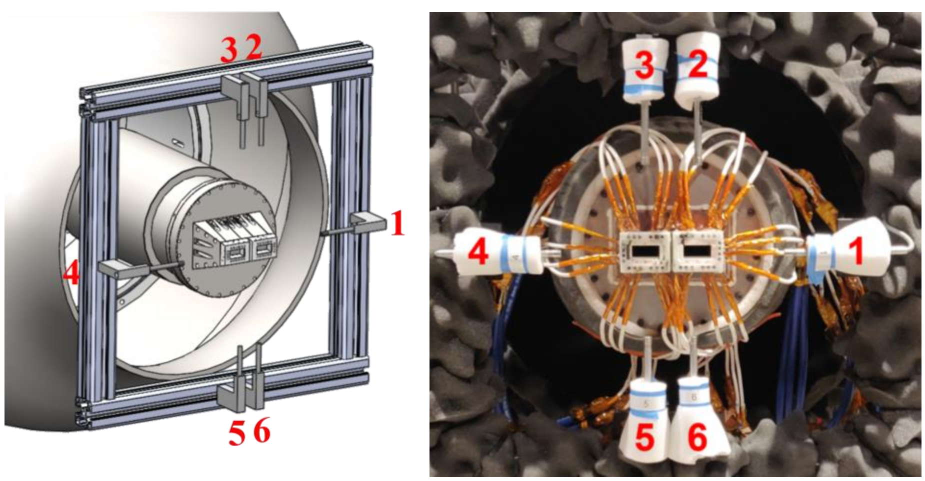
B. Facility and Instrumentation

All the experiments reported in this work have been conducted in the jet anechoic facility at the GDTL within the Aerospace Research Center at the Ohio State University. The facility is a 6.2 *m* × 5.6 *m* × 3.4 *m* chamber covered with fiberglass wedges and is designed to have a cut-off frequency of 160 Hz. High-pressure air is supplied by three five-stage reciprocating compressors that store the air in two 43 m^3 cylindrical tanks at a maximum pressure of 16 MPa. The air is then dried, filtered and passed through a series of screens in the settling chamber before being fed to the jet plenum. The facility is capable of heating the air in the stagnation chamber to a total temperature ratio (*TTR*) of 2.5. Forward flight conditions can be simulated using a co-flow duct that can provide a stream of air at up to 100 *m/s*. The co-flow duct and the twin jets nozzle assembly were covered with acoustic foam (as seen in Fig. 5) during the experiments to prevent acoustic reflections.

An array of experimental diagnostics is used for detailed flow and acoustic measurements in both baseline and actively controlled cases. Near-field acoustic measurements are carried out using an azimuthal microphone array (see Fig. 4) installed on a plane located at the nozzle exit to study jet coupling. The near-field array, which consists of a 15 in. × 15 in. rectangular frame and six Brüel and Kjær 4939 $\frac{1}{4}$ in. microphones, was used to collect data needed to study the coupling between the jets at various regimes. By computing the coherence and phase difference between the pressure traces from individual microphones in the array it was possible to assess the coupling mode of the jets at different operating Mach numbers. The number of microphones was chosen so that it would be possible to infer not only the screech mode of each jet [28] via microphones placed above and below but also the coherence and phase of the jets with respect to each other as reported by Raman and Taghavi [16]. All the near-field microphones were positioned at an axial location of $x/D_e = 0$ and at a radial location (measured from the nearest jet centerline) of $r/D_e = 4$. This radial distance is deemed to be sufficiently far from the jet boundary to register the acoustic signature of screech. The array and microphone mounts were wrapped in acoustic foam to prevent reflections, as seen in Fig. 4b.

The primary optical diagnostics technique used to visualize the jets' near-field was schlieren. Time-averaged schlieren imaging was used to study the jets' shock cell structure and spreading rate and high-speed schlieren imaging was employed to study the dynamics of coupling and screech. The setup used for visualizing axial density gradients in minor and major axis planes was a standard Z-type schlieren system. To acquire high-resolution, time-averaged maps of density gradient at a wide range of Mach numbers, a 5.5 MP LaVision Imager sCMOS camera was used. The knife edge was oriented vertically in order to highlight the horizontal density gradients and 300 images with a window size of 2500×2150 pixels were acquired at 50 frames per second for each test condition. An HPLS-36 high-powered pulsed LED from Lightspeed Technologies was used as the light source. The LED pulse width was set to 500 *ns* which was short enough to freeze the flow features even for the highest observed screech frequency. The Imager sCMOS camera was swapped with a Phantom v1210 camera for high-speed schlieren imaging experiments. The acquisition rate was fixed at 40,000 frames per second for all the tested Mach numbers and a set of 2000 frames with a window size of 512×340 pixels was recorded for each case. A Nikon zoom lens was used to set the field of view to include only the flow features of interest, namely the shock system, while reducing the window size to maximize the frame rate. In addition to those employed in this work, this facility also possesses the capability to perform tomographic PIV measurements and linear near-field and far-field acoustic measurements.

The actuators (LAFPAs) used in this work consist of a pair of tungsten electrodes that are driven by an in-house built arc generator. When triggered, the arc generator ramps up the voltage between the electrodes to about 7 *kV* before the air in the gap breaks down and an arc is formed. The repetition frequency and phase (relative timing) of each actuator can be independently controlled up to 20 *kHz*. This allows perturbations in various patterns (by varying the relative phase between the 16 available actuators) and frequencies to be introduced. Thermal energy of the arc couples to the flow thereby providing the perturbation needed to excite the instabilities in the flow. More details on the actuators' development and control mechanism can be found in Utkin et al. [31] and recent review articles by Samimy et al. [32,40]. The arc generators and requisite the DC power supplies are housed in a mobile cart. To reduce the voltage drop across the high-voltage cables – which affects the ability of the actuators to achieve breakdown under certain experimental conditions, the cart housing the pulsers and power supplies was moved inside the anechoic chamber. All the reflecting surfaces were covered with acoustic foam to prevent reflections as seen in Fig. 4b and Fig. 5.



(a) **(b)**

Fig. 4 Near-field microphone array a) CAD design of the array b) array installed in the anechoic chamber

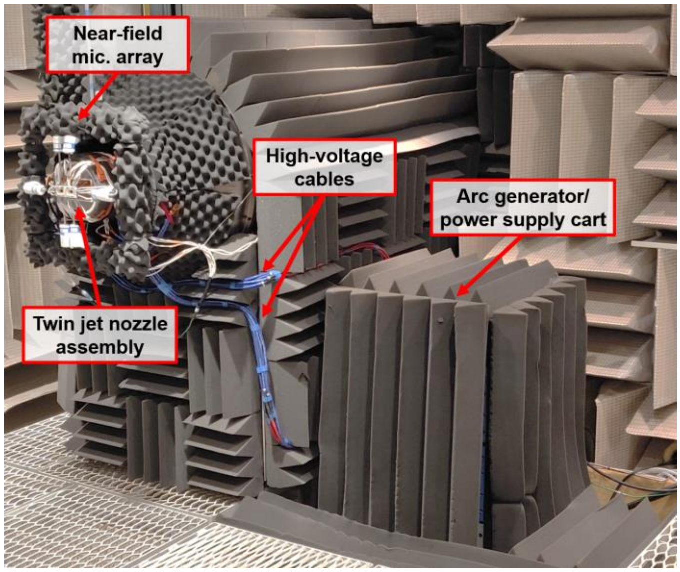


Fig. 5 Setup for coupling control experiments

C. Data Acquisition and Processing

Near-field acoustic signals collected by microphones (shown in Fig. 4) were amplified and band-pass filtered between 20 Hz and 100 *kHz* by Brüel and Kjær Nexus 2690 signal conditioners. Prior to acquiring a set of near-field 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 performed in-situ at the set gain values using a Brüel and Kjær model 4231 acoustic calibrator. The gain for near-field microphones during the experiments reported in this abstract was set to 1 *mV/Pa*. The calibration files were used while processing the data to convert measured voltage to equivalent *SPL*. The sampling frequency was 200 *kHz* and 100 blocks of 32,768 samples were acquired for each data point resulting in a 6.1 Hz frequency resolution.

A Fast Fourier Transform code in MATLAB was used to calculate the spectra presented in the plots for each block of data and then average values were calculated from 100 blocks. The calculated Power Spectral Density is then converted to sound pressure level in decibels referenced to 20 μPa.

In order to extract relative phase and coherence from the near-field microphone data and ascertain how phase and coherence vary in time, a MATLAB code was written to calculate the wavelet coherence between two microphone signals. This code calculates the magnitude and phase angle of the (Morlet) wavelet coherence between the pressure measured at various microphone locations as a function of both frequency and time. Regions of coherence greater than 0.7 are used to calculate the temporal averages of the coherence and phase. This allows the phase of the signals to be examined only when the coherence values are high (and therefore the phases are reliable).

Maps of average density gradients and standard deviation of density gradients were calculated from the time-averaged schlieren images in DaVis 8.2 and then imported into MATLAB where Log_{10} of standard deviation of axial density gradients was computed and plotted to ascertain jets' spreading rate and standing wave patterns for various excitation conditions. SPOD analysis was conducted on sample of 1000 images (resulting in a frequency bin size of 625 *Hz*) from high-speed schlieren experiments using a code provided by Schmidt and based on the SPOD formulation proposed by Towne et al. [43] and Schmidt and Colonius [44]. All the lower ranked SPOD modes for each case were studied and the trends recorded. The results, however, show that the majority of the flow energy is concentrated in the first SPOD mode for baseline and excited cases. As such, only those modes are presented in this report for brevity.

