Shock System Stability and Inlet-Isolator Flow Path Control with Scale-Resolved Simulations

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Objectives

- Identify causes of low-frequency streamwise shock-train oscillations in rectangular cross-section geometry ducts.
- Isolate upstream-propagating perturbations and assess whether their characteristic velocity supports low-frequency oscillation.
- Explore propagation pathways and modes of upstream travel.

Problem Definition

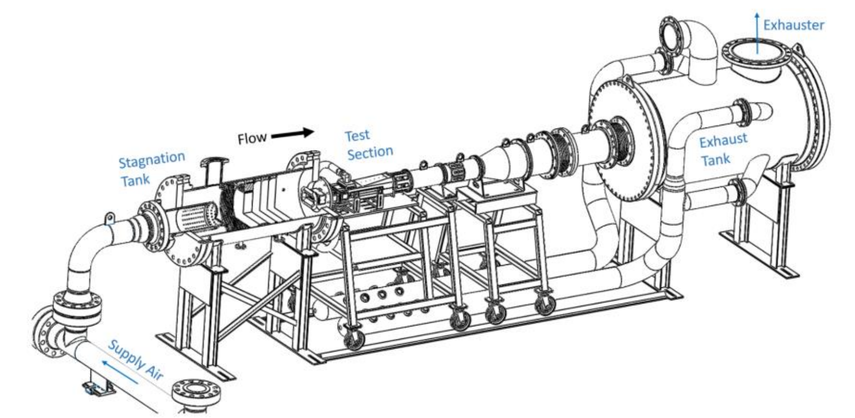
Experimental reference (*Benton et al. 2024 [1]*)

Behavior:
- Unsteady shock streamwise meandering known as shock-train unsteadiness

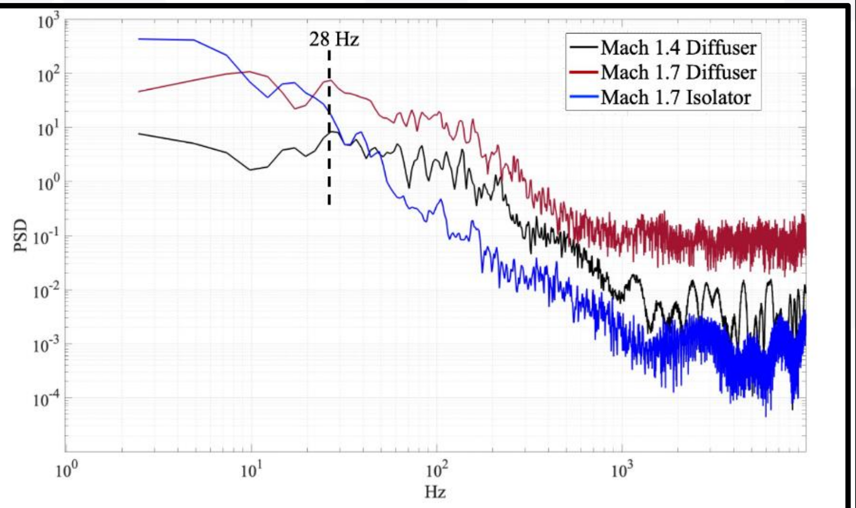
Repercussions
- Unsteady loads on vehicle
- Unsteady pressure recovery, combustion, and thrust
- Propensity for unstart

Possible causes:
- Innate shock-boundary layer interaction (SBLI) instabilities [2]
- Upstream turbulent boundary layer super-structures [3]
- Downstream perturbations [4]

