Turbulence and Aeroacoustics in High-Speed Jets

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INCITE 2019 and ALCF Discretionary Allocation and XSEDE for Computer time
NSF and ONR

Advanced Modeling and Simulations (AMS) Seminar
NASA Ames Research Center, June 1, 2021

Turbulence and Aeroacoustics in High-Speed Jets

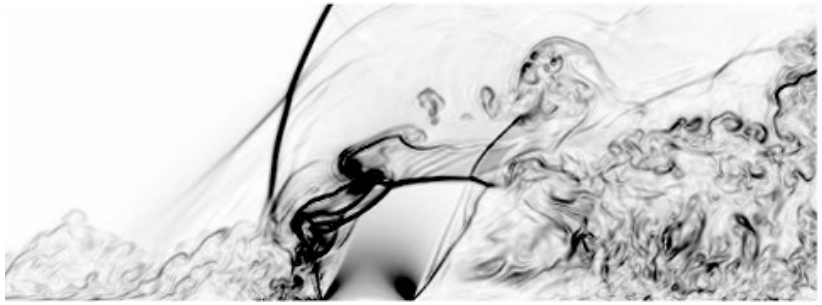
Outline:

- General comments on high-speed turbulent flows
- Compressibility effects in shear layers
- High-speed jet aeroacoustics – jet screech & twin jet coupling
- Summary

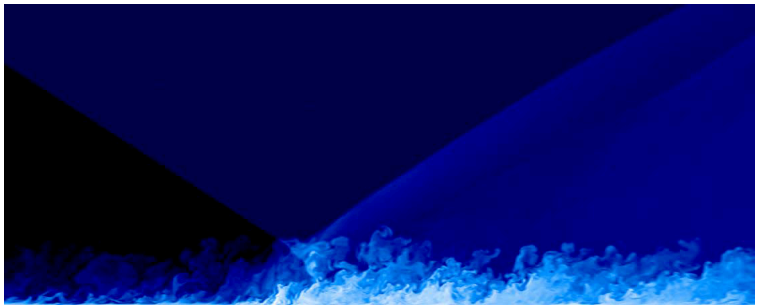
Introduction: High-speed turbulent flows

- Common place in aerospace applications -
  from transonic, supersonic and hypersonic aerodynamics
  to propulsion, rocket launch, reentry and descent
- RANS CFD has dominated engineering analysis and design
- Turbulence resolving simulations are impacting recent developments (in 10+ years)

Kawai & Lele 2010, AIAA J, Vol. 48



Morgan, Duraisamy & Lele, JFM, 2013

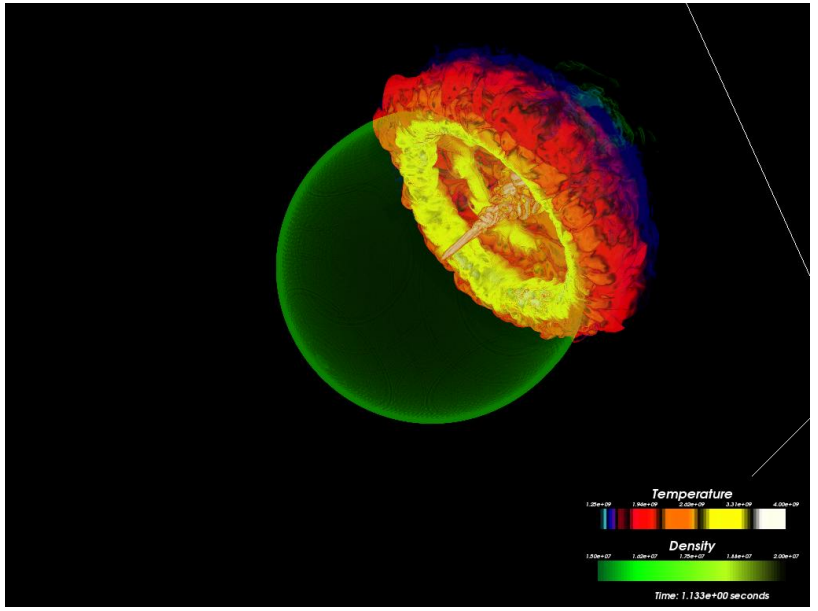


Olson & Lele, Phys. Fluids, 25, 110809 (2013); doi: 10.1063/1.4819349



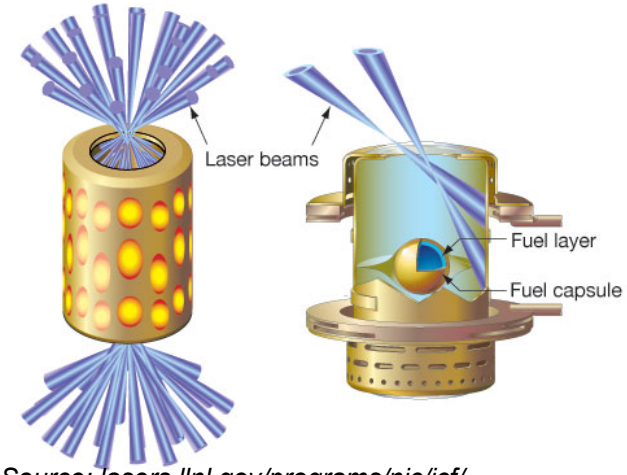
A Glimpse of other compressible turbulent flows

Solar convection
Supernova collapse
Intersteller density fluctuations
Inertial confinement fusion



Source: flash.uchicago.edu

Supernova explosion



Source: lasers.llnl.gov/programs/nic/icf/

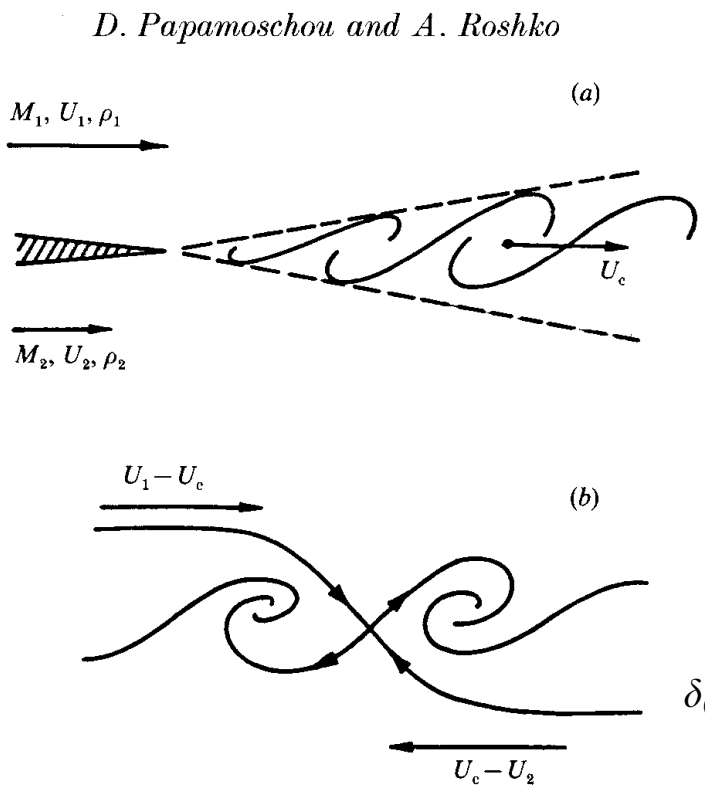
Inertial confinement fusion by shock-induced implosion of a deuterium/tritium capsule

