Abstract# E03.00021

THE OHIO STATE UNIVERSITY

Coupling Modes in Supersonic Twin Rectangular Jets

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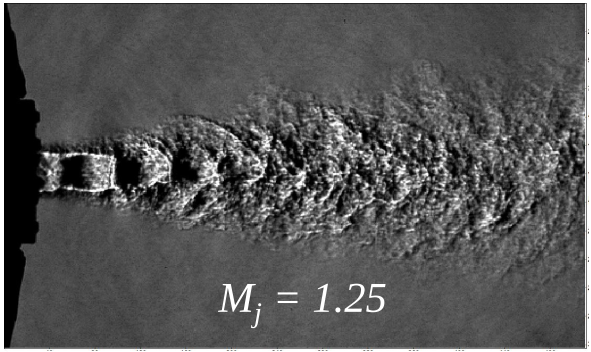

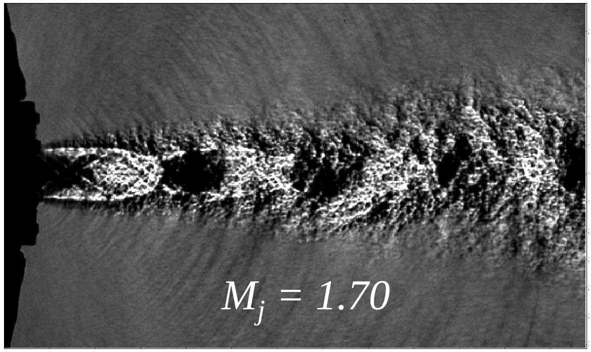

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Outline

- 1. Introduction
- 2. Experimental Setup
- 3. Results
  - Screech/ Coupling Modes
  - Standing Waves
- 4. Conclusions

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Introduction:

Single rectangular jet screech modes

- *Gutmark et al.* (1990) for the first time reported the existence of **symmetric** and **antisymmetric** (**flapping**) **screech modes in rectangular jets** via microphone measurements.

- *Raman and Rice* (1994) investigated an underexpanded jet and reported that a sinuous (**antisymmetric/ flapping**) **mode existed at screech frequency** while a varicose (**symmetric**) **mode existed simultaneously at the harmonic of screech frequency**

- *Gojon et al.* (2019) reported the existence of only an antisymmetric mode in their simulations of a hot, *AR* = 2 jet issued from a M_d = 1.5 nozzle

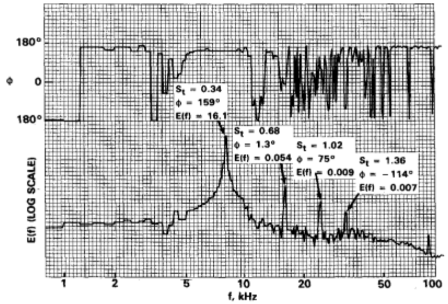
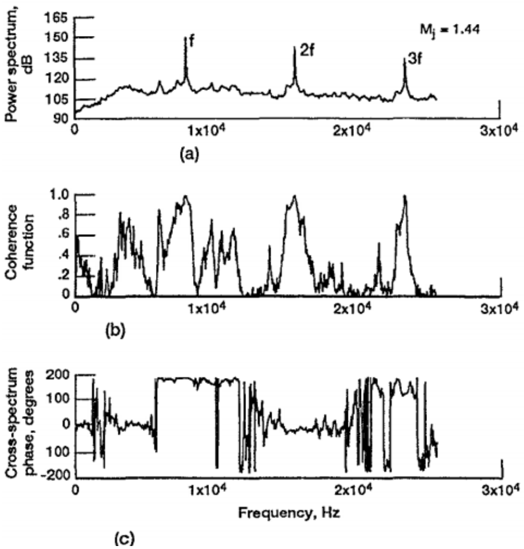
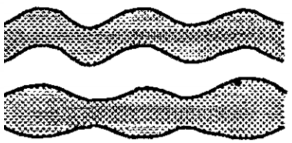


Fig. 12 Cross spectrum and relative phase of near-field pressure fluctuations at opposite jet boundaries, minor axis plane, $M = 1.34$ ($x/D_e = 0.67$, $r/D_e = \pm 0.94$).

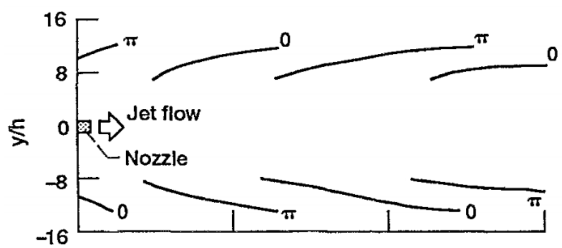
Gutmark et al. [1]