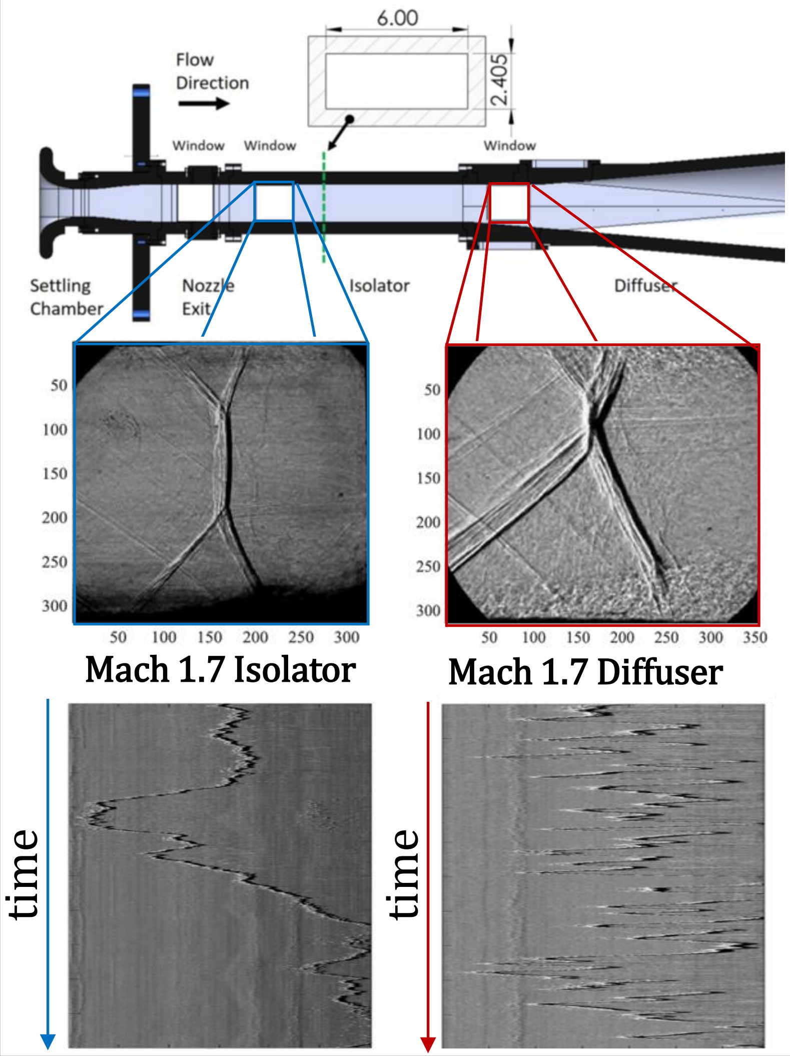
Experimental Conditions [5]
- $Mach$ = 1.4,1.7
- $P_O = 45$ psia
- T_O = 491 °R



Direct-Connect Transonic Internal Flow Facility



Low-frequency peaks from shadowgraph time traces of first normal shock.

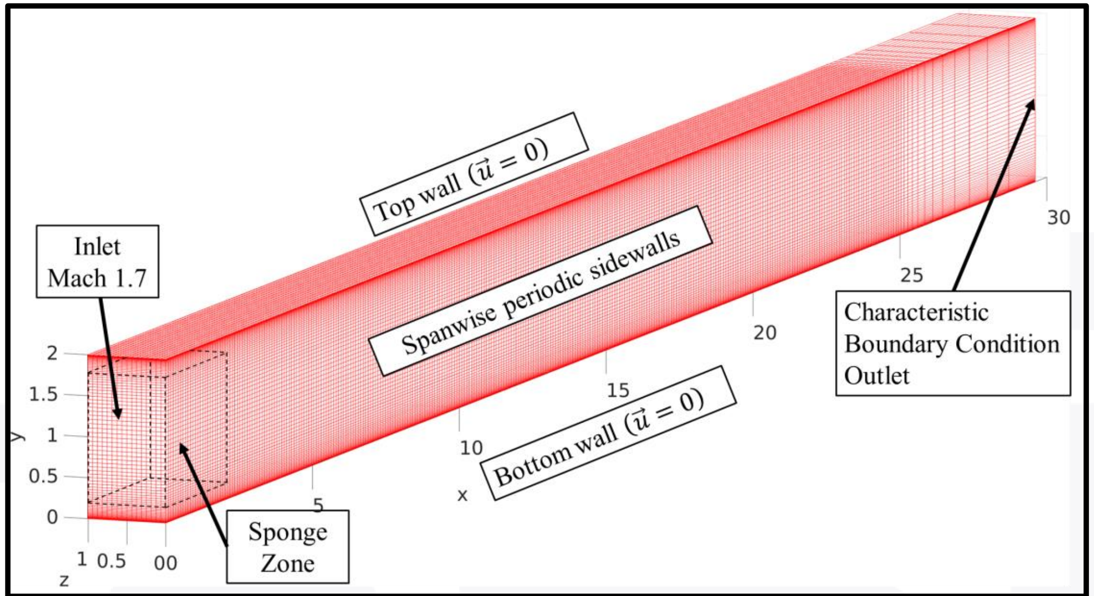


Flow path schematic, shadowgraph image, and centerline time trace

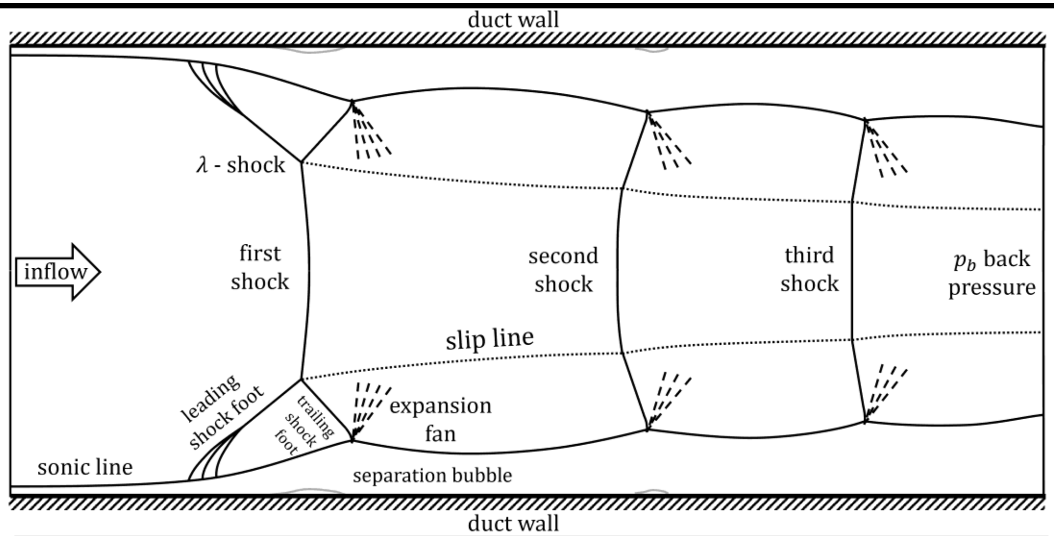
Investigating downstream perturbations as a cause of streamwise shock unsteadinesss