D. Experimental Operating Conditions

An extensive excitation sweep with various parameters was conducted to ascertain the effects of excitation over a large range of fully expanded jet Mach numbers from over-expanded to under-expanded cases. This paper focuses on the results obtained at an overexpanded Mach number (M_j) of 1.35 corresponding to a nozzle pressure ratio (*NPR*) of 2.97 at a jet total temperature ratio (*TTR*) of 1. As mentioned earlier, all the data sets were acquired with a nozzle spacing equal to 2.25 nozzle exit equivalent diameters ($2.25D_e$).

Our actuators enable us to control various characteristics involved in screech and coupling loops such as:

a. Shedding frequency of LSS (f)

b. Relative phase between LSS shed from the top and bottom shear layers of each jet (Φ_{sl})

c. Relative phase between LSS in the two adjacent jets (Φ_c)

by changing the actuation frequency and pattern. Various combinations of excitation patterns and frequencies were explored to better understand the effects of control on the flow and acoustic characteristics of twin jets and to develop a hypothesis governing the control. As jets tend to generate the most coherent LSS when excited around their jet column mode Strouhal numbers (*St*, ranging from 0.2 to 0.6), control in this range was assumed to be highly effective at disrupting or altering coupling and screech processes. As such, the majority of the excitation Strouhal numbers during the sweeps were selected to be in this range. The excitation frequency (f_e) chosen for the results reported in this paper was matched to the screech frequency ($f_e = f_s = 8.4\ kHz$, $St_e = St = 0.41$) of the jets at $M_j = 1.35$. The excitation Strouhal number is calculated using the jet equivalent diameter D_e as follows: $St_e = f_e D_e / u_j$ where u_j is the fully expanded jet velocity. We recently demonstrated that D_e is an appropriate scaling parameter for screech frequency in low aspect ratio rectangular jets [23]. Various excitation patterns were also tested during the experimental campaign. These included firing the top and bottom actuator rows in each nozzle either in-phase ($\Phi_{sl} = 0°$) or out-of-phase ($\Phi_{sl} = 180°$) causing in-phase or out-of-phase shedding of LSS in the top and bottom shear layers of each nozzle similar to naturally occurring symmetric or anti-symmetric screech modes in rectangular jets. The phase difference between the actuators on adjacent nozzles (Φ_c) can also be varied in order to control the coupling of the jets. A schematic of all the parameters that can be controlled is shown in Fig. 6. The actuation patterns used in experiments reported in this paper are shown in Fig. 7. The term in-phase ($\Phi_c = 0°$) means the structures generated in the two jets are in-phase. Out-of-phase ($\Phi_c = 180°$) excitation, on the other hand, indicates that the structures generated in the two jets are out-of-phase with respect to each other (see Fig. 6).

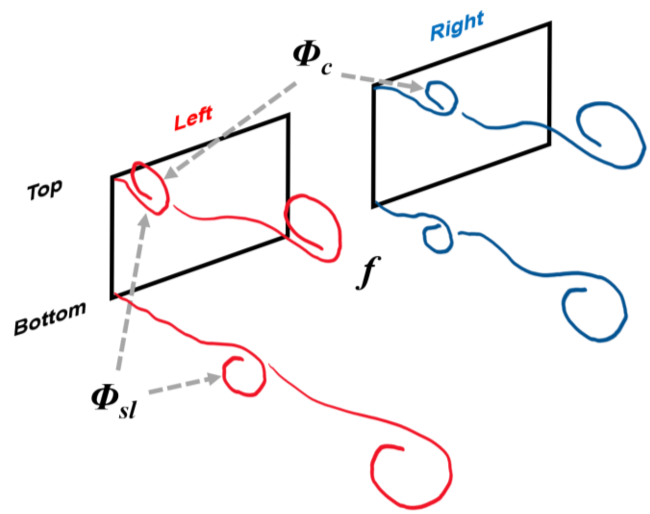


Fig. 6 Excitation parameters that can be controlled to affect the characteristics of screech and coupling loops: passage frequency of LSS (*f*), phase angle between LSS on top and bottom shear layers of a jet (Φ_{sl}), and phase angle between LSS in the adjacent jets (Φ_c)

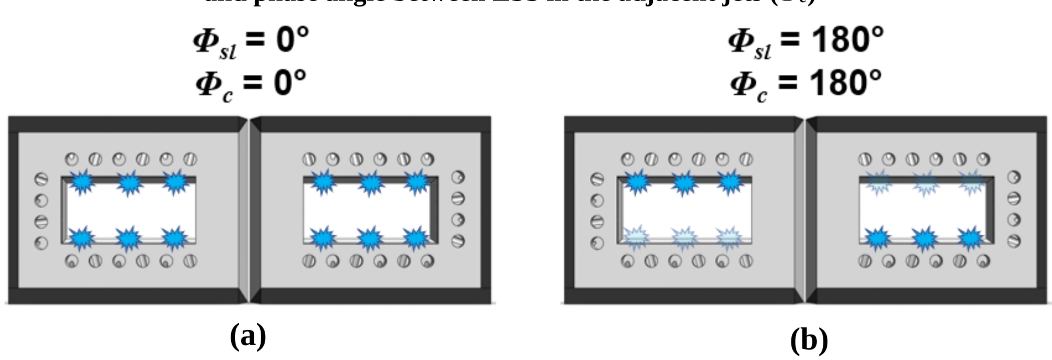


Fig. 7 Actuation modes used to excite the twin jets a) symmetric shear layer mode and in-phase twin jets b) anti-symmetric shear layer mode and out-of-phase twin jets

IV. Results

A summary of the results of characterizing the baseline (without control) jets across a wide range of fully expanded Mach numbers, reported earlier [23], and details of the results for excited jets at an overexpanded M_j of 1.35 are presented in this section.

A. Baseline Jets

A thorough understanding of the coupling dynamics and mode at different Mach numbers is critical in implementing active flow control in order to reduce noise levels or decouple the jets. Coupling between the jets in a twin jets setup is perhaps the most important and dominant process which drives the near-field pressure fluctuations and far-field noise signature and directivity [41,45]. As such, it is crucial to characterize this phenomenon through a wide range of fully expanded Mach numbers to have an overall view of how its behavior changes as the jets transition from the overexpanded to the ideally expanded and underexpanded regimes. The coupling modes along with the individual screech mode of each jet were extensively characterized using the azimuthal near-field array in the early stages of the project and the results were reported in our SciTech 2021 paper [23]. The data sets were retaken several times to ensure repeatability and the results, including screech frequency and the coupling modes, were compared with those from similar facilities to corroborate the viability of the results. Screech frequencies showed excellent repeatability and agreement with data in the literature [23] and while the overall trend in variation of coupling mode versus M_j is repeatable, differences in coherence or coupling mode for some transitional M_js are seen in the data sets collected with different stagnation and ambient temperatures. However, the observed coupling modes show good agreement with similar facilities and computational results for a comparable geometry [20,23]

The observed coupling modes from a highly overexpanded Mach number of 1.20 to a highly underexpanded Mach number of 1.90 are shown in Fig. 8. Upon establishing a screech loop for the first time at $M_j = 1.20$, the jets demonstrate an intermittent coupling behavior in the minor axis plane where periods of in-phase coupling are interrupted repeatedly. This behavior continues until the jets transition to moderately overexpanded M_js at which point the coupling behavior changes to out-of-phase coupling in the minor axis plane. Our experiments have shown that the exact fully expanded Mach number where this transition occurs changes depending on the stagnation and ambient temperatures at which the data was taken. More work is needed to firmly establish the underlying cause of this variation. As the fully expanded Mach number of the jets is increased beyond the design Mach number, coherence between the jets in the minor axis plane disappears. Then, following a narrow region where screech amplitude and coupling coherence approach their absolute minimum values, the jets begin to demonstrate in-phase coupling in the major and minor axis planes at slightly to moderately underexpanded Mach numbers. Further increases in Mach number result in the coherence in the horizontal plane disappearing. The jets are now exclusively coupled in-phase in the minor axis plane. This behavior continues through the highest tested Mach number, $M_j = 1.90$. As stated in our previous report [23], the jets at all Mach numbers show a tendency to adopt an anti-symmetric screech mode regardless of the coupling mode.