Compressibility Effects on Turbulence - Fundamentals

Flow Physics of Supersonic Mixing

Suppression of mechanical mixing

Brown & Roshko (1974), Bogdonoff (1983), Papamoschou & Roshko (1986)



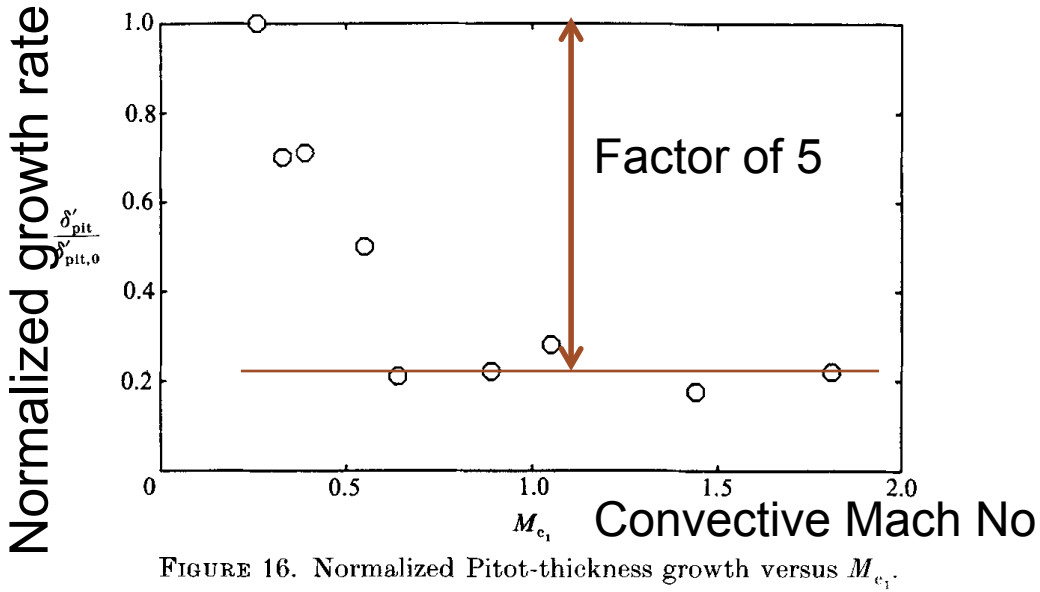


FIGURE 16. Normalized Pitot-thickness growth versus M_{c_1}.

$$\delta_0'(x;r,s) \simeq C_\delta \frac{(1-r)(1+s^{1/2})}{2(1+s^{1/2}r)} \left\{ 1 - \frac{(1-s^{1/2})/(1+s^{1/2})}{1+2.9(1+r)/(1-r)} \right\},$$

$$M_c = (U_1 - U_2)/(C_1 + C_2)$$

Compressibility Effects on Turbulence - Fundamentals

Absence of significant effects in Supersonic/Hypersonic TBLs

Morkovin (1962), Bradshaw (1977), Smits & Dussauge (1986)

DNS Duan & Martin, JFM (2011)

$$U_{\mathrm{VD}}^{+} = \int_0^{u^+} \left(\frac{\bar{\rho}}{\rho_w}\right)^{1/2} du^+,$$

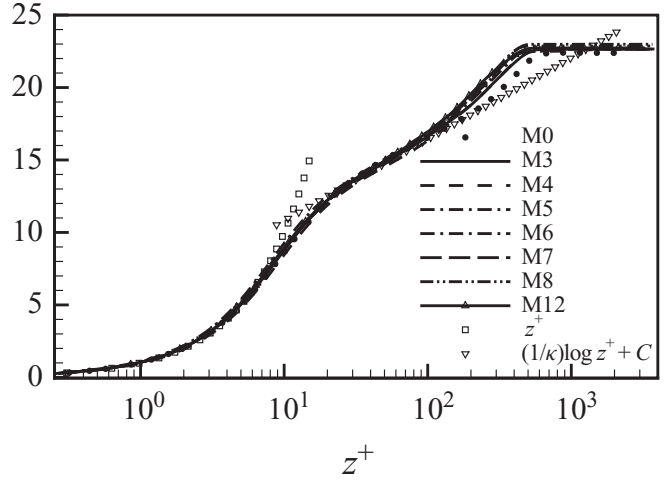


FIGURE 4. Van Driest transformed velocity for different free-stream Mach number cases.

Case	M_δ	ρ_δ (kg m^{-3})	T_δ (K)	T_w/T_δ	Re_θ	Re_τ	$Re_{\delta 2}$	θ (mm)	H	δ (mm)
M0	0.30	0.0900	220.0	1.00	1514.7.6	569.9	1515.2	2.76	1.41	23.0
M3	2.97	0.0910	219.9	2.51	3028.6	486.9	1586.7	0.619	5.09	8.85
M4	3.98	0.0902	219.2	3.83	4093.7	438.2	1587.4	0.658	8.01	12.0
M5	4.90	0.0962	224.4	5.31	4931.7	416.5	1578.0	0.682	11.29	15.1
M6	5.81	0.0990	230.7	7.02	5775.1	412.8	1582.2	0.730	15.4	19.7
M7	6.89	0.0929	224.2	9.49	7207.3	391.7	1586.4	0.838	20.2	28.1
M8	7.70	0.0990	232.8	11.2	7508.3	397.5	1577.5	0.861	24.2	31.8
M12	11.93	0.0906	228.0	27.6	11356.4	376.8	1577.5	1.33	46.1	84.7

TABLE 1. Dimensional boundary-layer edge and wall parameters for the DNS database.