Computational Approach: Large Eddy Simulations (LES)

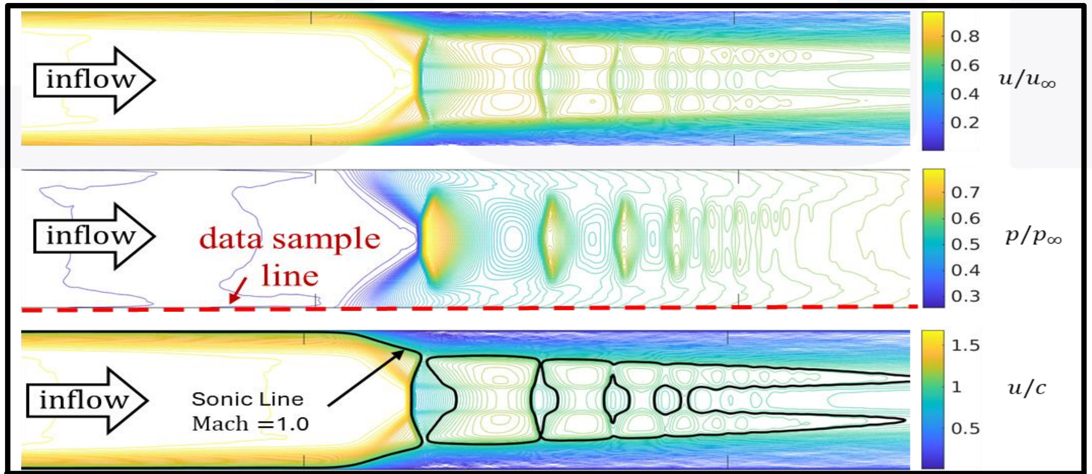
- High-fidelity computational fluid dynamics used to simulate the isolator shock-train.
- $Mach = 1.7$, $Re_h = 50{,}000$ (h = channel half height)
- Computational Domain
  - $(\hat{x}, \hat{y}, \hat{z}) = (29.6061, 2.0, 1.0)$
  - $(\hat{\imath}, \hat{\jmath}, \hat{k}) = (1241, 321, 65)$
- Spatial scheme: 6th order compact, switching to 3rd order Roe near shock discontinuities.
- Spatial filtering (oscillation damping): 8th order implicit.
- Time integration: 3rd order Runge-Kutta.
- Digital filtering (turbulent inflow). No sub grid model



Computational grid with boundary conditions. Every 5th point shown.



Schematic of shock-train structure with shock-boundary layer interactions (SBLI)



Mean flow profiles from LES. Top, u-velocity. Middle, pressure. Bottom, Mach number

Doak's Momentum Potential Theory: Acoustics

Objective: Identify acoustic content
Tool: Doak decomposition separates acoustics from hydrodynamic and thermal content.
Process:
A Helmholtz Decomposition separates mass flux (ρu_i) into solenoidal (B_i) and irrotational ($-\nabla\psi$) components.
Continuity equation invoked.
The irrotational ($-\nabla\psi$) component is further decomposed into acoustic ($-\nabla\psi_A$) and thermal ($-\nabla\psi_T$) fields which are solved via means of three Poisson equations (in practice only (1) and (2) must be solved)

P.E. Doak 1989 [4]