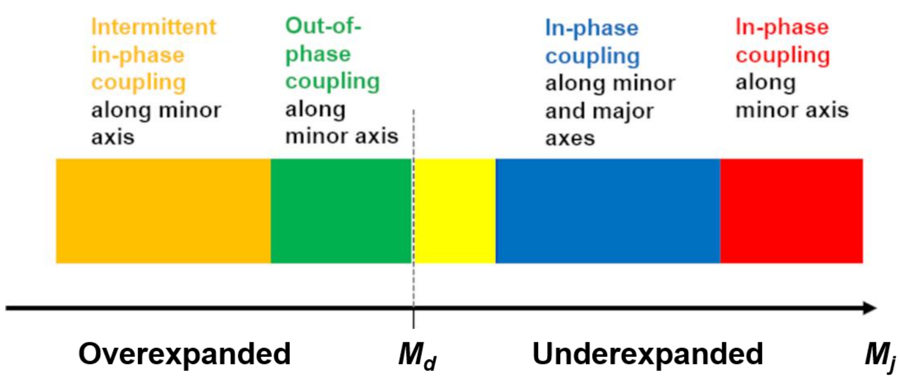


Fig. 8 Coupling behavior of the low *AR*, rectangular twin jets investigated in this paper over a wide range of M_js

An overexpanded condition, $M_j = 1.35$, was selected for conducting the excitation parameter sweep to better understand the effects of control on the flow and acoustic characteristics of twin jets and to develop a hypothesis describing the control mechanism. It is crucial to study the attributes and nature of coupling in the baseline flow before implementing control. As such, the baseline acoustics and coupling dynamics at $M_j = 1.35$ are discussed here. A time-averaged near-field spectrum calculated from microphone 2 data (see Fig. 4) is shown in Fig. 9a. The spectra from other microphones (not shown here) confirm the existence of two closely spaced peaks at 8.25 and 8.40 *kHz* (corresponding to $St = 0.3992$ and 0.4065, respectively) as seen in Fig. 9a. According to Raman and Rice [26], the presence of closely spaced peaks is indicative of jet switching rapidly between two screech frequencies. While it might seem that this could potentially complicate the task of exactly matching the screech frequency when exciting the jets, the fact that jets respond to a wide range of frequencies near the jet column mode ($0.2 < St < 0.6$) renders this a non-issue. Time-averaged plots of coherence and phase between the jets (Fig. 9b) shows that the coupling is relatively strong in the vertical plane (along the minor axis) and the jets have a phase difference close to 0° ($\Phi_c = 0°$), indicating in-phase coupling. The nature of the coupling, i.e., whether it is steady or intermittent in time cannot be established based on this plot, therefore time-resolved plots of wavelet coherence and phase are provided (Fig. 9c and d, respectively) to shed some light on this aspect of coupling. Examining Fig. 9c shows that periods of strong in-phase coupling between the jets are regularly interrupted at an approximate frequency of 123 *Hz*. There is no evidence of phase drift (Fig. 9d) in the time-resolved plot of wavelet phase, however, and as a result it appears that there is no phase mismatch between the jets as was observed in our earlier results [23]. It appears that the observed intermittency between the jets can be attributed to slight differences in screech loop frequency of the adjacent jets. This in turn gives rise to the closely-spaced screech tones that compete for dominance [16,26] and cause the coupling loop to be intermittent. As will be shown in the following section, it is possible to eliminate this intermittency by forcing the shedding of LSS to be more organized via active control exerted by LAFPAs.

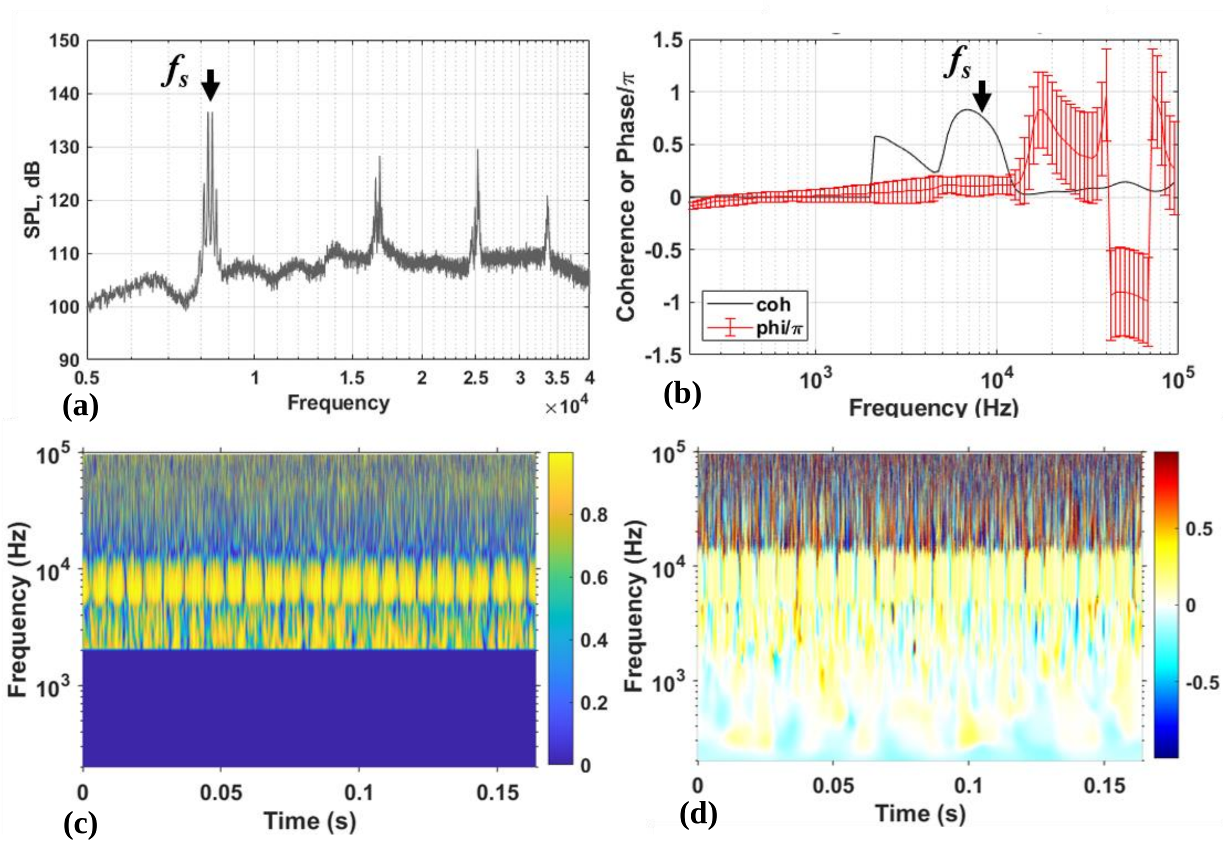


Fig. 9 Screech and coupling behavior of the baseline, twin jets at $M_j = 1.35$: a) sound pressure level spectra from microphone 2, b) time-averaged coherence and phase difference between microphone 2&3, c) wavelet coherence between microphone 2&3, d) phase from wavelet coherence between microphone 2&3

B. Excited Jets

As was mentioned in section II, the excited flow experiments were designed to investigate how the screech and coupling loops can be altered with perturbations provided by LAFPAs. It is possible to change the excitation frequency or tailor the excitation pattern such that either or both of the mentioned loops are affected. In closely spaced twin rectangular jets, the downstream propagating LSS that are generated naturally through amplification of disturbances by the Kelvin-Helmholtz instability [32,40,46] in each individual jet, interact with the shock train and generate acoustic waves through a complex interaction process in which shock leakage (first studied by Manning and Lele [47]) plays a major part [46]. The upstream-travelling components of these acoustic waves are an integral part of the screech loop and perturb the shear layer at the nozzle lip where it is most receptive. That, in turn, through a process called receptivity [48], leads to the generation of new downstream propagating LSS. This process can lead to closing of the screech loop if the acoustic perturbation timing is in phase with the LSS genesis. The elements of the screech loop described above, including the distance that the downstream propagating structures travel (X_{h1}) and the upstream travelling acoustic waves (X_{a1}) are shown in Fig. 10. The upstream travelling acoustic waves also reach the adjacent nozzle lip (see Fig. 10) and thus, perturb the shear layer of the adjacent jet as well. This, as was the case with the screech loop, can also lead to the roll up and generation of LSS in the shear layer of the adjacent jet. If these LSS are in phase with the acoustic feedback waves, a coupling loop will be established. Simply put, in coupled jets at any time, the screech and coupling loops coexist. Furthermore, the acoustic feedback waves for these loops do not necessarily need to originate from the same shock cell. That is demonstrated in Fig. 10 where $X_{h1} \neq X_{h2}$. Our aim is to better understand these processes and investigate how altering either of these loops affects the overall coupling and screech.

Since we will be examining only the results of exciting the jets at their natural screech frequency ($St_e = St = 0.41$) in this paper, only Φ_{sl} and Φ_c were varied to affect either the screech or coupling loop. We can have a similar effect by solely changing the excitation frequency or the excitation frequency along with Φc. Those results will be presented in a future publication.