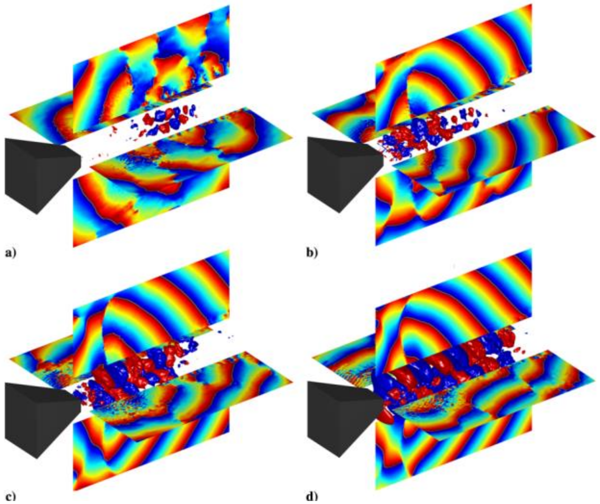
f (sinuous)



2f (varicose)



Raman and Rice [2]



Gojon et al. [3]

Introduction:

Twin rectangular jet screech coupling modes

- *Zilz and Wlezien* (1990) produced the first report on coupling in rectangular jets. While they reported only **in-phase** or **out-of-phase flapping motions for high-aspect-ratio** rectangular jets, their results indicated that **lateral motions in low *AR* jets are possible**

- *Raman and Taghavi* (1998) later on carried out detailed near-field measurements to ascertain the phase difference between two high *AR* jets

- They reported **out-of-phase and in-phase flapping along the vertical axis for high *AR* jets** and that a frequency mismatch existed between the jets even though they had the same source of high-pressure air.

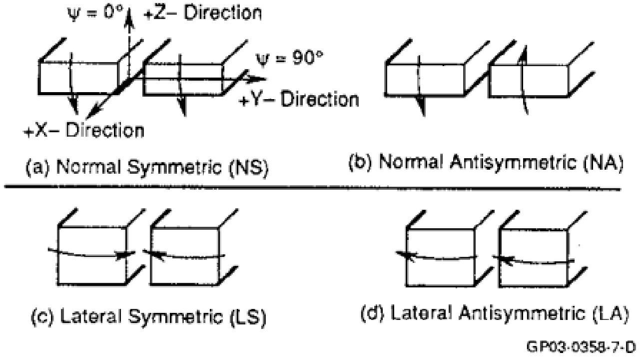
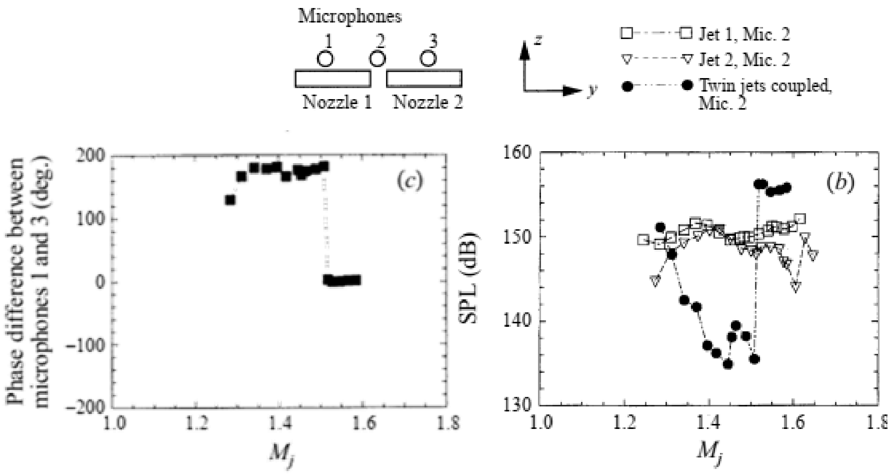


Fig. 5 Illustration Of Four Jet Interaction Modes and Nozzle Coordinate System

Zilz and Wlezien [3]



Raman and Taghavi [4]

Introduction:

Key questions

- We are attempting to answer the following questions in this work:
  - What are the single jet screech mode and twin jet coupling modes across a wide range of Mach numbers in a low AR rectangular twin jet setup?
  - How does the screech amplitude vary with the mode of the jets?

➢ More details on coupling and standing waves in twin rectangular jets will be included in our upcoming SciTech paper:

Esfahani, Ata, Webb, Nathan, and Mo Samimy. "*Flow Physics and Aeroacoustics of Twin Rectangular Supersonic Jets.*" 2021 AIAA SciTech Forum