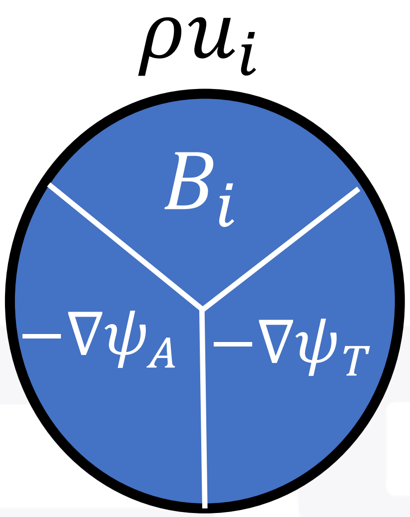
$$\rho u_i = B_i - \nabla\psi$$

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho u_i) = 0$$

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(B_i - \nabla\psi) = 0$$

$$\nabla\cdot B = \cancel{\nabla\cdot\bar{B}} + \cancel{\nabla\cdot B_i'} = 0$$

$$\nabla\psi = \cancel{\nabla\cdot\overline{\psi_i}} + \nabla\psi';$$



$$\nabla^2\psi' = \frac{\partial\rho'}{\partial t} \quad (1)$$

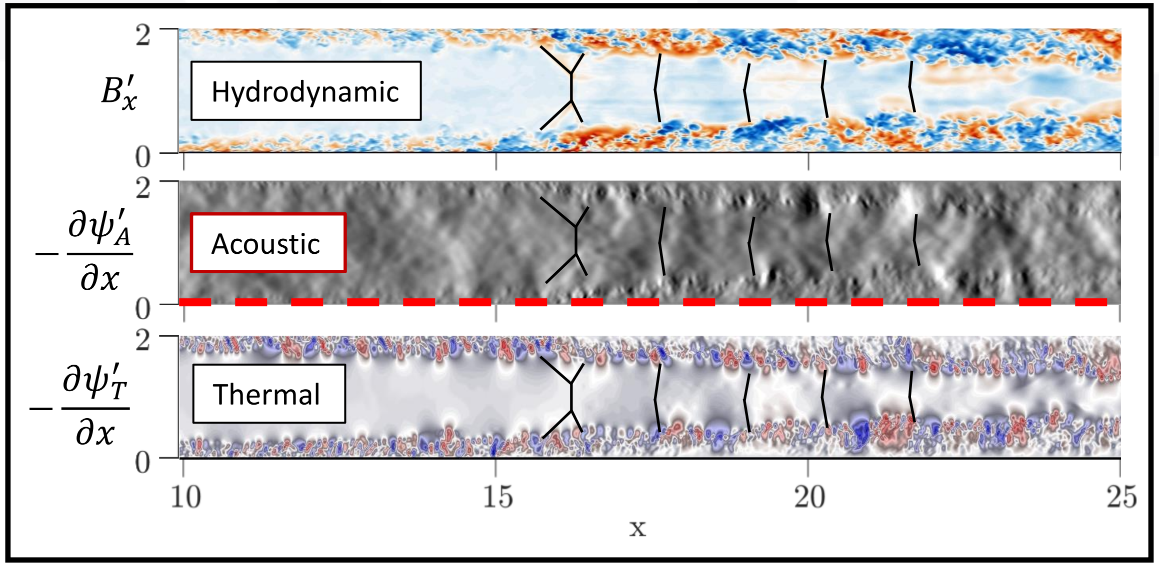
$$\psi' = \psi_A' + \psi_T'$$

$$\nabla^2\psi_A' = \frac{1}{c^2}\frac{\partial p'}{\partial t} \quad (2)$$

$$\nabla^2\psi_T' = \frac{\partial\rho}{\partial S}\frac{\partial S'}{\partial t} \quad (3)$$