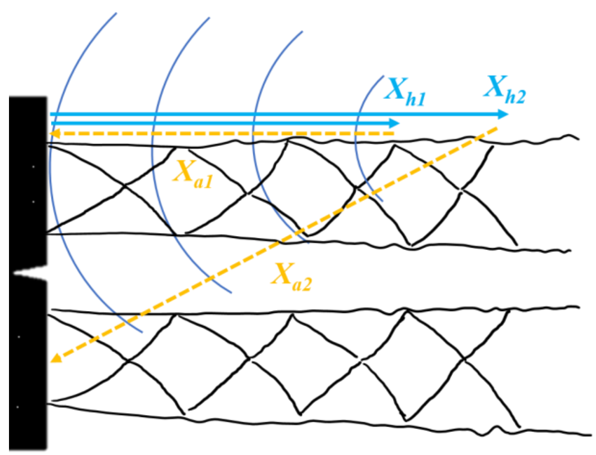


Fig. 10 Schematic of screech and coupling feedback loops

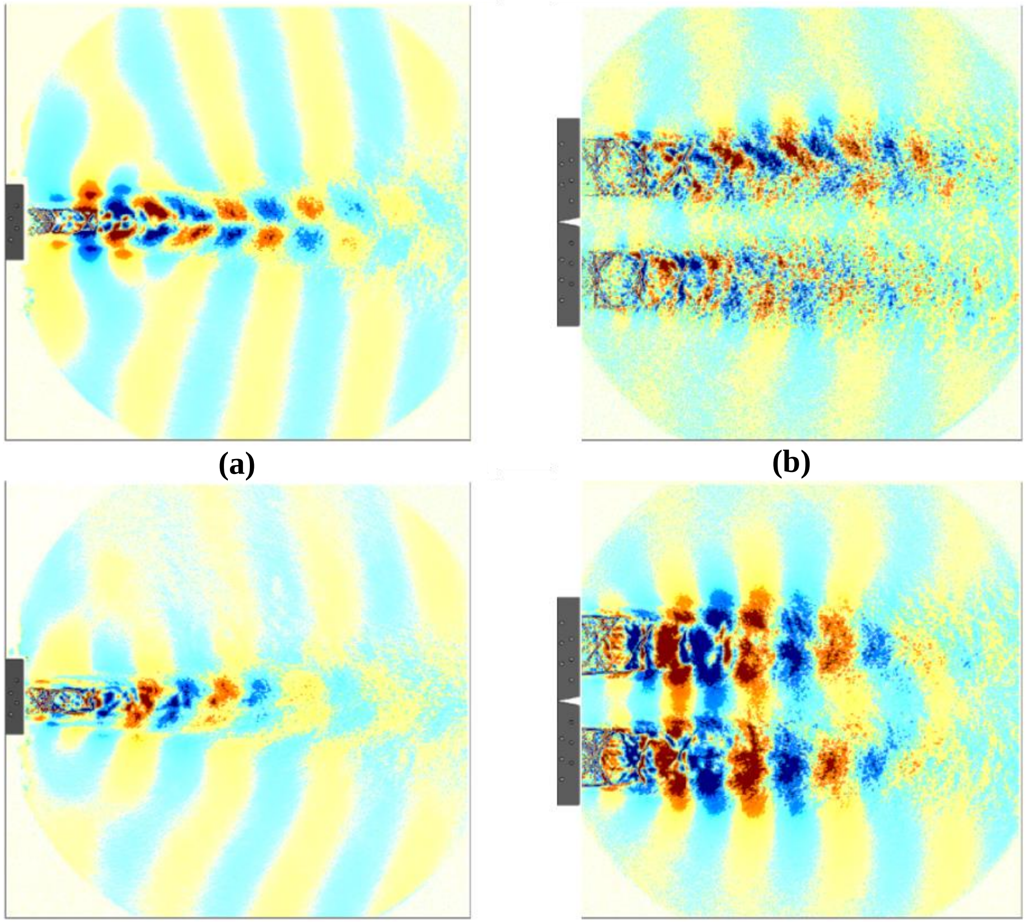
In what follows, the results of experiments designed to understand the effects of each control parameter on the dynamics of screech and coupling are presented. First, excitation is introduced to cause the jets to adopt a screech mode other than their natural preference while matching the excitation Strouhal number (St_e) to the jets' natural screech *St* number. The goal is to ascertain how affecting the screech loop by changing its mode affects the flow and acoustic fields. Subsequently, the jets are excited to induce a coupling mode that opposes the jets' natural coupling tendency while matching the jets' natural screech mode and Strouhal number. The results of this experiment illustrate the effects of manipulating the coupling loop on the jets' flow-field and acoustics. Insights gained from these experiments not only serve as a guide for designing the best control strategies for decoupling the jets and suppressing noise but also shed further light on the complicated dynamics of screech and coupling in twin rectangular jets. In that sense, LAFPAs not only serve as control devices, but also as invaluable diagnostic tools that offer insights which otherwise would be impossible to obtain.

1. Controlling jet screech mode (jet shear layer mode)

As was mentioned in the previous section, this experiment is designed to control the jets to adopt a symmetric screech mode. Note that the jets naturally adopt an anti-symmetric screech mode at all tested M_js. This objective is achieved by firing the top and bottom row actuators in-phase ($\Phi_{sl} = 0°$) which results in simultaneous shedding of LSS in the top and bottom shear layers. In other words, the structures in the top and bottom shear layers of each jet will be in-phase as a result of excitation. This directly affects the time of arrival of acoustic feedback waves at the nozzle lip and alters the screech loop of each jet by opposing the natural tendency of the jets to adopt an anti-symmetric mode. To examine the effect of varying each parameter in isolation, the relative phase between large-scale structures in adjacent jets was matched to that of the natural in-phase coupling mode of the jets, i.e., $\Phi_c = 0°$. As mentioned before, the excitation frequency was selected so that it matched the natural screech frequency of the jets ($St_e = St$). The actuation pattern used for this experiment is shown in Fig. 7a. It is instructive to first investigate the response of the jets. The first (most energetic) SPOD modes of the baseline and excited jets in the minor and major axis planes are shown in Fig. 11. The alternating red and blue lobes (which correlate with LSS) within the baseline jet, seen in Fig. 11a, confirm that the natural screech mode of the baseline jet is anti-symmetric. The staggered standing wave pattern formed outside the jet [45] due to interference between the pressure field of downstream propagating vortices (i.e. pressure signature of LSS in the jet shear layer) and upstream travelling acoustic waves, also reflects the out-of-phase shedding of vortices from top and bottom shear layers. Note that schlieren is a line-of-sight integrative technique and given the in-phase nature of coupling along the minor axis plane, the alternating standing wave pattern outside the jet and the lobes seen inside the jet appear particularly strong as Fig.11a is obtained by looking through both jets.

If we examine the jets in a different plane, however, the overall picture is different. Fig.11b shows the first SPOD mode of the baseline jets in the major axis plane. The relatively low coherence of the standing wave pattern surrounding the jets, as well as the lobes inside the jets, are the results of the line-of-sight integration of the schlieren technique and the anti-symmetric mode of the top and bottom shear layers. As was mentioned in section IV.A, the slight frequency difference between screech loop of the adjacent jets gives rise to a competition between them for dominance. It appears that the LSS shed in the shear layer of the top jet are slightly more coherent and hence, it is likely the dominant jet at the selected frequency.

The effects of in-phase, symmetric excitation on the jets is shown in Fig. 11c and d. In contrast to the baseline jet, the lobes are no longer alternating indicating in-phase shedding of the vortices from the top and bottom shear layers ($\Phi_{sl} = 0°$). This indicates the control authority of actuators as the jets respond to the perturbations centered around screech frequency. Furthermore, it is evident that the screech mode can be dictated via excitation. The standing waves outside the jet also reflect the in-phase shedding of structures due to excitation as the wave pattern is no longer staggered. It is interesting to note that, as expected, the wavelength of the standing waves has not changed after excitation and only the phase difference between the top and bottom wave patterns has changed. This is in line with the fact that only the phase difference between the LSS in top and bottom shear layers has been changed in this experiment. Examining the first mode of the jets in the major axis plane (Fig. 11d) clearly shows the effect of exciting the adjacent jets in-phase ($\Phi_c = 0°$). The dark colors of the lobes indicate high coherence and correlate with organized shedding of the large-scale structures due to excitation. In contrast to the baseline jets, the shedding of LSS has become significantly more organized. The standing wave patterns outside the jet and the lobes inside the jets indicate that the jets are strongly in-phase. The strong coherence of the highly energetic major axis plane mode 1 (Fig. 11d) and the correspondence of the lobe organization with the imposed excitation pattern clearly shows that the jets respond strongly to this excitation condition.



(a) (b) (c) (d)

Fig. 11 First SPOD mode at screech frequency on the minor and major axes planes showing the effects of control: a, b) baseline jets, c, d) controlled jets (St_e = 0.41, Φ_{sl} = 0°, Φ_c = 0°)

The acoustic response of the jets to excitation can be investigated by studying plots of time-averaged spectra and spectrograms of baseline and excited jets shown in Fig. 12. The baseline jets' intermittent coupling behavior can be seen in the spectrogram of Fig. 12b where the screech tone is not continuous in time. Exciting the jets at St_e = 0.41 with Φ_{sl} = 0° eliminates the periodic disruptions of the screech loop by forcing the organized shedding of LSS in the top and bottom shear layers. Highly energetic and organized shedding of LSS due to excitation eliminates the jitter and slight changes in the frequency that led to the baseline jet having a relatively wide tone base (Fig. 12a) and eliminate unsteadiness and side peaks around the screech/excitation frequency (Fig. 12c). Since the shedding frequency of LSS is now accurately dictated by the actuation frequency of LAFPAs, the screech tone has a very narrow base. It must be noted that LAFPAs generate a strong acoustic tone (compression wave) at their actuation frequency that is registered by all near-field microphones. This extremely narrow tone, also referred to as "self-noise" is overlaid on the screech tone at St = 0.41 in the spectra (Fig. 12c). The coherence plots from microphones 2 and 6 (above and below the right jet – not shown here) indicate the screech loop has been significantly strengthened due to excitation. That explains the 8 dB increase in screech tone seen in Fig. 12c. The spectrogram of microphone 2 data shown in Fig. 12d indicates that the screech loop is now continuous and without the periodic disruptions that the baseline jets experienced (Fig. 12b). This is a direct consequence of excitation which organizes shedding of LSS and strengthens the screech loop of each jet.