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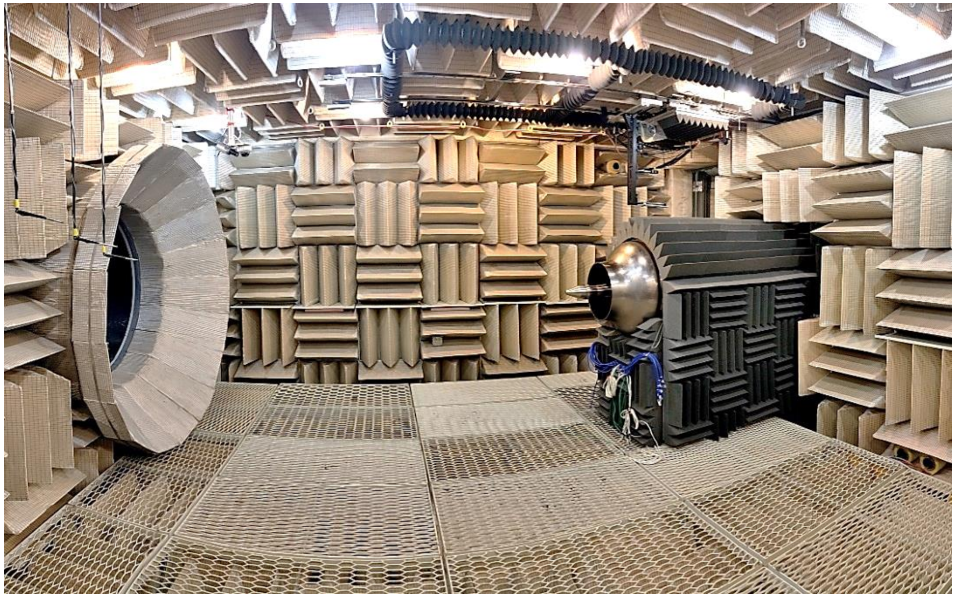
Experimental Setup:

Facility: Anechoic chamber

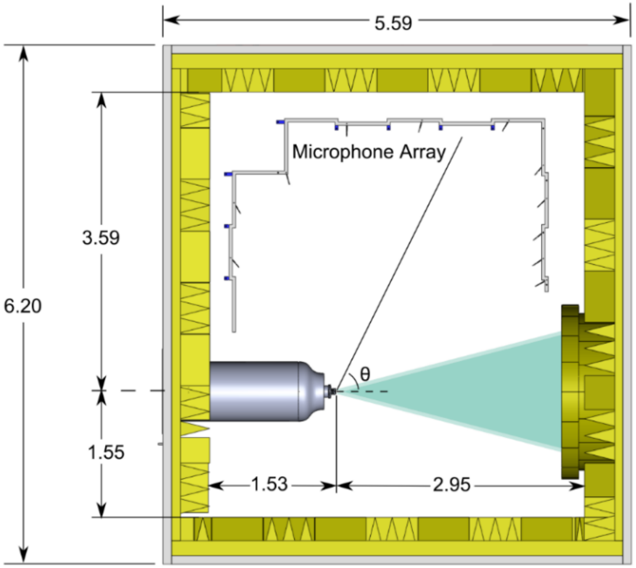
- 6.2 *m* x 5.6 *m* x 3.4 *m* chamber is anechoic down to 160 *Hz*
- Compressed air source for continuous running of unheated jets with various nozzle sizes and capable of running heated jet up to *TTR* ~ 2.5 (800 *K*)



Diagnostics:

- Near and far-field mic. array (*θ*:25°-135°)
  - ¼ inch B&K microphones
- Stereo and tomo-PIV
- Z-type Schlieren (high-resolution and high-speed imaging)

Chamber interior



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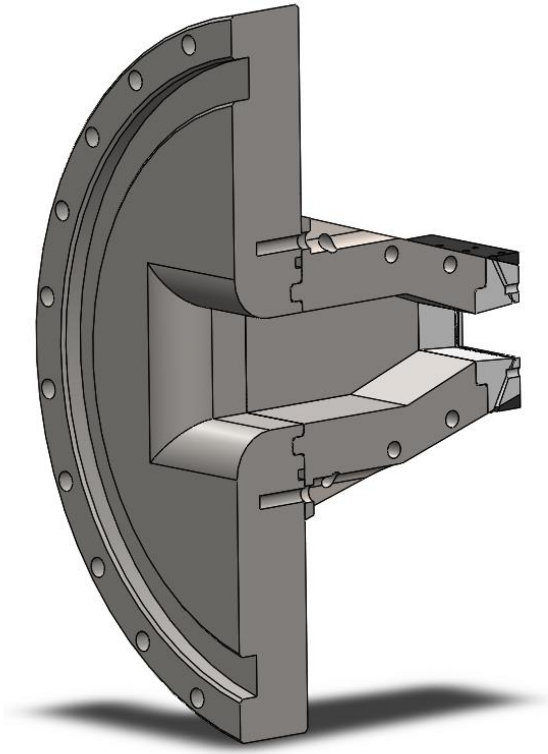
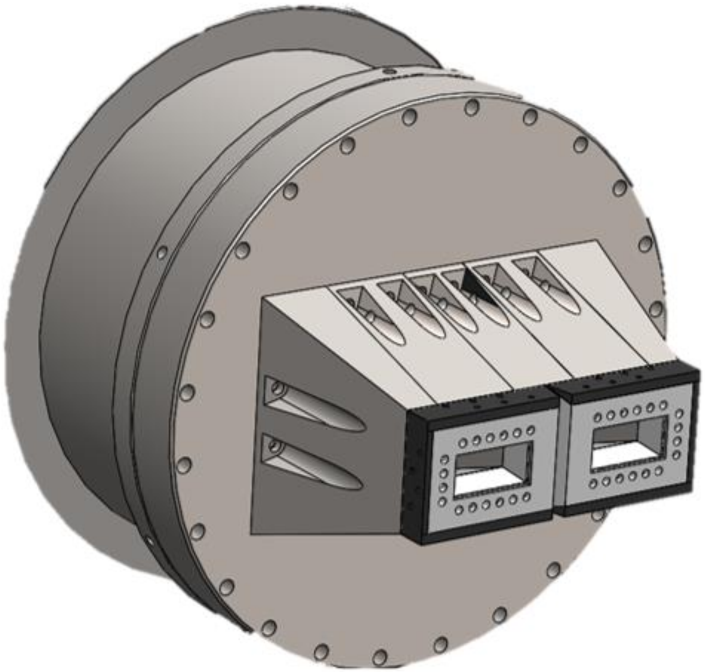
Experimental Setup:

Facility: Twin Jets





- Two 2.41× 1.21 *cm* (***AR* = 2**), bi-conical nozzles
- $\boldsymbol{M_d = 1.5}$
- Center-to-center nozzle spacing: $\boldsymbol{s/D_e = 2.35}$ (D_e = 1.92 *cm*)
- Modular design

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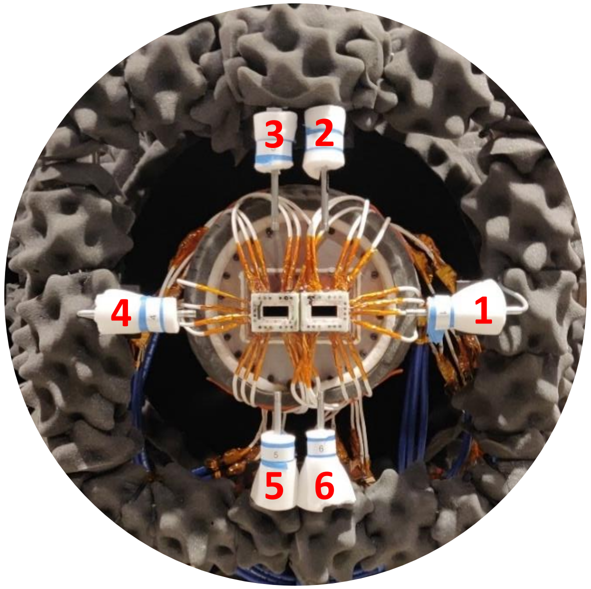
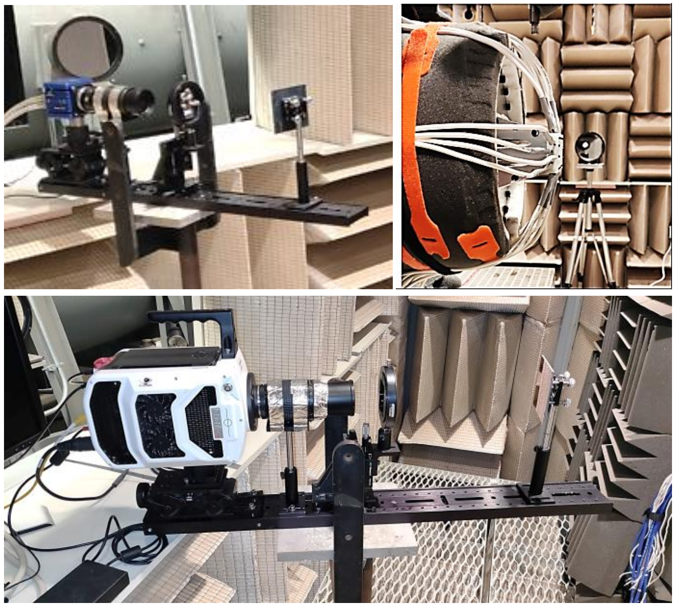
Experimental Setup:

Diagnostics: Near-field Microphone Array/ Schlieren





- All microphones are located at x/D_e **= 0** and r/D_e **= 4** (7.3 *cm* from nozzle centerline)
- Low signal conditioner gain: 1 *mV/Pa*
- **100 blocks** of **32,768 samples** at **200 *kHz*** were acquired for each case
- Mach number sweep from M_j = 1.10 (overexpanded) to 1.85 (underexpanded) in increments of 0.05

- *LaVision Imager sCMOS* camera for time-averaged schlieren → **50 fps** (**window size: 2500 x 2150 px**), **300 images** for each Mach number
- A *Phantom v1210* camera for high-speed imaging → **60,000 fps** (**window size: 512 x 340 px**), **1000 images** for each Mach number
- LED light source pulse width**: 500 ns**
- Post-processing was performed in *DaVis 8.4* and *MATLAB*

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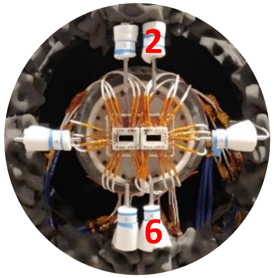
Results:

Single jet screech modes – near-field microphone 2&6

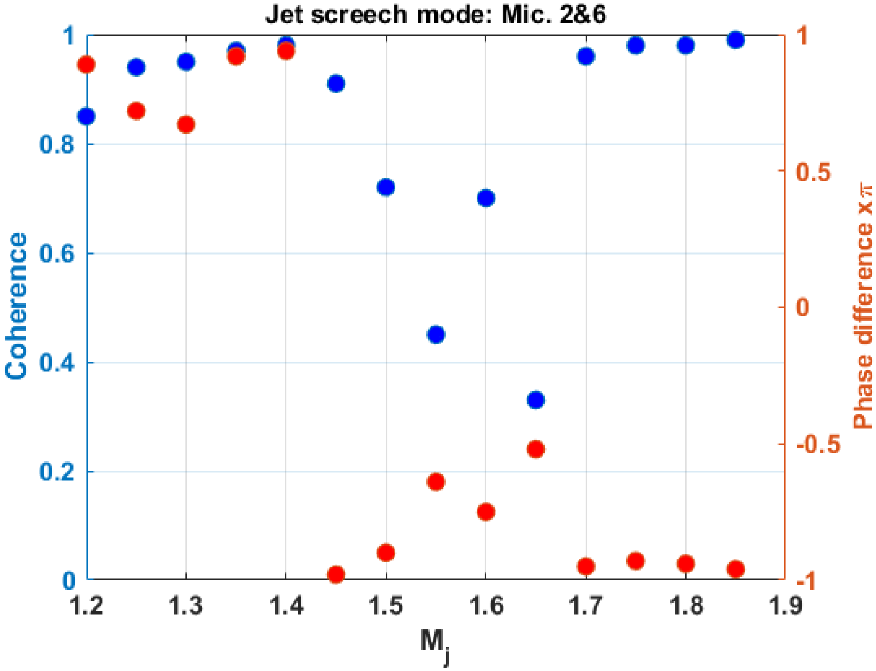


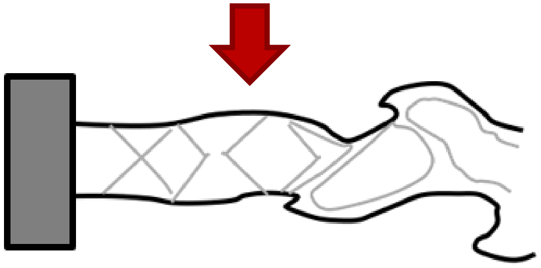
- Examining the plot of phase and coherence from microphones located above and below the right jet shows that the phase difference between the signals is close to $\pm\pi$ for a wide range of Mach numbers.

- The phase difference between the signals and relatively high coherence values indicate that the jet's screech mode is asymmetric (flapping)

- The screech at highly overexpanded cases is intermittent (leads to lower time-averaged coherence values) whereas in underexpanded cases, the screech peaks are highly consistent in time and coherence values are high

- The strength of coherence is reduced as we approach the design Mach number (M_j = 1.5). Weakening of the shock system originating from the nozzle lip leads to a reduction in screech amplitude and coherence values between microphones 2 and 6





Asymmetric (flapping) mode

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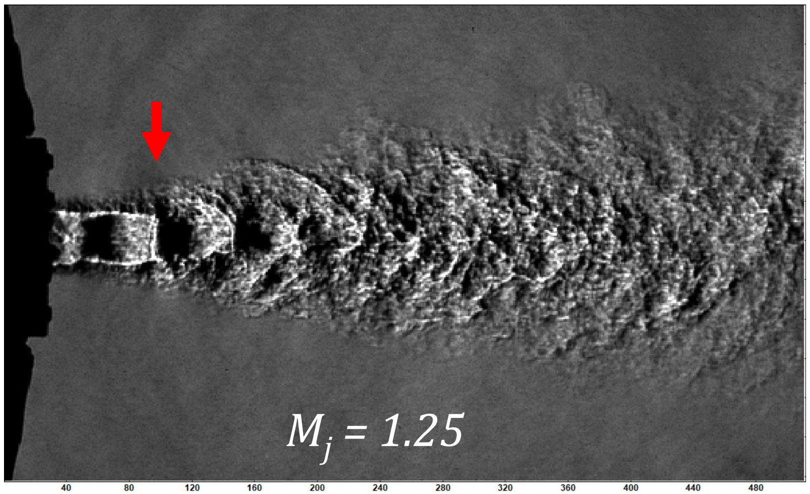
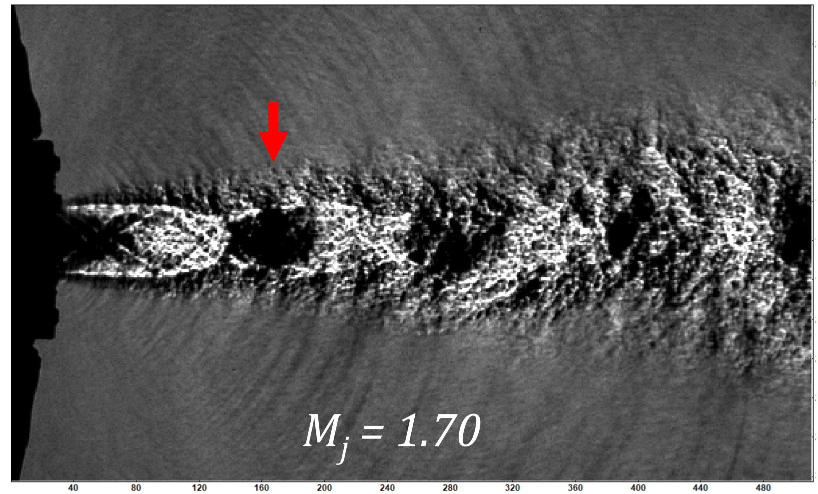
Results:

Single jet screech modes – time-resolved schlieren

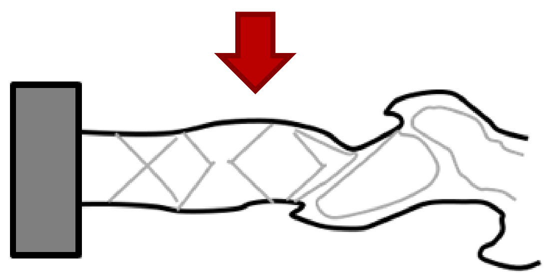
Recorded at 60,000 fps
Playback speed: 12 fps





- Further evidence supporting the existing of an asymmetric screech mode in both overexpanded and underexpanded regimes can be found in high-speed schlieren movies of the jets for cases representing each regime.

- We can see the flapping motion of the shock cells (indicated by red arrows) for both cases presented above



Asymmetric (flapping) mode

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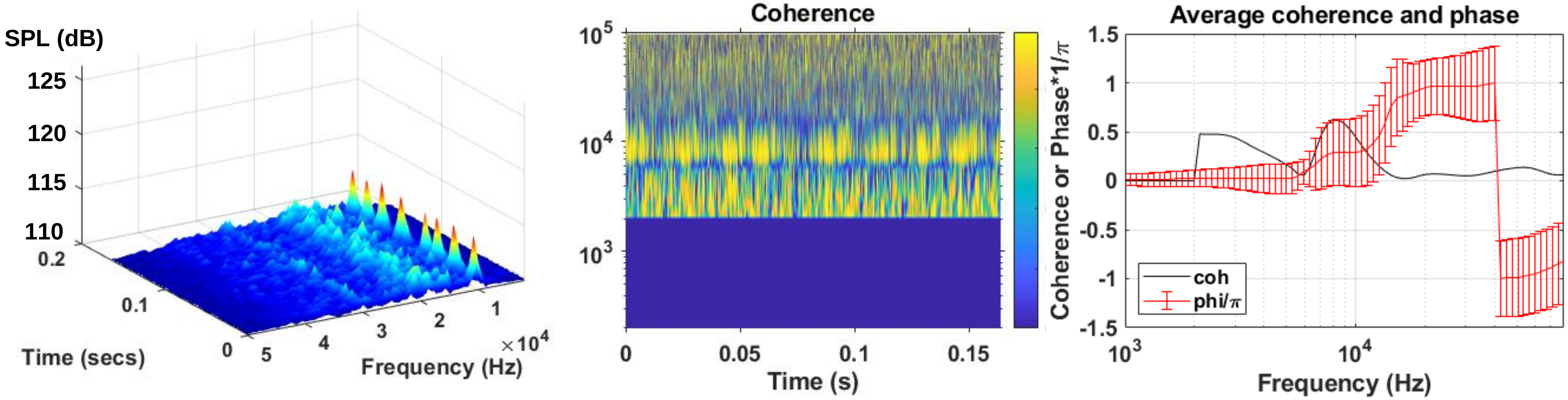
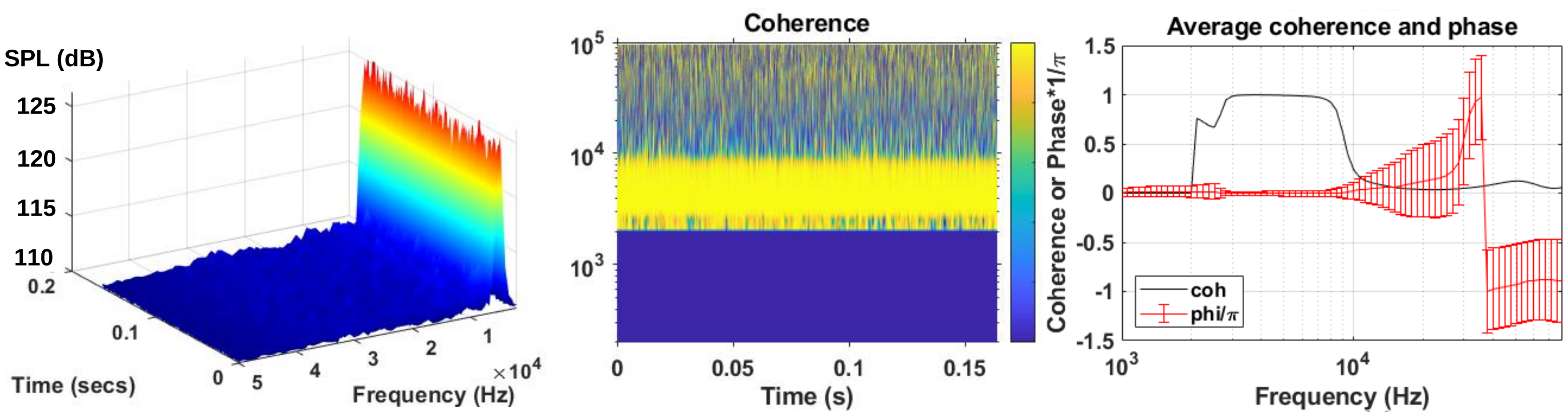
Results:

Twin jet coupling modes – near-field microphone 2&3

$M_j = 1.25$



$M_j = 1.70$



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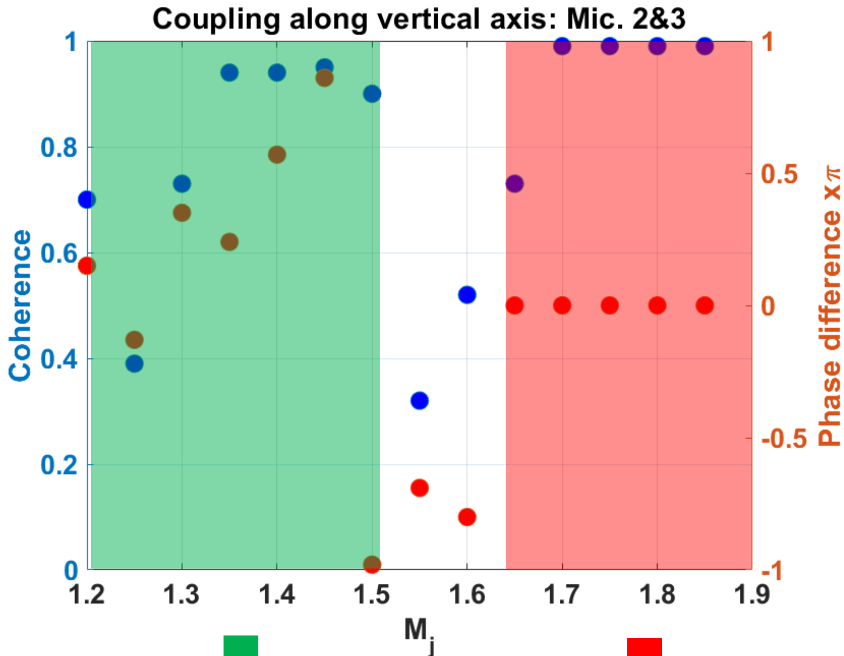
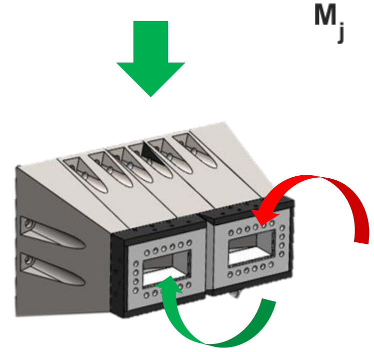
Results:

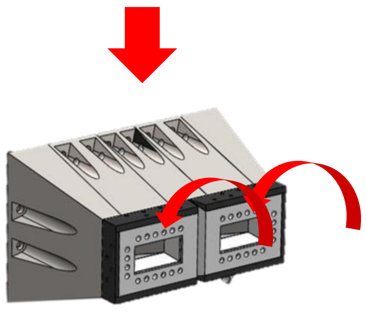
Jet coupling modes – near-field microphone 2&3

- The coupling mode of the jets can be inferred by calculating the phase difference between the signals from microphones located above each jet
- **The jets are coupled intermittently out of phase in overexpanded cases**. As we cross over to **underexpanded regime, coupling mode changes to in-phase flapping**
- Due to a **frequency mismatch and intermittent coupling** between the jets in the overexpanded regime, the **phase between the microphone signals drifts** and therefore the time-averaged phase is not exactly π
- **Intermittent screech** observed in the **overexpanded regime** is the likely source of lower coherence between the jets → see $M_j = 1.25$ results in previous slide
- At **higher Mach numbers in the underexpanded regime**, **screech tones are stronger** and **consistent in time** → coherence values are high and phase drift is absent (see $M_j = 1.70$ results in previous slide)