Compressibility Effects on Turbulence - Fundamentals

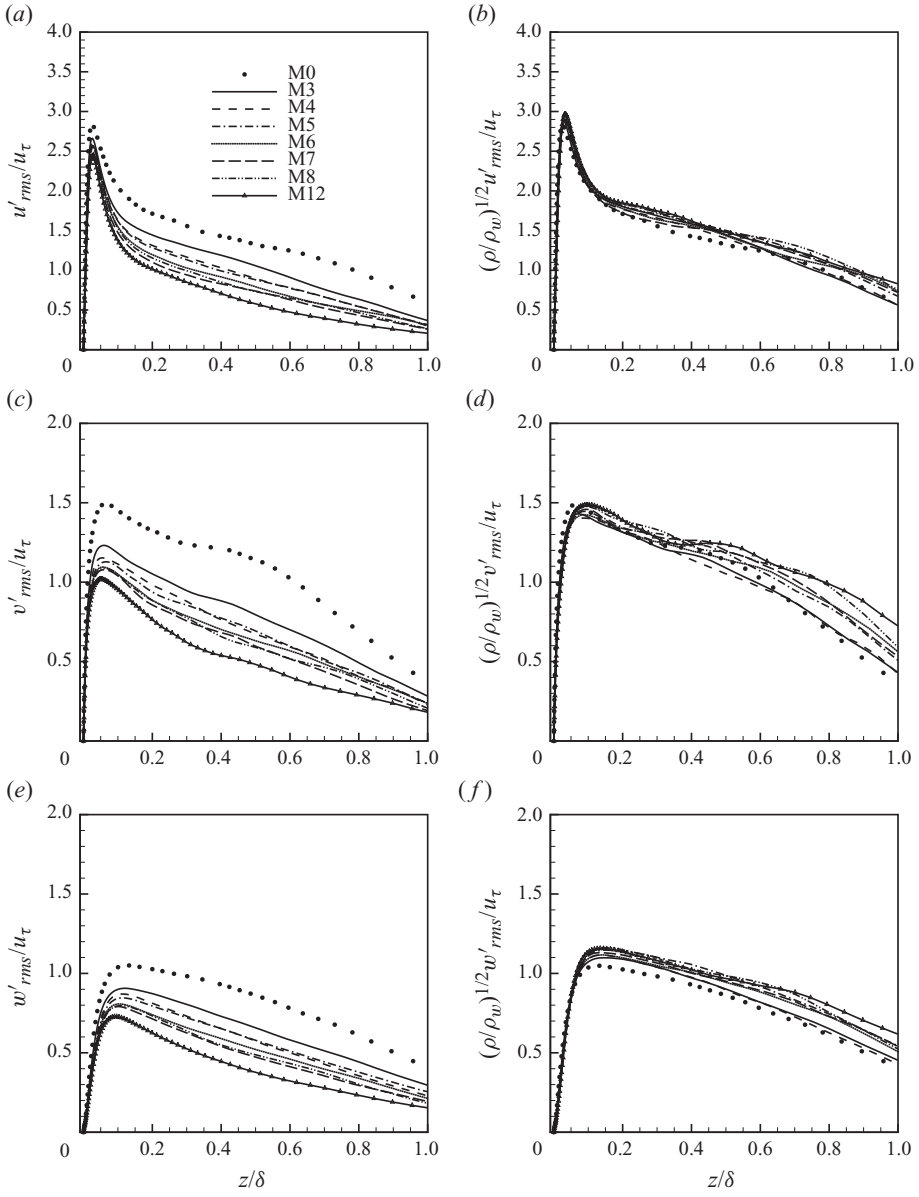


FIGURE 6. Turbulence intensities and density-weighted turbulence intensities of the (a,b) streamwise, (c,d) spanwise and (e,f) wall-normal fluctuating velocity components for different free-stream Mach number cases.

Local density scaling

DNS

Duan & Martin, JFM (2011)

Sonic limitation in highly compressible shear layer turbulence★

Sanjiva K. Lele and Kristen Matsuno

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★Matsuno, K and Lele, S. K., (2021) *J. Fluid Mech.* Vol. 907

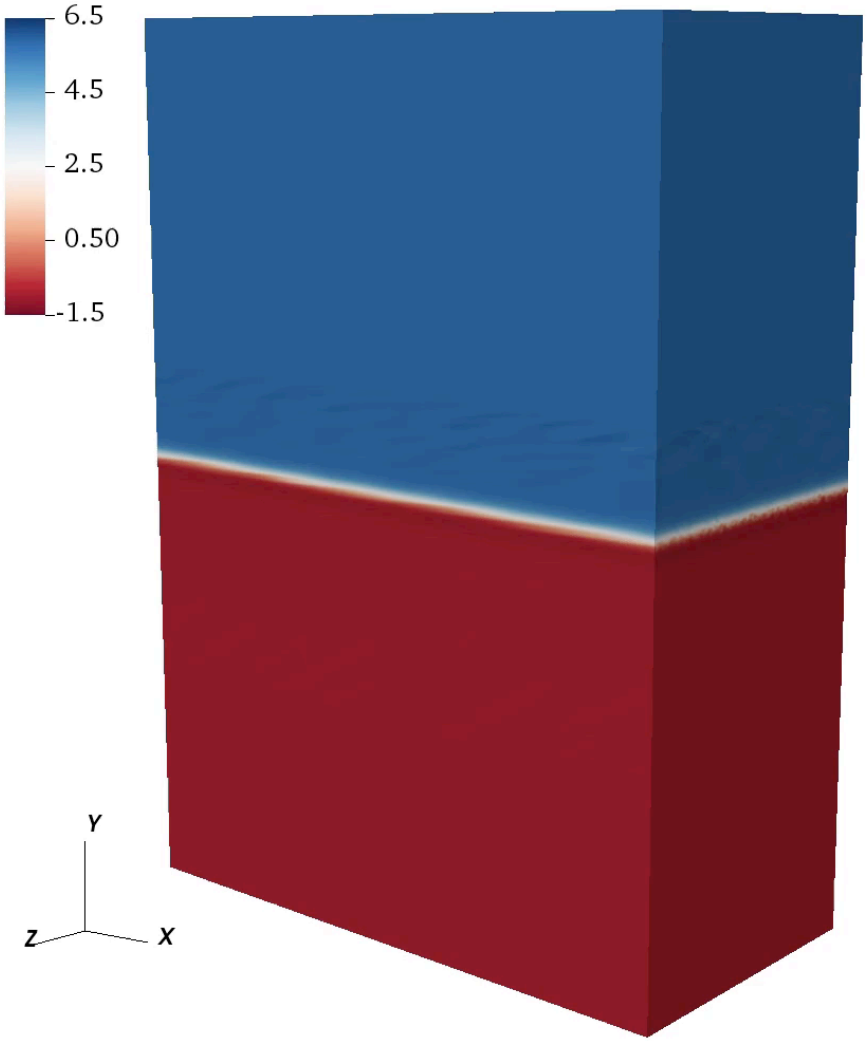
INCITE 2019 and ALCF Discretionary Allocation for Computer time
NSF Graduate Fellowship