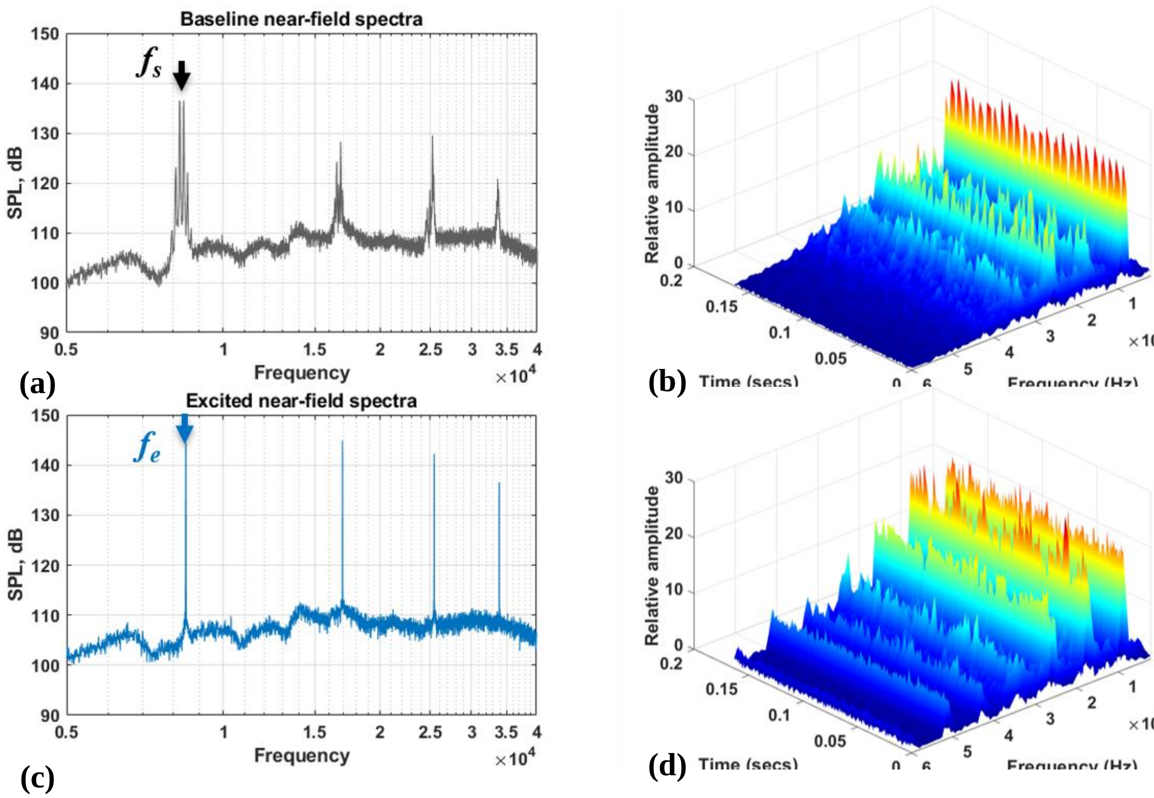


Fig. 12 Time-averaged spectra and spectrograms from mic. 2 showing the effects of control a, b) baseline jets c, d) controlled jets (St_e = 0.41, Φ_{sl} = 0°, Φ_c = 0°)

The effects of excitation on jets' coupling are shown in Fig. 13. Exciting the jets not only results in a strong, continuous screech tone in each jet (Fig. 12d), but it also strengthens the coupling between the jets in the minor axis plane as seen in the time-resolved wavelet coherence plot of Fig. 13c. The time-averaged coherence value has also been increased considerably (Fig. 13d) compared to the baseline case due to elimination of screech intermittency. The error bars on time-averaged phase are smaller in the excited jets (Fig. 13d) indicating less scatter in the relative phase of upstream travelling acoustic feedback waves. This is a direct consequence of the organized shedding of LSS due to excitation. In conclusion, in-phase excitation of the jets with a symmetric mode at the screech frequency resulted in a narrower and stronger screech tone, elimination of intermittency and strengthening of the screech loop. Perhaps the most important takeaway from these results is that organized shedding of LSS, due to excitation, strengthens the screech loop and matching the excitation phase difference between the jets to the natural coupling tendency of the jets, causes the coupling to be enhanced/strengthened. In other words, enhancing the screech can strengthen and enhance coupling. It is interesting to note that opposing the natural jet mode tendency appears that have no disruptive effects on the strength of the coupling or response of the jet.

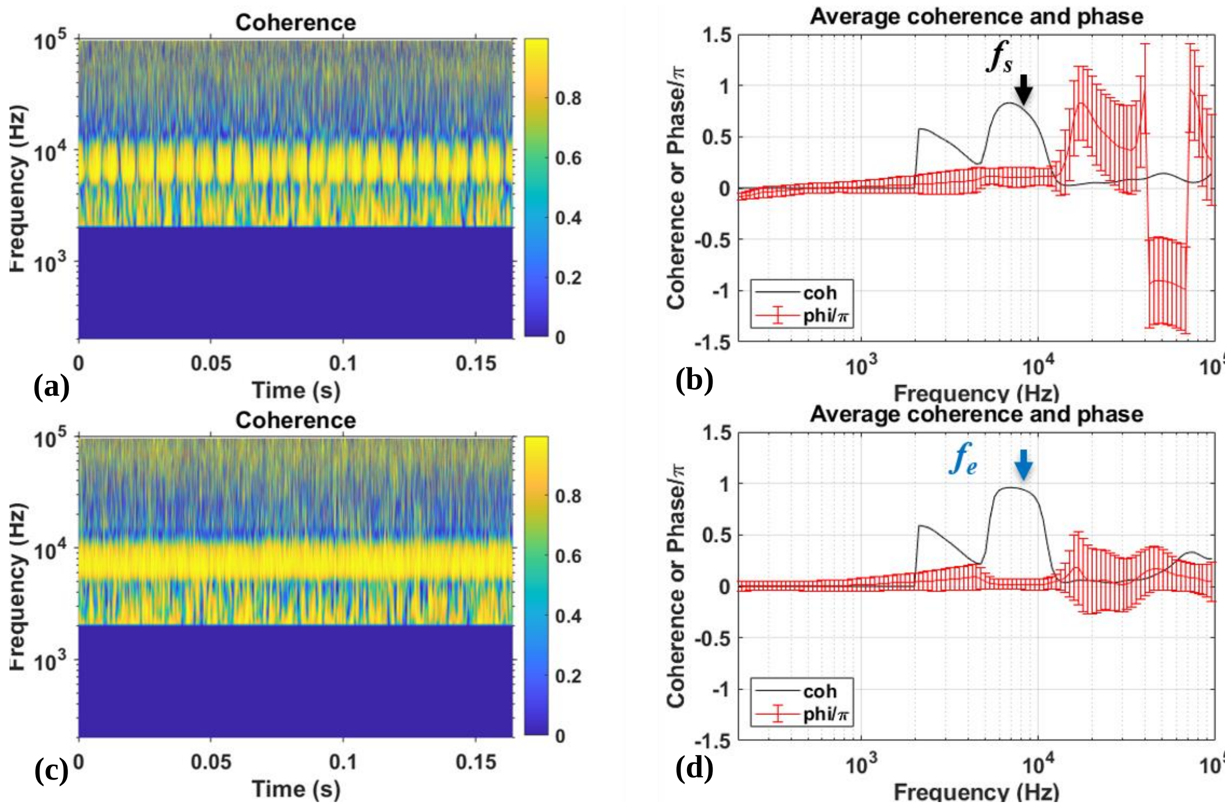


Fig. 13 Time-resolved and time-averaged wavelet coherence showing the effects of control: a, b) baseline jets, c, d) controlled jets (St_e = 0.41, Φ_{sl} = 0°, Φ_c = 0°)

2. Controlling jet coupling mode

The goal of the second experiment was to assess the effect of altering the phase of the two jets from the in-phase (see Fig. 9b and d) baseline condition at this M_j to out-of-phase (see Fig. 7b). While this excitation pattern (shown in Fig. 7b) does not modify the frequency or mode of the screech loop, it alters the coupling loop by changing the relative shedding phase of LSS in adjacent nozzles from 0 (as in the baseline case) to π. As stated before, since our goal is to investigate the effect of Φ_{sl} and Φ_c in isolation, in this experiment, we set Φ_{sl} = 180° so that it matches the natural tendency of the jets to adopt an anti-symmetric screech mode. The frequency of the excitation also matches the natural screech frequency of the jets at M_j = 1.35 (St_e = St = 0.41). The relative phase between large-scale structures in adjacent jets, however, is chosen (Φ_c = 180°) so that it opposes the natural tendency of the jets to have in-phase shedding in their top and bottom shear layers. As we saw in section IV.B.1, opposing the natural mode of the jets does not appear to have a disruptive effective on the screech or coupling loops. In fact, the jets strongly respond to perturbations that matched their natural screech frequency and excitation leads to strengthening of screech and coupling loops.

As before, the effects of excitation are examined by considering the flow-field response of the jets to organized perturbations provided by LAFPAs. The most energetic (first) SPOD modes for baseline and excited jets in minor and major axis planes are shown in Fig. 14. The baseline modes are repeated to facilitate comparison with excited flow results. SPOD modes in the minor axis plane (Fig. 14c) do not provide useful information due to line-of-sight integration. When the jets are excited out-of-phase with respect to each other, the flow features including the lobes that correlate with the LSS generated due to excitation wash out and cancel one another. The highly skewed and blurred standing wave patterns outside of the jets and non-existent lobes within the jets (when strong shedding of LSS due to excitation are expected) indicate that it is not possible to fully appreciate the details of flow-field response in images taken along the minor axis plane. The response of the jets imaged in the major axis plane is shown in Fig. 14d. This figure must be compared against the baseline (Fig. 14b) and in-phase excited (Fig. 11d) jets. Compared to the baseline jets, it appears that the top jet is responding to excitation with more coherent structures. The differences in the response of the jets can be potentially explained by considering that the excitation frequency (f_e = 8.4 *kHz*) is matching the screech frequency of the dominant jet and is somewhat higher than the baseline frequency of the other jet (f = 8.25 *kHz*). Matching the natural coupling tendency of the jets in the first experiment resulted in a strong jet response that manifested as strengthening of the screech loop and enhancement of coupling. In contrast, opposing the coupling preference of the jets has resulted in a jet response that is not highly coherent.