Where S = entropy

Poisson equations



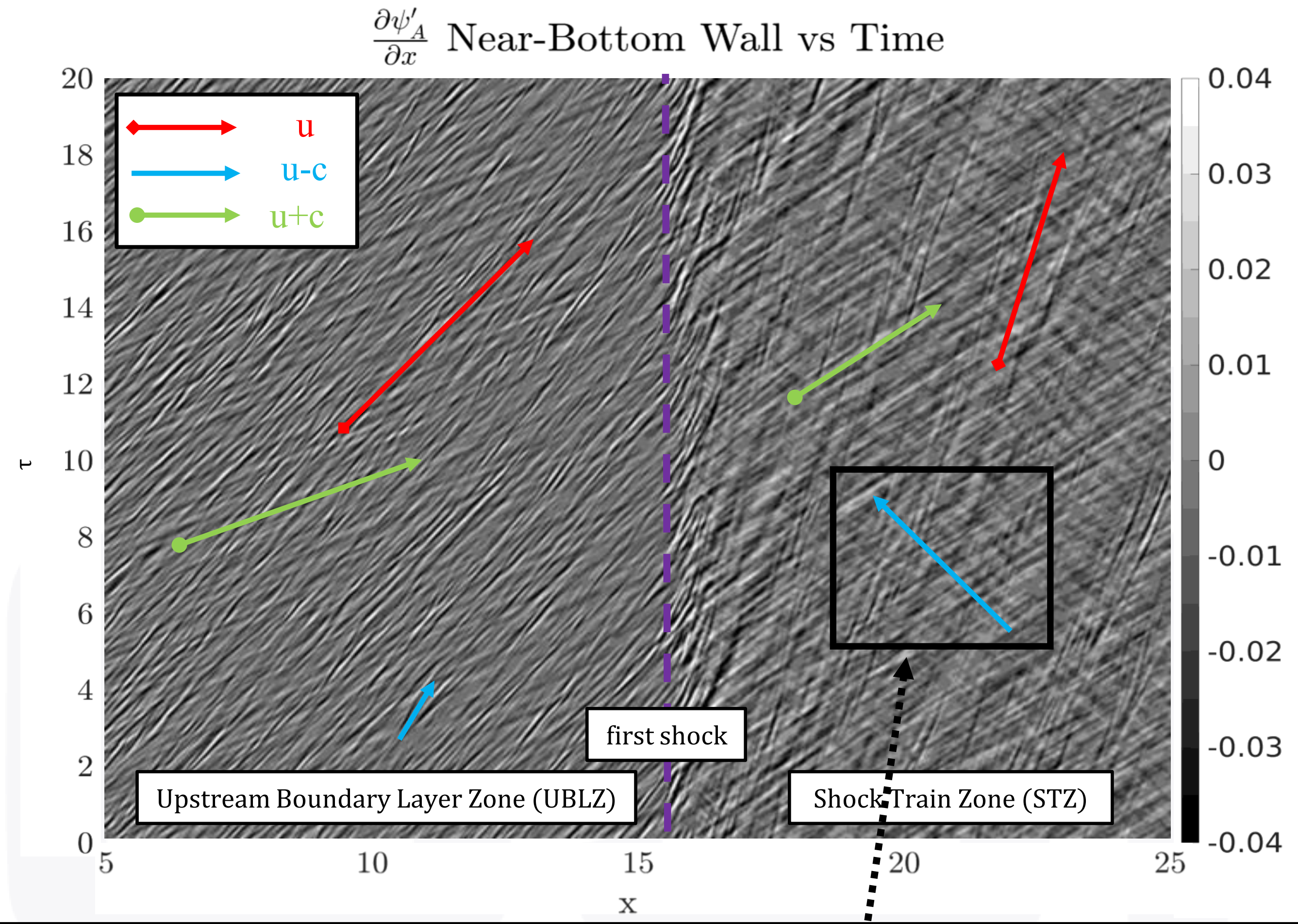
Space-Time Analysis

Purpose: To visualize direction and speed of acoustic signal motion near isolator wall
Procedure:
Sample streamwise line near bottom wall and plot over time. Fluctuations only.
Significance: $v = 1/\Delta t/\Delta x$
Positive-slope = downstream | Low-slope = fast
Negative-slope = upstream | High-slope = slow

Three families of sloped lines per zone.

Upstream boundary layer zone has no upstream fluctuations
Shock-train zone has one upstream fluctuation

Can calculate velocity of individual structures. However, only measuring one structure is undesirable, and measuring many lines is tedious.



Space-time (chronogram) plot of Doak-decomposed acoustic variable in streamwise direction.

		u	$u+c$	$u-c$	$c^+ = (u+c) - u$	$c^- = u - (u-c)$	c_{avg}
UBLZ	$-\frac{\partial \psi'_A}{\partial x}$	0.720	1.836	0.430	1.116	0.290	0.703
STZ	$-\frac{\partial \psi'_A}{\partial x}$	0.197	1.180	-0.727	0.983	0.924	0.954

Upstream-running acoustics

Frequency-Wavenumber analysis

Purpose: To measure velocity of an ensemble of acoustic structures

Procedure:

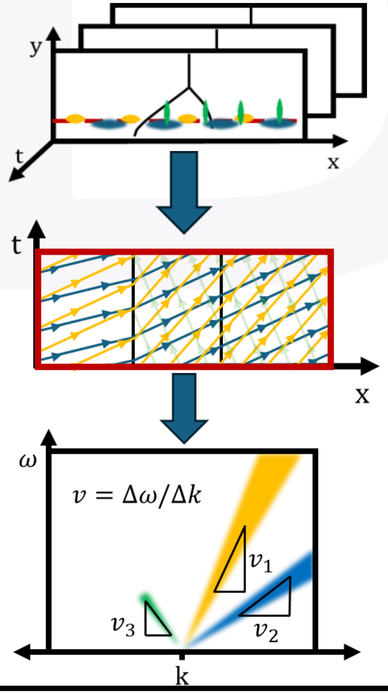
Sample streamwise line near bottom wall and plot over time. Fluctuations only.

2D-Fourier transform into frequency-wavenumber space.