Compressible shear layer mixing

Kristen Matsuno & SKL



Mc = 2.0, s=7: Streamwise momentum



Varied M_c, Density ratio

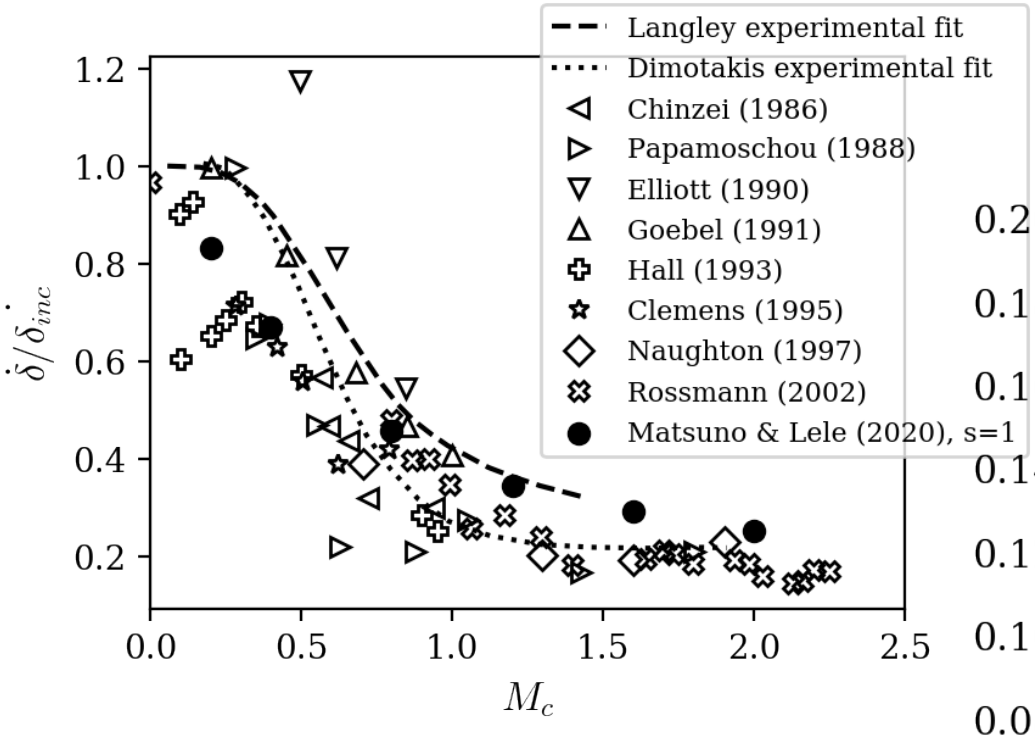
$M_c = \Delta U/(C_1 + C_2)$ 2.0

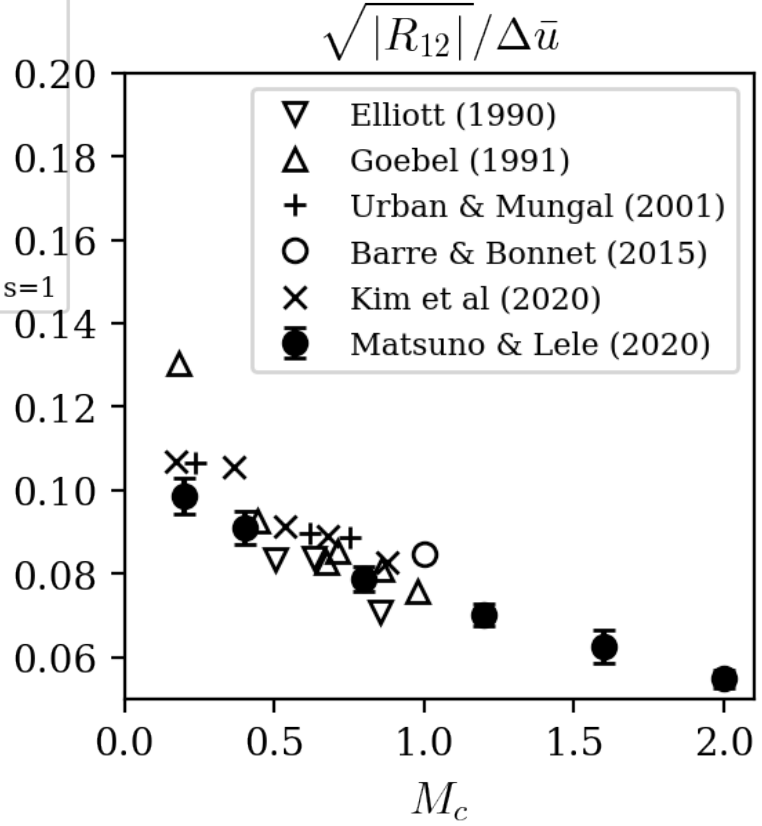
$\rho_2/\rho_1 = s$ 7.0

Computer time through INCITE 2019

Compressible shear layer mixing

Kristen Matsuno & SKL





$M_c = \Delta U/(C_1 + C_2)$

$\rho_2/\rho_1 = s$

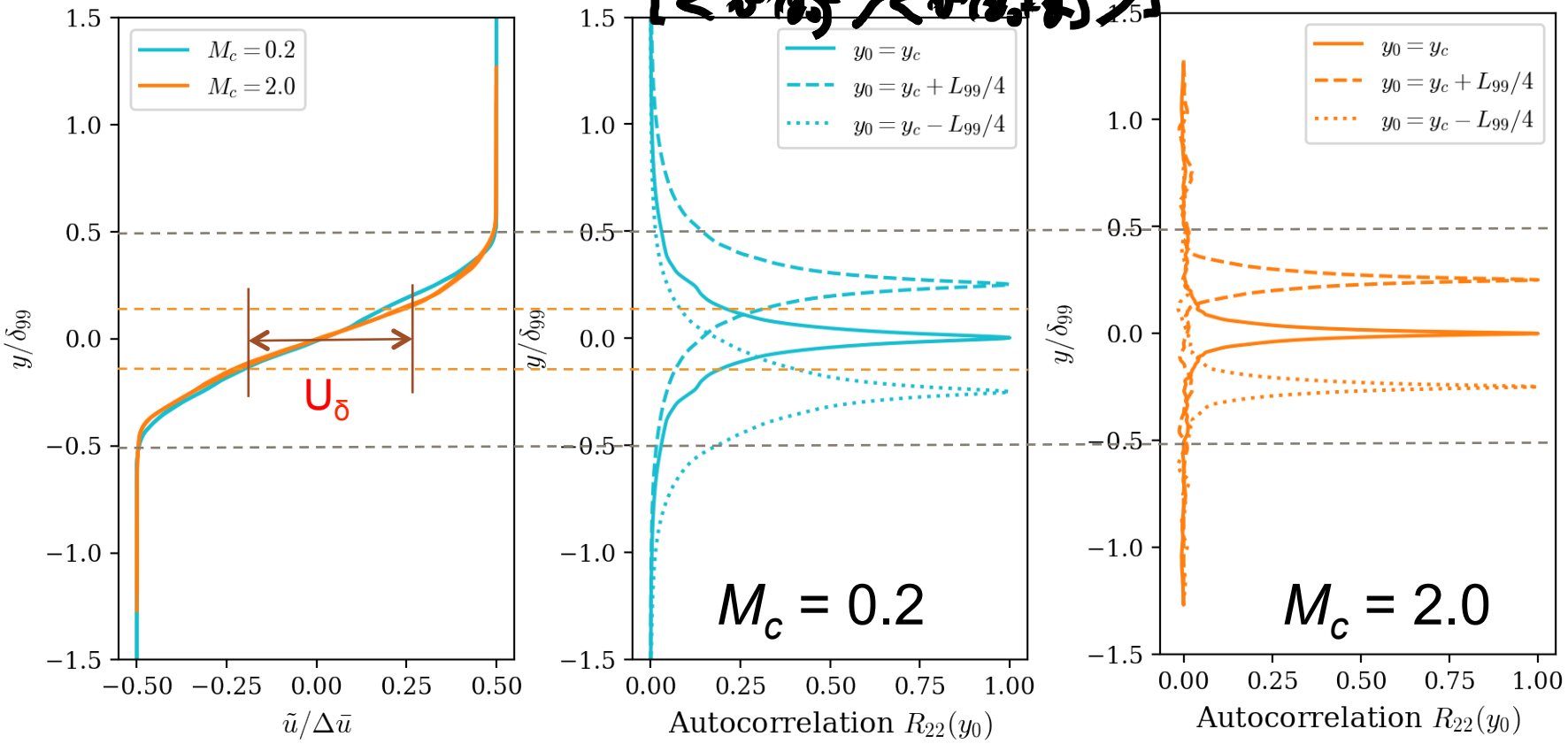
Compressible shear layer mixing

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Favre avg. mean x velocity

Transverse velocity correlation with transverse separation