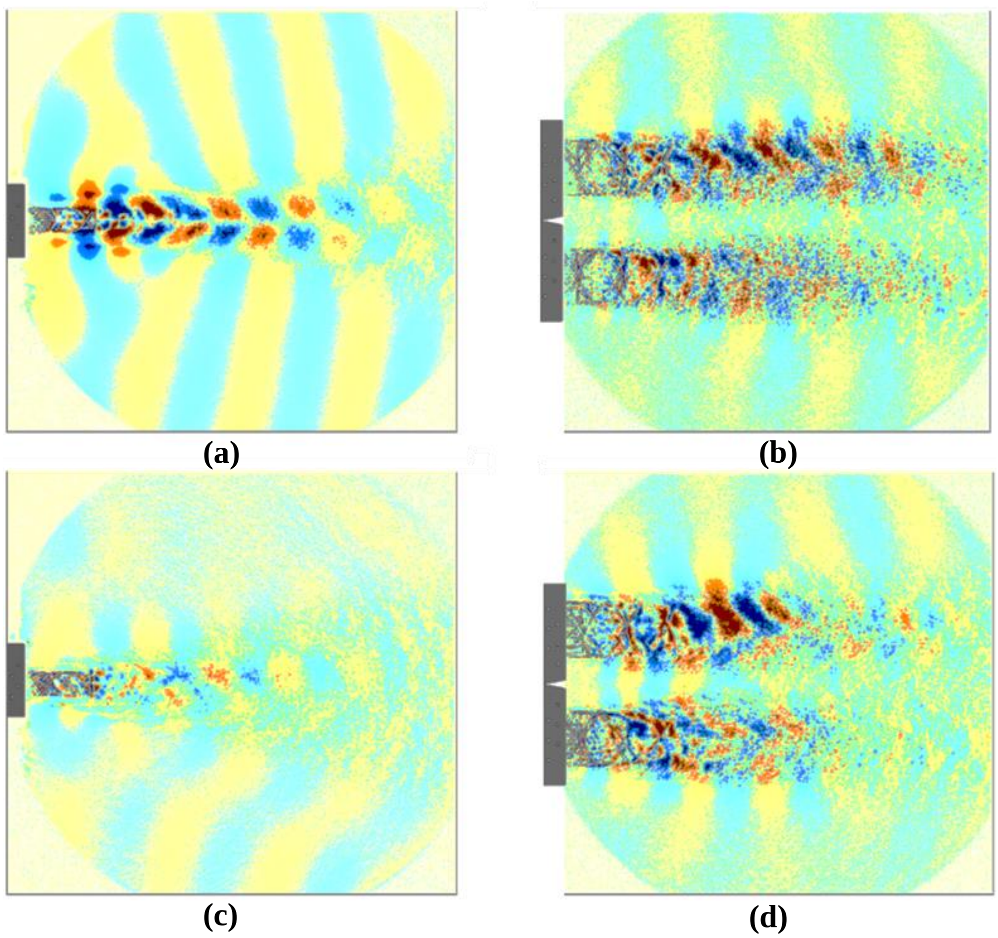


Fig. 14 First SPOD mode at screech frequency on the minor and major axes planes showing the effects of control: a, b) baseline jets, c, d) controlled jets (St_e = 0.41, Φ_{sl} = 180°, Φ_c = 180°)

The acoustics of the jet response, presented in the form of spectra and spectrograms from microphone 2 in Fig. 15 will shed further light on the effects of altering the phase between the two jets. Baseline plots are repeated to facilitate comparison of the results. The amplitude of the tone near the natural screech frequency for the excited case (see Fig. 15c) has been reduced by 7 dB and the present narrow peak has no base indicating the possible absence of a screech tone. It is likely that the peak present in spectra at St = 0.41 is simply self-noise from the LAFPAs. Plots of time-averaged and time-resolved coherence between microphones 2 and 6 (not shown here) confirm the absence and complete disruption of screech. It is interesting to note that the amplitude of the first harmonic of the screech frequency has increased by 14 dB in the excited case, possibly indicating a strong flapping motion of the jet that corresponds to the Φ_{sl} = 180° actuation pattern. This could suggest that the jets indeed respond to excitation by shedding LSS, even though the screech loop has been disrupted on the right-hand side nozzle. The spectrogram of the excited jet from microphone 2 indicates that the intermittency of screech tones, as was seen in the baseline jets, has been eliminated; further suggesting that the tones that were competing for dominance (closely spaced tones at 8.25 and 8.40 *kHz*) are no longer present.

The effects of excitation on coupling along the minor axis plane can be seen in time-resolved and time-averaged coherence plots of Fig. 16. Based on the results shown in Fig. 16c and d, out-of-phase excitation of the jets has led to decoupling of the jets along the minor axis. This is likely due to the change in relative phase and time of arrival of acoustic feedback waves that close the coupling loop. The baseline jets at M_j = 1.35 tend to close the coupling loop in-phase and controlling the relative shedding on the jets to be out-of-phase has likely resulted in disruption of that loop.

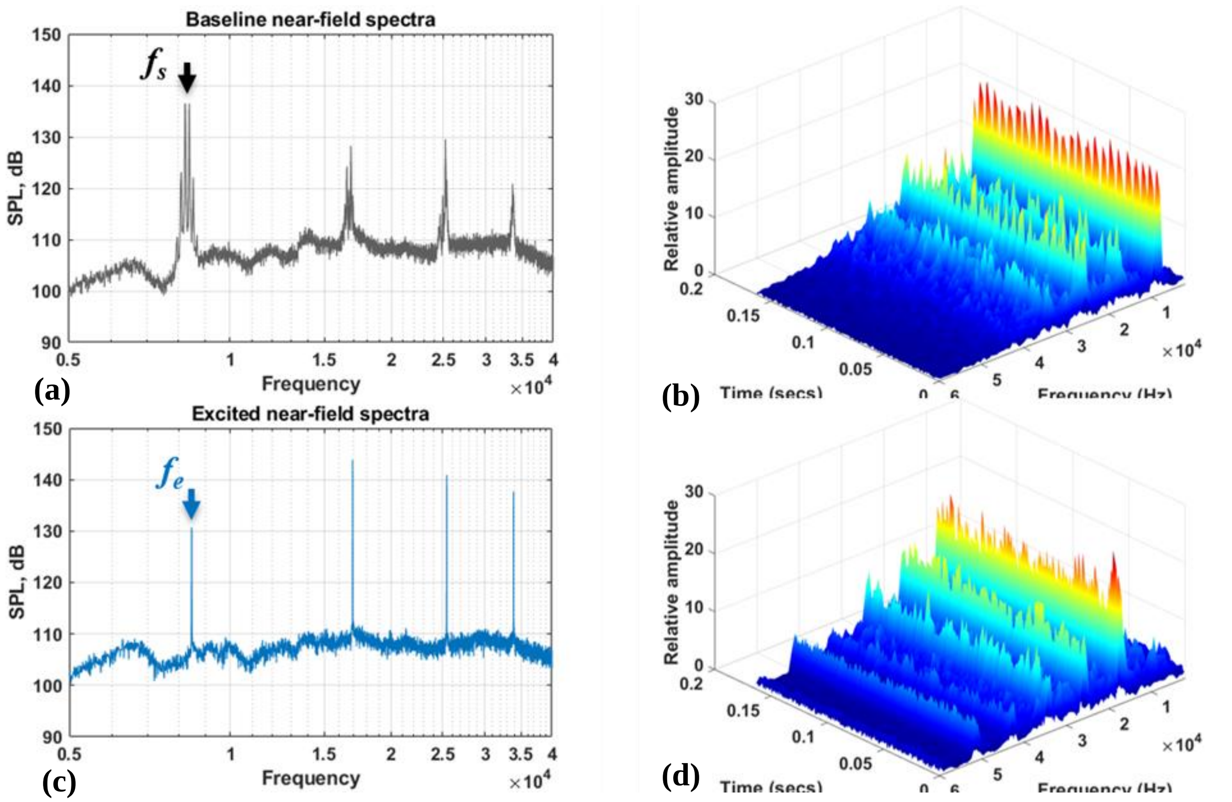


Fig. 15 Time-averaged spectra and spectrograms from mic. 2 showing the effects of control a, b) baseline jets c, d) controlled jets (St_e = 0.41, Φ_{sl} = 180°, Φ_c = 180°)