Significance: $v = \Delta\omega/\Delta k$

Positive-slope = downstream | Low-slope = slow

Negative-slope = upstream | High-slope = fast



- Time-accurate data

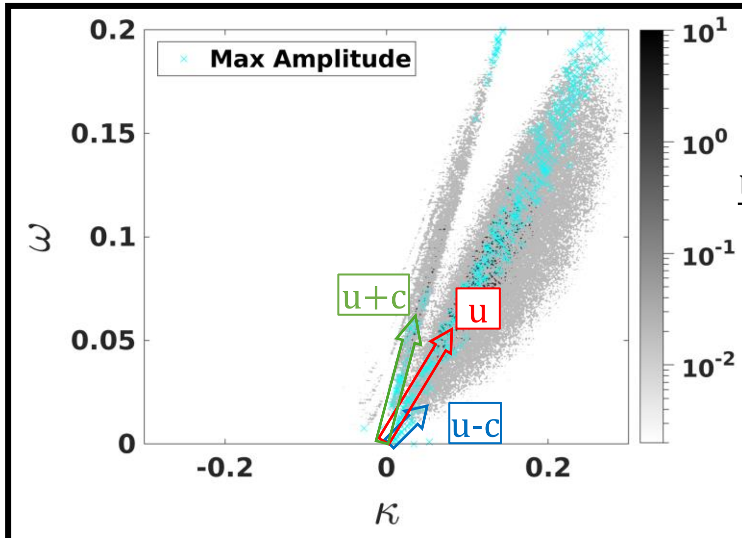
Line sample

- Space-time $(x - t)$

2D Fourier Transform

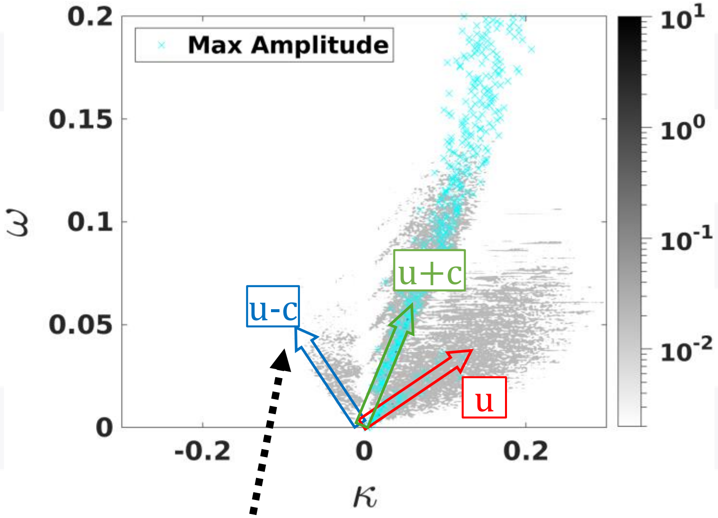
$$F(k,\omega) = \sum_{x=0}^{M-1}\sum_{t=0}^{N-1} f(x,t)e^{-j2\pi\left(x\frac{k}{M}+t\frac{\omega}{N}\right)}$$

- Frequency-wavenumber $(\omega - k)$



$-\frac{\partial \psi'_A}{\partial x}$

Upstream Boundary Layer Zone



$-\frac{\partial \psi'_A}{\partial x}$

Shock-train Zone

Frequency-wavenumber plots for UBLZ and STZ

	$k-\omega$	u	$u+c$	$u-c$	$c^+ = (u+c) - u$	$c^- = u - (u-c)$	c_{avg}
UBLZ	$-\frac{\partial \psi'_A}{\partial x}$	0.710	1.641	0.384	0.931	0.326	0.629
STZ	$-\frac{\partial \psi'_A}{\partial x}$	0.306	1.074	-0.662	0.768	0.968	0.868

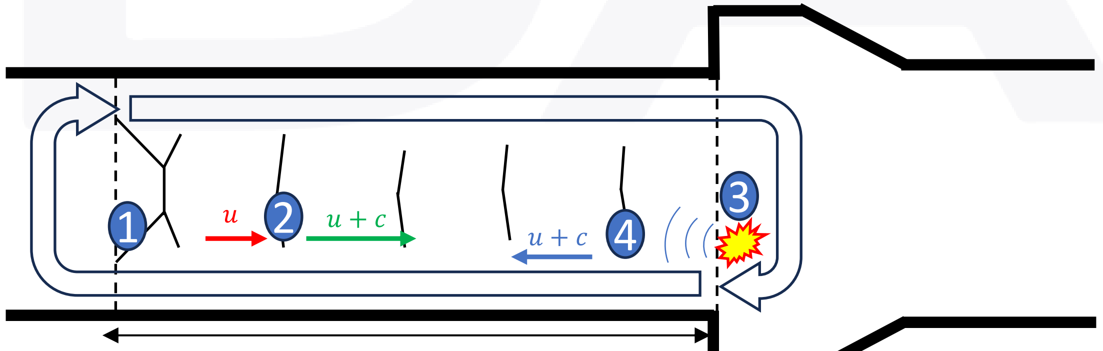
Ensemble averaged upstream-running acoustics

Feedback frequencies

<u>Purpose</u>: Construct scenario for perturbation feedback mechanism within channel and compare frequencies with experiments.