$$\frac{\langle v''(y_0)\, v''(y_0+y)\rangle}{\left[\langle v''(y_0)^2\rangle \langle v''(y_0+y)^2\rangle\right]^{1/2}}$$



At high M_c shear layer develops layers of independent eddies!

Internal regulation ➔ Correlation scale & Effective velocity U_δ

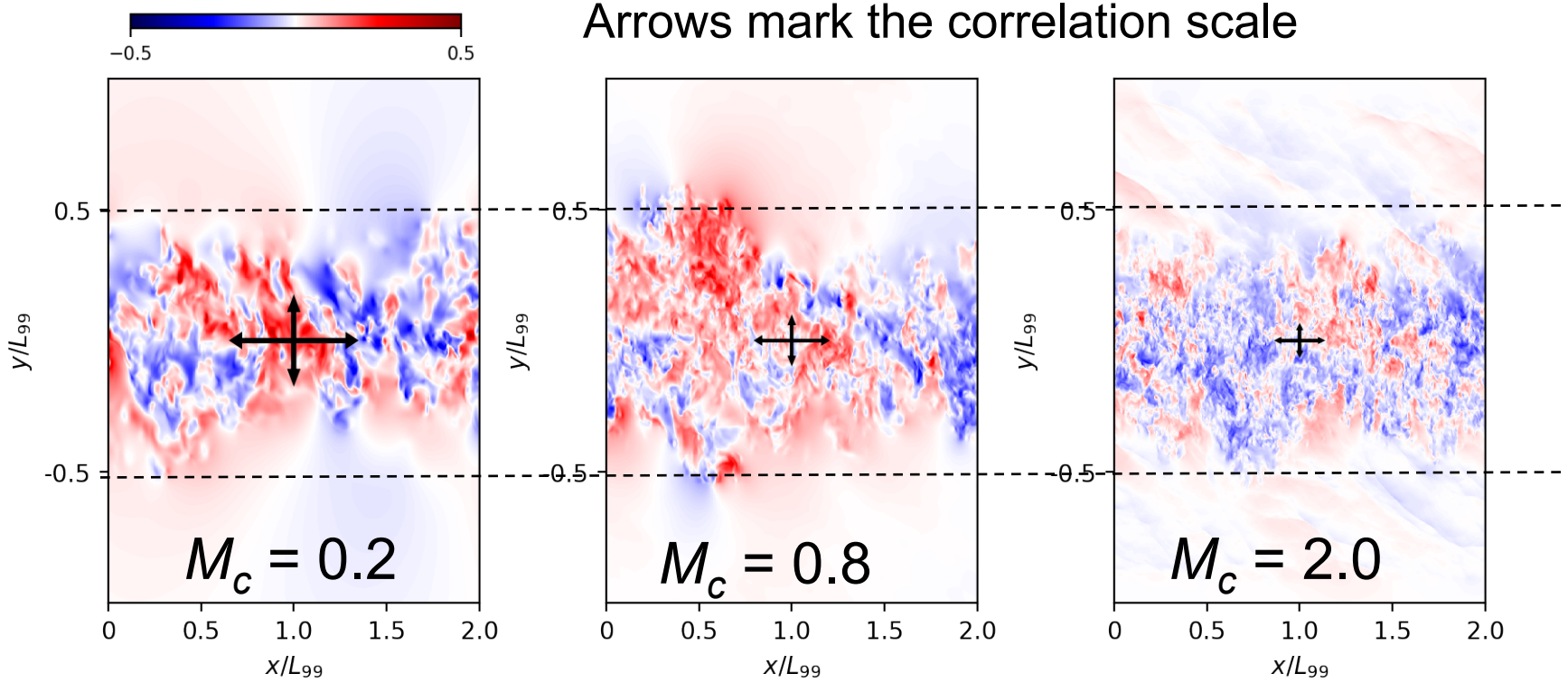
$M_c = \Delta U/(C_1 + C_2)$ $\quad \rho_2/\rho_1 = s = 1$

Compressible shear layer mixing

Kristen Matsuno & SKL

Transverse velocity contours **scaled by U_δ** (plan view)

Arrows mark the correlation scale



At high M_c shear layer develops layers of independent eddies

Internal regulation ➔ Correlation. scale & Effective velocity U_δ

Eddy scale shrinks in all directions (approx. same aspect ratio)