Out-of-phase flapping



In-phase flapping

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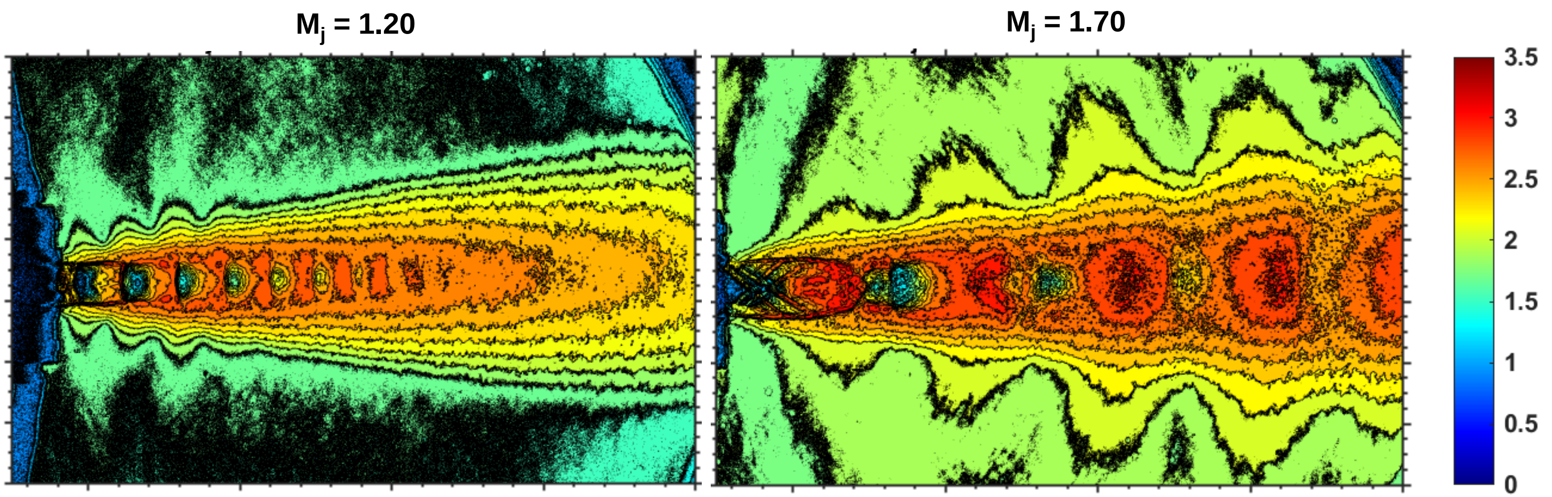
Results:

Standing waves



- The results indicate that **standing waves (SWs) appear whenever there is a significant jump in the screech amplitude and coherence of the jets**
- Standing waves form due to **interference** between **acoustic waves** (upstream propagating feedback for screech) and **hydrodynamic waves** (signature of downstream-convecting large-scale structures) → If SWs are present + acoustic feedback is strong → we expect coherent shedding of large-scale structures
- Two representative cases of **weak (M_j = 1.20)** and **strong (M_j = 1.70)** standing waves are shown in the figures above. Theses figures present maps of *log* of intensity standard deviation.
- More details on our investigation of standing waves will be included in our upcoming SciTech 2021 paper [6].

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Conclusions:

- The only screech mode observed across a wide range of Mach numbers is **asymmetric (flapping) mode**
- The jets are **intermittently coupled out-of-phase** in the **overexpanded regime**
- **Intermittent screech** and a **frequency mismatch** between the jets in the **overexpanded regime** lead to **low coherence** between the jets and a **drift in relative phase**
- The jets are **coupled in-phase at higher Mach numbers in the underexpanded regime**. Strong and consistent screech tones for such cases result in steady relative phase and high coherence values
- Standing waves are present in the jet flow-field for some Mach numbers and are related to the screech phenomenon. More information will be included in our upcoming SciTech 2021 paper

References:

[1] Gutmark, E., K. C. Schadow, and C. J. Bicker. "Near acoustic field and shock structure of rectangular supersonic jets." *AIAA journal* 28, No. 7 (1990): 1163-1170.

[2] Raman, Ganesh, and Edward J. Rice. "Instability modes excited by natural screech tones in a supersonic rectangular jet." *Physics of fluids* 6, No. 12 (1994): 3999-4008.

[3] Gojon, Romain, Ephraim Gutmark, and Mihai Mihaescu. "Antisymmetric oscillation modes in rectangular screeching jets." *AIAA Journal* 57, no. 8 (2019): 3422-3441.

[4] Zilz, David, and Richard Wlezien. "The sensitivity of near-field acoustics to the orientation of twin two-dimensional supersonic nozzles." In *26th Joint Propulsion Conference*, AIAA paper 90-2149

[5] Raman, Ganesh, and Ray Taghavi. "Coupling of twin rectangular supersonic jets." *J. Fluid Mech* 354 (1998): 123-146.

[6] Esfahani, Ata, Webb, Nathan, and Mo Samimy. "Flow Physics and Aeroacoustics of Twin Rectangular Supersonic Jets." *2021 AIAA SciTech Forum*