<u>Setup</u>:

1. Assume perturbations begin at 1st shock, purely in streamwise direction
2. Perturbations travel downstream at either u or $u + c$ velocity measured from frequency-wavenumber analysis.
3. End of isolator = beginning of combustor. Assume downstream perturbation creates combustor instability and upstream perturbation.
4. Perturbations travel upstream at $u - c$



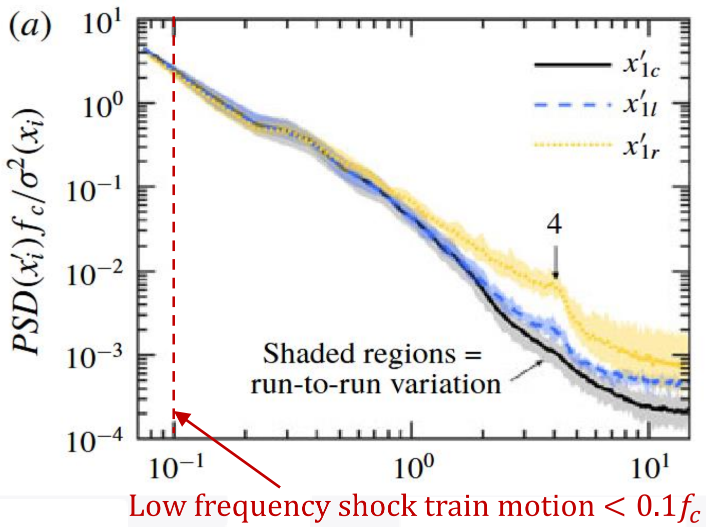
Pseudoshock length = L_p

$L_p(sim) = 14.6\text{h}$ (nondimensionalized by channel half height h)

Pseudoshock = shock-train + turbulent mixing region

Experimental Frequency Spectrum

Hunt and Gamba 2019 [4]



<u>Frequencies are scaled by pseudoshock length.</u>

	u	$u+c$	$u-c$	$c^+ = (u+c) - u$	$c^- = u - (u-c)$	c_{avg}
$-\frac{\partial \psi'_A}{\partial x}$	0.306	1.074	-0.662	0.768	0.968	0.868

$$f_{fast} = \frac{1}{\frac{L_p}{u+c} + \frac{L_p}{u-c}}$$

$$f_{fast-scaled} = 0.410 f_c$$

$$0.410 f_c > 0.1 f_c$$

$$f_{convective} = \frac{1}{\frac{L_p}{u} + \frac{L_p}{u-c}}$$

$$f_{conv-scaled} = 0.209 f_c$$

$$0.209 f_c > 0.1 f_c$$

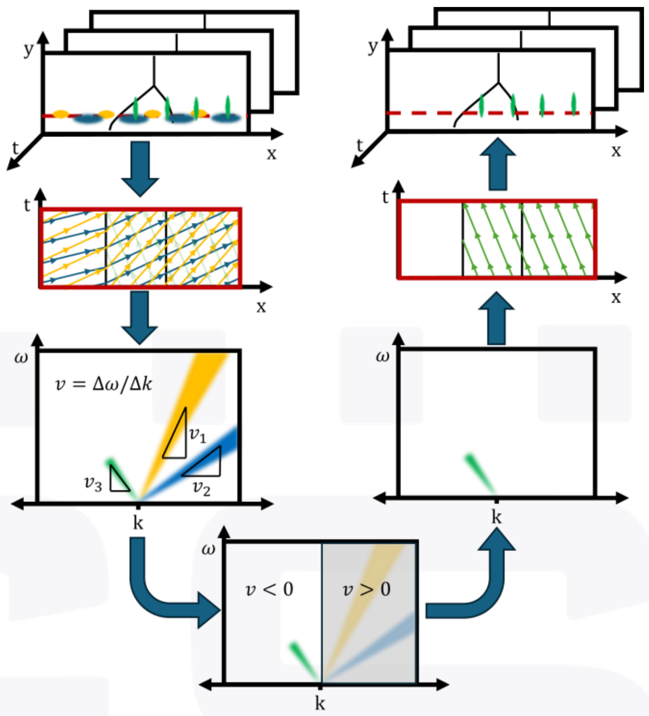
Scaled frequencies are **<u>2 to 4 times higher</u>** than the experimental low-frequency unsteadiness