$M_c = \Delta U/(C_1 + C_2)$ $\rho_2/\rho_1 = s = 1$

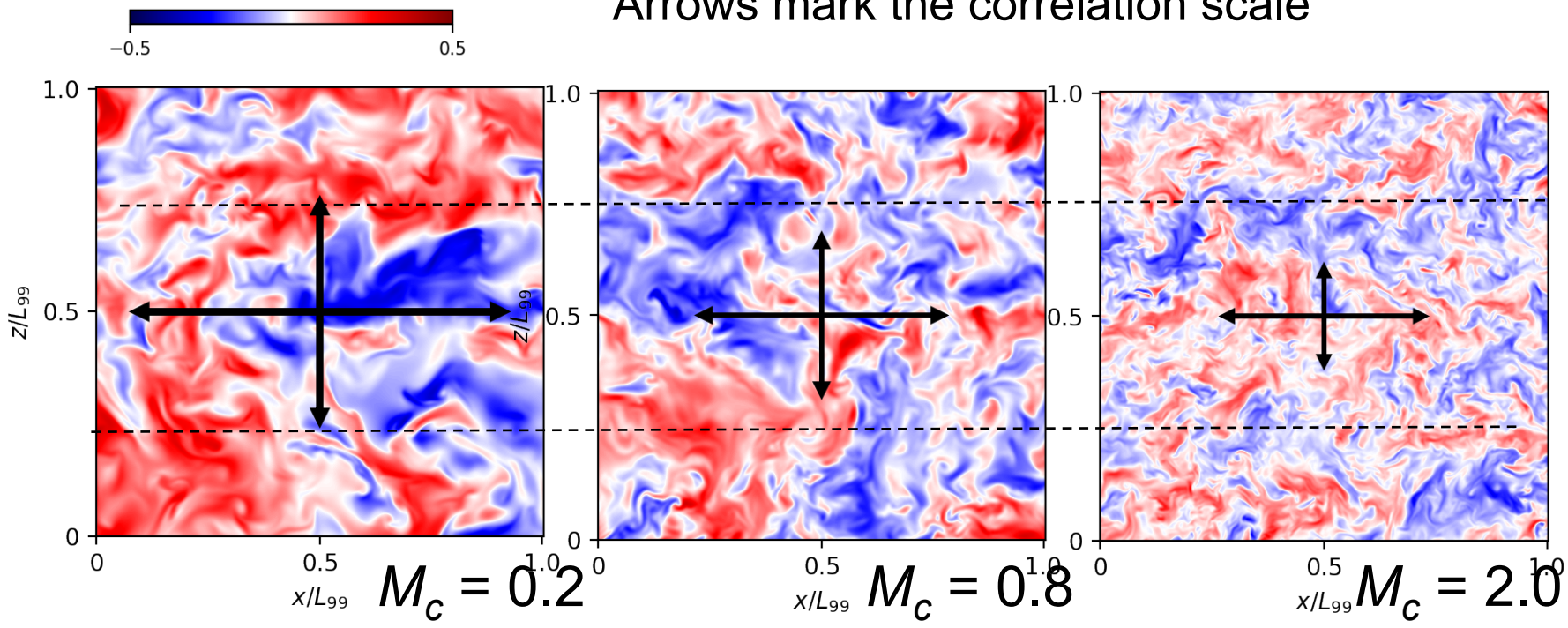
Stanford University

Compressible shear layer mixing

Kristen Matsuno & SKL

Transverse velocity contours **scaled by U_δ** (top view)

Arrows mark the correlation scale



At high M_c shear layer develops layers of independent eddies

Internal regulation ➔ Scaling of Corrln. scale & Effective velocity U_δ

Eddy scale shrinks in all directions (approx. same aspect ratio)

$M_c = \Delta U/(C_1 + C_2)$ $\rho_2/\rho_1 = s = 1$

Compressible shear layer mixing

Kristen Matsuno & SKL

At high M_c shear layer develops layers of independent eddies

Internal regulation ➔ Scaling of Corrln. scale & Effective velocity U_δ

Eddy scale shrinks in all directions (approx. same aspect ratio)

Why? implication for modeling?

No complete theory yet.

Working hypothesis:
Acoustic communication limits the eddy scales

Briedenthal R. E. (1992) *Sonic eddy - A model for compressible turbulence AIAA J. vol. 30.*