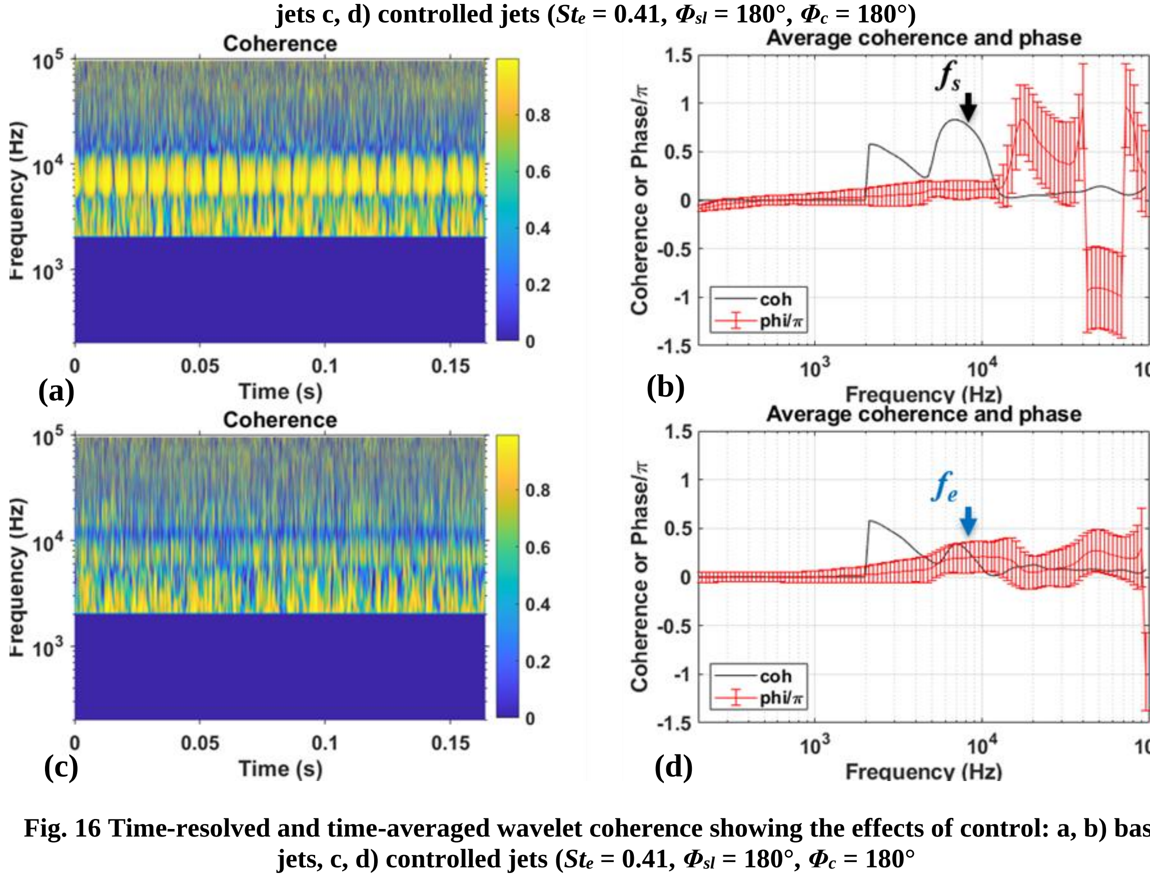


Fig. 16 Time-resolved and time-averaged wavelet coherence showing the effects of control: a, b) baseline jets, c, d) controlled jets (St_e = 0.41, Φ_{sl} = 180°, Φ_c = 180°

The results of the second experiment suggest that the jets were decoupled primarily as a result of altering the coupling loop. This was achieved by changing the relative shedding phase of LSS in adjacent jets (Φ_c = 180°). We must note that actuation and frequency were selected to ensure that the shedding of LSS from the top and bottom shear layers conformed to the natural tendency of the jets. We did not change the frequency of the either of the loops or the coupling phase in the first experiment. Consequently, it appears that altering the feedback time of arrival in the coupling loop (by changing the relative excitation phase of the jets) is an effective approach to disrupting it and decoupling the jets.

V. Conclusions

The results of active flow control experiments aimed at better understanding the dynamics of screech and coupling processes in closely spaced, low *AR*, twin rectangular jets were discussed in this paper. A recently designed facility at the GDTL was used to implement active flow control with the overall aim of reducing near-field pressure fluctuations and far-field noise. Control of screech and coupling loops was realized using localized arc filament plasma actuators (LAFPAs) developed at the GDTL. Experiments were conducted at an overexpanded M_j of 1.35. The baseline jets at this fully expanded Mach number demonstrated a tendency to intermittently couple in-phase. The intermittent nature of coupling is related to a slight difference in screech frequency of the adjacent jets, which gives rise to a competition between them for dominance.

With excitation frequency chosen to match the natural screech Strouhal number of 0.41, the main parameters that were explored in the process of altering the screech and coupling loops were the relative phase between LSS in adjacent jets (Φ_c) and the phase between LSS shed from the top and bottom shear layers of each jet (Φ_{sl}). Two separate experiments were designed and conducted to investigate the effects of altering the screech and coupling loops using these two parameters. In the first experiment, the excitation frequency and relative phase between the adjacent jets were matched to the natural screech frequency of the jets and their coupling tendency ($St_e = St = 0.41$, Φ_c = 0°) but the jets were forced to adopt a symmetric mode by setting Φ_{sl} = 0°. The results showed that organizing the shedding of LSS through excitation results in strengthening of the screech loop which in turn enhances and strengthens coupling.

In the following experiment, the excitation was set to match the jets' natural screech frequency and mode ((St_e = St = 0.41, Φ_{sl} = 180°) but oppose the coupling preference of the baseline jets by setting Φ_c = 180°. Results showed that such an excitation pattern leads to decoupling of the jets and disruption of the screech loop of one of the jets. This is likely caused by the time of arrival of the acoustic feedback waves being disrupted by out-of-phase shedding of LSS in the shear layers of adjacent jets.

Consequently, it appears that altering the feedback time of arrival in the coupling loop (by changing the relative excitation phase of the jets) is an effective approach to decoupling the jets. This is our working hypothesis. We intend to examine the validity of our hypothesis over a wide range of jet NPRs in our upcoming publications. That includes presenting detailed measurements of near-field pressure fluctuations and far-field acoustics to show the effect of suppressing/weakening the screech and/or decoupling the jet by changing actuation frequency and pattern.

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References

[1] Dusa, D., Speir, D., Rowe, R., and Leavitt, L. Advanced Technology Exhaust Nozzle Development. In *19th Joint Propulsion Conference*, AIAA paper 1983-1286, June 1983

[2] Wiegand, C. F-35 Air Vehicle Technology Overview. In *2018 Aviation Technology, Integration, and Operations Conference*, AIAA paper 2018-3368, June 2018.

[3] Alkislar, M. B., Krothapalli, A., and Lourenco, L. M. "Structure of a Screeching Rectangular Jet: A Stereoscopic Particle Image Velocimetry Study." *Journal of Fluid Mechanics*, Vol. 489, 2003, pp. 121–154. https://doi.org/10.1017/S0022112003005032.

[4] Krothapalli, A., Baganoff, D., and Karamcheti, K. "On the Mixing of a Rectangular Jet." *Journal of Fluid Mechanics*, Vol. 107, 1981, pp. 201–220. https://doi.org/10.1017/S0022112081001730.

[5] Mixson, J. S., and Roussos, L. A. Acoustic Fatigue: Overview of Activities at NASA Langley. *NASA Technical Memorandum* NTM-89143, April 1987.

[6] Berndt, D. E. Dynamic pressure fluctuations in the internozzle region of a twin-jet nacelle. No. 841540. SAE Technical Paper, 1984.

[7] Shaw, L. "Twin-Jet Screech Suppression." *Journal of Aircraft*, Vol. 27, No. 8, 1990, pp. 708–715. https://doi.org/10.2514/3.25344.

[8] Walker, S. Twin Jet Screech Suppression Concepts Tested for 4.7 Percent Axisymmetric and Two-Dimensional Nozzle Configurations. In *26th Joint Propulsion Conference*, AIAA paper 90-2150, July 1990.

[9] Harper-Bourne, M. Twin-Jet near-Field Noise Prediction. In *6th Aeroacoustics Conference and Exhibit*, AIAA paper 2000-2084, June 2000.

[10] Panickar, P., Srinivasan, K., and Raman, G. "Aeroacoustic Features of Coupled Twin Jets with Spanwise Oblique Shock-Cells." *Journal of Sound and Vibration*, Vol. 278, No. 1, 2004, pp. 155–179. https://doi.org/10.1016/j.jsv.2003.10.011.

[11] Panickar, P., Srinivasan, K., and Raman, G. "Aeroacoustic Features of Coupled Twin Jets with Spanwise Oblique Shock-Cells." *Journal of Sound and Vibration*, Vol. 278, No. 1, 2004, pp. 155–179. https://doi.org/10.1016/j.jsv.2003.10.011.

[12] Bell, G., Cluts, J., Samimy, M., Soria, J., and Edgington-Mitchell, D. "Intermittent Modal Coupling in Screeching Underexpanded Circular Twin Jets." *Journal of Fluid Mechanics*, Vol. 910, 2021. https://doi.org/10.1017/jfm.2020.909.

[13] Nogueira, P. A. S., and Edgington-Mitchell, D. M. "Investigation of Supersonic Twin-Jet Coupling Using Spatial Linear Stability Analysis." *Journal of Fluid Mechanics*, Vol. 918, 2021. https://doi.org/10.1017/jfm.2021.366.

[14] Zilz, D., and Wlezien, R. The Sensitivity of Near-Field Acoustics to the Orientation of Twin Two-Dimensional Supersonic Nozzles. In *26th Joint Propulsion Conference*, AIAA paper 1990-2149, July 1990.

[15] Zeierman, S., Gutmark, E., and Nosseir, N. Characteristics of Two Adjacent Rectangular Jets. In *30th Aerospace Sciences Meeting and Exhibit*, AIAA paper 1992-237, January 1992.