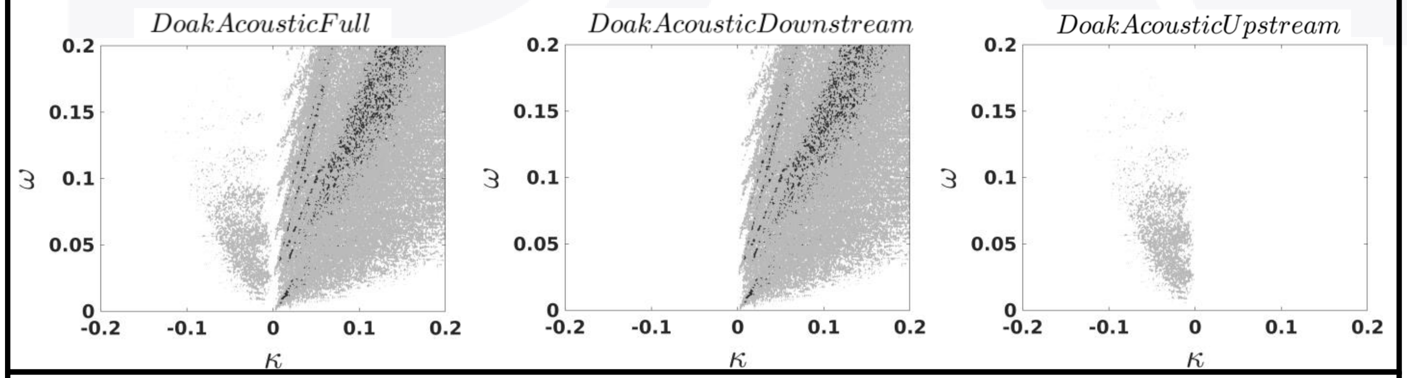
Velocity Filtering

Do perturbations only travel in streamwise direction? Or do they also bounce off walls?

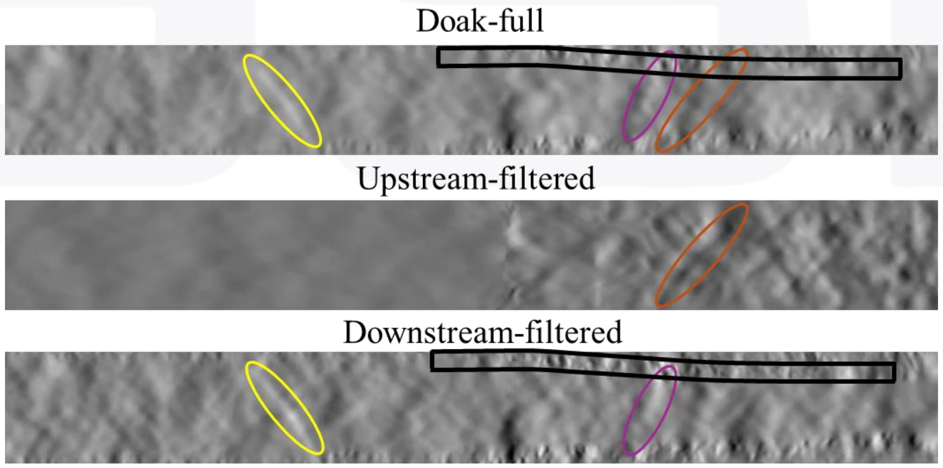
Purpose: Use velocity filtering to isolate upstream and downstream velocity signals in acoustic field.
Method: Frequency-wavenumber space can differentiate upstream and downstream waves.
Procedure:

1. Convert line data into frequency-wavenumber space
2. Set positive velocity data to zero
3. Convert back to space-time
4. Repeat for all lines
5. Plot in 2D





Velocity-filtered frequency-wavenumber plots



Waves travel obliquely. Suggests bouncing off walls. May lengthen the pathway of perturbations and reduce frequency

Conclusions

- Time-accurate isolator simulation was constructed.
- Doak’s decomposition employed to isolate acoustic perturbations.
- Demonstrated the presence of upstream-running perturbations.
  - First identified using space-time analysis for near-wall streamwise line sample.
- Velocity of perturbations in the shock-train zone were measured.
  - Frequency-wavenumber technique used to obtain ensemble averaged velocities.
- Framework for feedback frequency constructed.
  - Downstream perturbations carried by u and $u + c$ signals.
  - Upstream perturbations carried by $u - c$.
  - Frequencies scaled by pseudo-shock length.
  - Did not agree with experimental low-frequency dynamics.
- Velocity-filtering employed in frequency-wavenumber space.
  - Visually isolating upstream-downstream waves showed angled wave fronts bouncing off walls.
  - Can lengthen propagation pathway, lengthen cycle period, reduce frequency.

References

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[2] Dolling D, Or C. Unsteadiness of the shock wave structure in attached and separated compression ramp flows. Exp Fluids 1985;3:24–32.

[3] Ganapathisubramani, B., Clemens, N. T., & Dolling, D. S. "Effects of upstream boundary layer on the unsteadiness of shock-induced separation." Journal of fluid Mechanics, 2007, *585*, 369-394.

[4] Hunt, R. L., and Gamba, M., "On the origin and propagation of perturbations that cause shock train inherent unsteadiness," *Journal of Fluid Mechanics*, Vol. 861, 2019, pp. 815–859.

[5] Stahl, S. L., & Benton, S. I., "Computational Investigation of Unsteady Shock Motion in an Isolator-Diffuser Flow Path." AIAA SCITECH 2025 Forum, 2025, p. 0093.

[6] Doak, P., "Momentum potential theory of energy flux carried by momentum fluctuations," *Journal of sound and vibration*, Vol. 131, No. 1, 1989, pp. 67–90.

[7] Unnikrishnan, S., and Gaitonde, D. V., "Acoustic, hydrodynamic and thermal modes in a supersonic cold jet," *Journal of Fluid Mechanics*, Vol. 800, 2016, pp. 387–432.