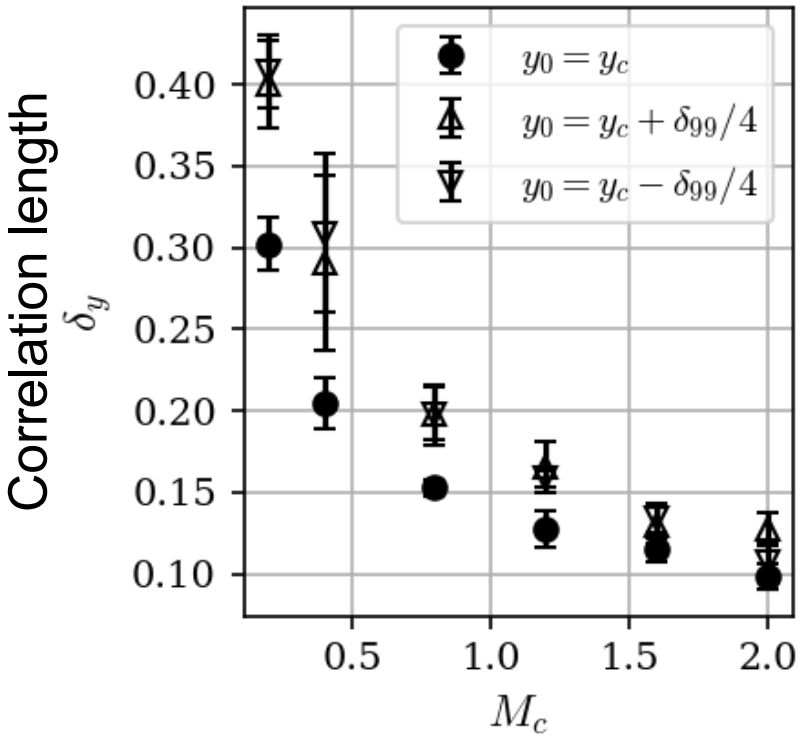
Compressible shear layer mixing

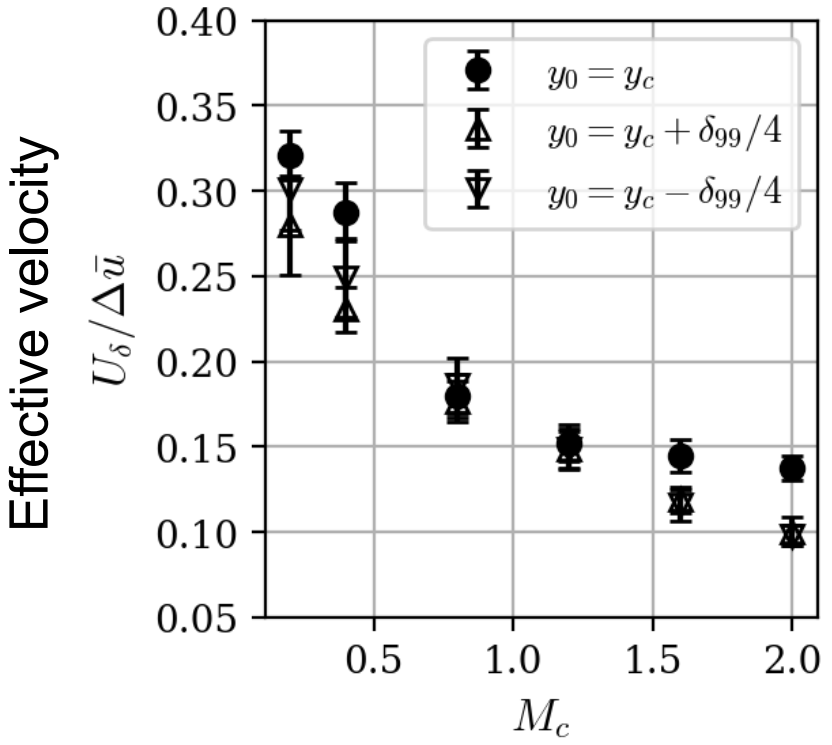
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Working hypothesis:

Acoustic communication limits the eddy scales (internal regulation)

Supporting evidence for internal regulation





$M_c = \Delta U/(C_1 + C_2)$

$\rho_2/\rho_1 = s$

Compressible shear layer mixing

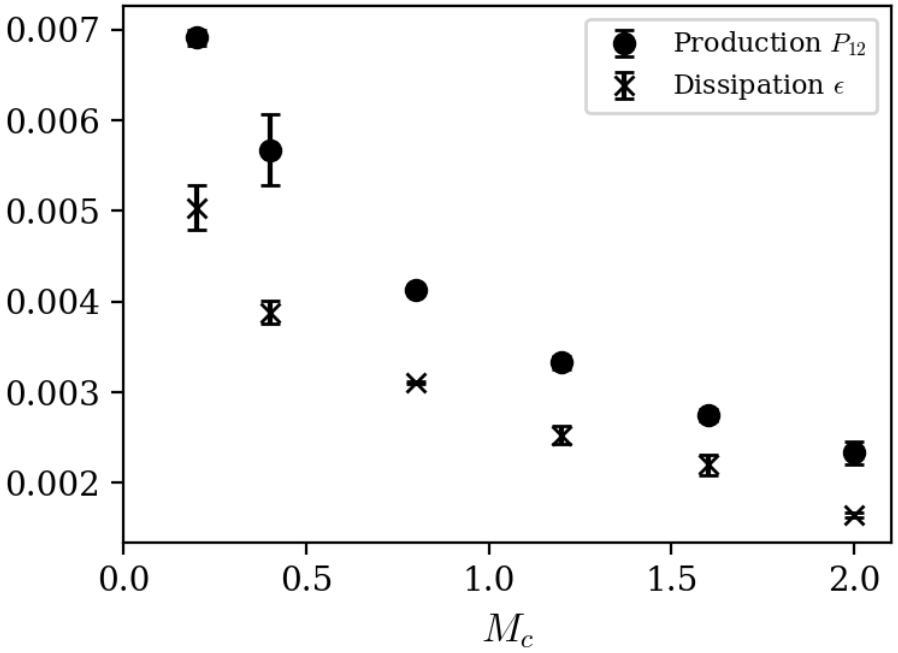
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Working hypothesis:

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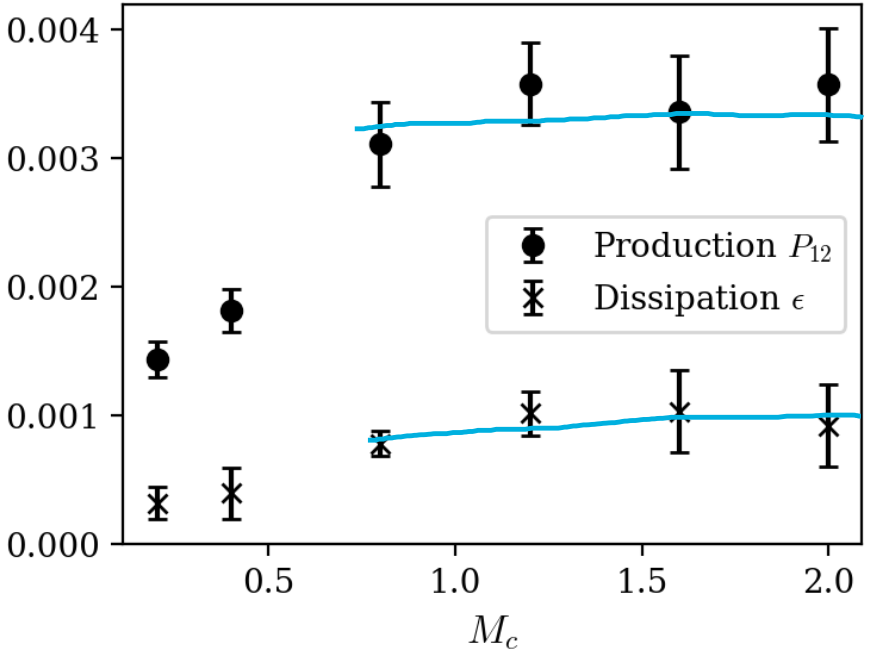
Supporting evidence for internal regulation

TKE production & Dissipation



Asymptotic scaling at high Mc

Scaled TKE production & Dissipation



Other terms in TKE and variance budgets e.g. pressure-strain corrln also scale well

$M_c = \Delta U/(C_1 + C_2)$

$\rho_2/\rho_1 = s$

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Compressible shear layer mixing