[16] Raman, G., and Taghavi, R. "Coupling of Twin Rectangular Supersonic Jets." *Journal of Fluid Mechanics*, Vol. 354, 1998, pp. 123–146. https://doi.org/10.1017/S0022112097007441.

[17] Raman, G., and Taghavi, R. "Resonant Interaction of a Linear Array of Supersonic Rectangular Jets: An Experimental Study." *Journal of Fluid Mechanics*, Vol. 309, 1996, pp. 93–111. https://doi.org/10.1017/S0022112096001577.

[18] Bozak, R. Twin Jet Effects on Noise of Round and Rectangular Jets: Experiment and Model. In *20th AIAA/CEAS Aeroacoustics Conference*, AIAA paper 2014-2890, June 2014.

[19] Bozak, R., and Wernet, M. P. Subsonic Round and Rectangular Twin Jet Flow Effects. In *50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, AIAA paper 2014-3736, July 2014.

[20] Karnam, A., Baier, F., and Gutmark, E. J. Nature of Flow Field & Acoustics of Twin Supersonic Rectangular Jets. In *AIAA Scitech 2020 Forum*, AIAA paper 2020-0500, January 2020.

[21] Kalagotla, D., Karnam, A., and Gutmark, E. J. Comparison of Flow Characteristics of Single and Twin Rectangular Jets Using OVERFLOW Code. In *AIAA Scitech 2020 Forum*, AIAA paper 2020-1334, January 2020.

[22] Viswanath, K., Liu, J., Ramamurti, R., Karnam, A., Baier, F., and Gutmark, E. J. Noise Characteristics of Low Aspect Ratio Supersonic Twin Jet Configuration. In *AIAA Scitech 2020 Forum*, AIAA paper 2020-0496, January 2020.

[23] Esfahani, A., Webb, N., and Samimy, M. Coupling Modes in Supersonic Twin Rectangular Jets. In *AIAA Scitech 2021 Forum*, AIAA paper 2021-1292, January 2021.

[24] Gutmark, E., Schadow, K. C., and Bicker, C. J. "Near Acoustic Field and Shock Structure of Rectangular Supersonic Jets." *AIAA Journal*, Vol. 28, No. 7, 1990, pp. 1163–1170. https://doi.org/10.2514/3.25187.

[25] Shih, C., Krothapalli, A., and Gogineni, S. "Experimental Observations of Instability Modes in a Rectangular Jet." *AIAA Journal*, Vol. 30, No. 10, 1992, pp. 2388–2394. https://doi.org/10.2514/3.11238.

[26] Raman, G., and Rice, E. J. "Instability Modes Excited by Natural Screech Tones in a Supersonic Rectangular Jet." *Physics of Fluids*, Vol. 6, No. 12, 1994, pp. 3999–4008. https://doi.org/10.1063/1.868389.

[27] Gojon, R., Gutmark, E., and Mihaescu, M. "Antisymmetric Oscillation Modes in Rectangular Screeching Jets." *AIAA Journal*, Vol. 57, No. 8, 2019, pp. 3422–3441. https://doi.org/10.2514/1.J057514.

[28] Suda, H., Manning, T., and Kaji, S. Transition of Oscillation Modes of Rectangular Supersonic Jet in Screech. In *15th Aeroacoustics Conference*, AIAA paper 93-4323, October 1993.

[29] Kuo, C.-W., Cluts, J., and Samimy, M. "Exploring Physics and Control of Twin Supersonic Circular Jets." *AIAA Journal*, Vol. 55, No. 1, 2017, pp. 68–85. https://doi.org/10.2514/1.J054977.

[30] Samimy, M., Adamovich, I., Webb, B., Kastner, J., Hileman, J., Keshav, S., and Palm, P. "Development and Characterization of Plasma Actuators for High-Speed Jet Control." *Experiments in Fluids*, Vol. 37, No. 4, 2004, pp. 577–588. https://doi.org/10.1007/s00348-004-0854-7.

[31] Utkin, Y. G., Keshav, S., Kim, J.-H., Kastner, J., Adamovich, I. V., and Samimy, M. "Development and Use of Localized Arc Filament Plasma Actuators for High-Speed Flow Control." *Journal of Physics D: Applied Physics*, Vol. 40, No. 3, 2007, pp. 685–694. https://doi.org/10.1088/0022-3727/40/3/S06.

[32] Samimy, M., Webb, N., and Crawley, M. "Excitation of Free Shear-Layer Instabilities for High-Speed Flow Control." *AIAA Journal*, Vol. 56, No. 5, 2018, pp. 1770–1791. https://doi.org/10.2514/1.J056610.

[33] Samimy, M., Kim, J.-H., Kastner, J., Adamovich, I., and Utkin, Y. "Active Control of High-Speed and High-Reynolds-Number Jets Using Plasma Actuators." *Journal of Fluid Mechanics*, Vol. 578, 2007, pp. 305–330. https://doi.org/10.1017/S0022112007004867.

[34] Samimy, M., Kearney-Fischer, M., and Kim, J.-H. "High-Speed and High-Reynolds-Number Jet Control Using Localized Arc Filament Plasma Actuators." *Journal of Propulsion and Power*, Vol. 28, No. 2, 2012, pp. 269–280. https://doi.org/10.2514/1.B34272.

[35] Esfahani, A., Webb, N., and Samimy, M. "Flow Separation Control over a Thin Post-Stall Airfoil: Effects of Excitation Frequency." *AIAA Journal*, Vol. 57, No. 5, 2019, pp. 1826–1838. https://doi.org/10.2514/1.J057796.

[36] Yugulis, K., Hansford, S., Gregory, J. W., and Samimy, M. "Control of High Subsonic Cavity Flow Using Plasma Actuators." *AIAA Journal*, Vol. 52, No. 7, 2014, pp. 1542–1554. https://doi.org/10.2514/1.J052668.

[37] Webb, N., and Samimy, M. "Control of Supersonic Cavity Flow Using Plasma Actuators." *AIAA Journal*, Vol. 55, No. 10, 2017, pp. 3346–3355. https://doi.org/10.2514/1.J055720.

[38] Kearney-Fischer, M., Kim, J.-H., and Samimy, M. "Control of a High Reynolds Number Mach 0.9 Heated Jet Using Plasma Actuators." *Physics of Fluids*, Vol. 21, No. 9, 2009, p. 095101. https://doi.org/10.1063/1.3210771.

[39] Sinha, A., Alkandry, H., Kearney-Fischer, M., Samimy, M., and Colonius, T. "The Impulse Response of a High-Speed Jet Forced with Localized Arc Filament Plasma Actuators." *Physics of Fluids*, Vol. 24, No. 12, 2012, p. 125104. https://doi.org/10.1063/1.4772191.

[40] Samimy, M., Webb, N., and Esfahani, A. "Reinventing the Wheel: Excitation of Flow Instabilities for Active Flow Control Using Plasma Actuators." *Journal of Physics D: Applied Physics*, Vol. 52, No. 35, 2019, p. 354002. https://doi.org/10.1088/1361-6463/ab272d.

[41] Karnam, A., Baier, F., Gutmark, E. J., Jeun, J., Wu, G. J., and Lele, S. K. An Investigation into Flow Field Interactions between Twin Supersonic Rectangular Jets. In *AIAA Scitech 2021 Forum*, AIAA paper 2021-1291, January 2021.

[42] Hahn, C., Kearney-Fischer, M., and Samimy, M. "On Factors Influencing Arc Filament Plasma Actuator Performance in Control of High-Speed Jets." *Experiments in Fluids*, Vol. 51, 2011, pp. 1591–1603. https://doi.org/10.1007/s00348-011-1172-5.

[43] Towne, A., Schmidt, O. T., and Colonius, T. "Spectral Proper Orthogonal Decomposition and Its Relationship to Dynamic Mode Decomposition and Resolvent Analysis." *Journal of Fluid Mechanics*, Vol. 847, 2018, pp. 821–867. https://doi.org/10.1017/jfm.2018.283.

[44] Schmidt, O. T., and Colonius, T. "Guide to Spectral Proper Orthogonal Decomposition." *AIAA Journal*, Vol. 58, No. 3, 2020, pp. 1023–1033. https://doi.org/10.2514/1.J058809.

[45] Jeun, J., Wu, G. J., Lele, S. K., Karnam, A., Baier, F., and Gutmark, E. J. Twin Rectangular Jet Screech and Coupling: Numerical Study and Validation. In *AIAA Scitech 2021 Forum*, AIAA paper 2021-1290, January 2021.

[46] Edgington-Mitchell, D. "Aeroacoustic Resonance and Self-Excitation in Screeching and Impinging Supersonic Jets – A Review." *International Journal of Aeroacoustics*, Vol. 18, Nos. 2–3, 2019, pp. 118–188. https://doi.org/10.1177/1475472X19834521.

[47] Manning, T., and Lele, S. Numerical Simulations of Shock-Vortex Interactions in Supersonic Jet Screech. In *36th AIAA Aerospace Sciences Meeting and Exhibit*, AIAA paper 1998-282, January 1998.

[48] Jones, D. S., and Morgan, J. D. "The Instability Due to Acoustic Radiation Striking a Vortex Sheet on a Supersonic Stream*." *Proceedings of the Royal Society of Edinburgh Section A: Mathematics*, Vol. 71, No. 2, 1973, pp. 121–140. https://doi.org/10.1017/S0080454100009298.