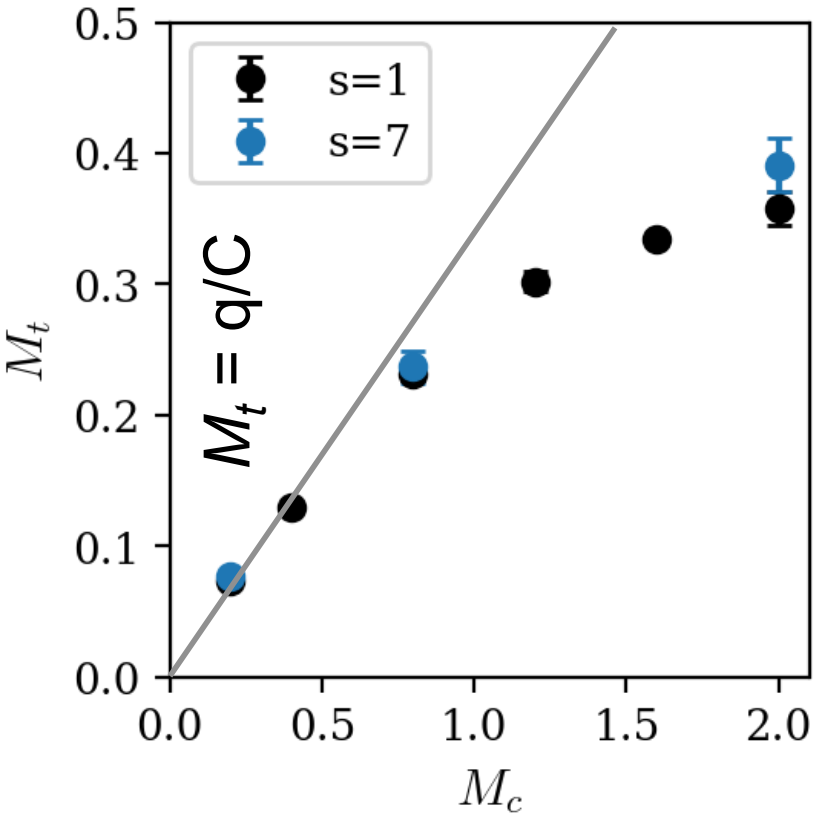
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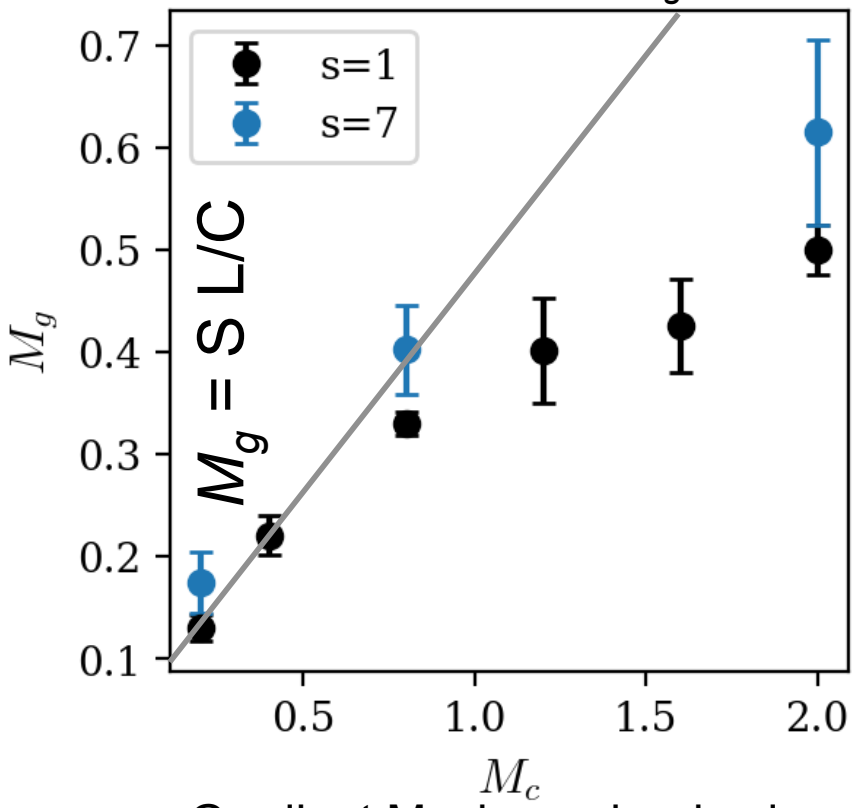
Working hypothesis:

Acoustic communication limits the eddy scales (internal regulation)

Supporting evidence for internal regulation

What does saturation of M_t or M_g imply?





Gradient Mach number is also a ratio of eddy scale to sonic scale

$M_c = \Delta U/(C_1 + C_2)$

$\rho_2/\rho_1 = s$

Summary and Open Issues

Simulation data at high Mc show:

- Trends in growth rate and turbulence consistent with experiments
- Correlation scales shrink as a fraction of overall flow scale
- Trend of active overturning scale is supportive of sonic limitation
- Effective velocity scale (mean velocity difference across actively overturning scale) provides good scaling
  - for Reynolds stress, pressure fluctuation, TKE dissipation, Pressure strain

Theoretical framework still insufficient

How does acoustic communication impact vortex dynamics?

Causal vortex dynamics

Engineering models incorporating physics of variable-density and compressibility

Limited experiments with detailed turbulence measurements

Confirmation of phenomena and scaling laws observed in idealized simulations

Single and twin Rectangular Jet Screech using LES*

Sanjiva K. Lele, Gao Jun Wu & Jinah Jeun

STANFORD UNIVERSITY

★Wu, Lele and Jeun, 2020 CTR Annual Briefs
Jeun, Wu and Lele, 2020 CTR Annual Briefs

XSEDE Allocation for Computer time
Cascade Technologies for CharLES and Dr. Guillaume Bres for help
Office of Naval Research for support
Grant No. N00014-18-1-2391
Dr. Steven Martens (Program Manager)

Overview

Goals

Improve scientific understanding of jet screech and twin jet plume resonance

Objectives

Develop computational modeling capable of predicting the amplitude and mode-switching of jet screech and twin jet coupling

Naval Relevance

Jet screech (when present) is acoustically significant part of jet noise

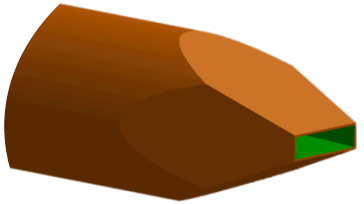
Jet screech and twin jet coupling are responsible for structural fatigue of nozzles and airframe

Closely coupled propulsion and airframe increase possibility of screech and jet to jet coupling (twin engines and distributed propulsion)

Problem Setup

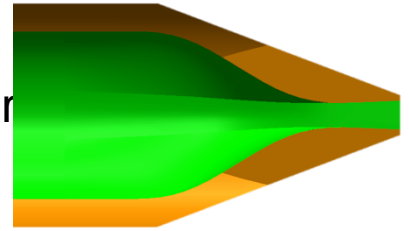
Numerical Software

- Charles by Cascade Technologies
- Voronoi Mesh
- Built-in FW-H tool



Single Jet Nozzle Geometry

- Rectangular Exit, 1:4 aspect ratio
- Circular cross section transitioning to Rectangular
- M_d = 1.44, NPR_{design} = 3.37
- **Experiments done at FSU (Prof. R. Kumar)**

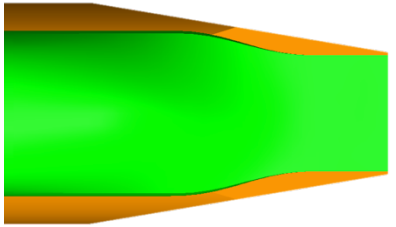


xy plane
h = 10 mm

Operating points

- NPR = 4.01,
- **NPR = 4.86,**
- NPR = 5.57,

  Under-expanded cold jet



xz plane
w = 40 mm

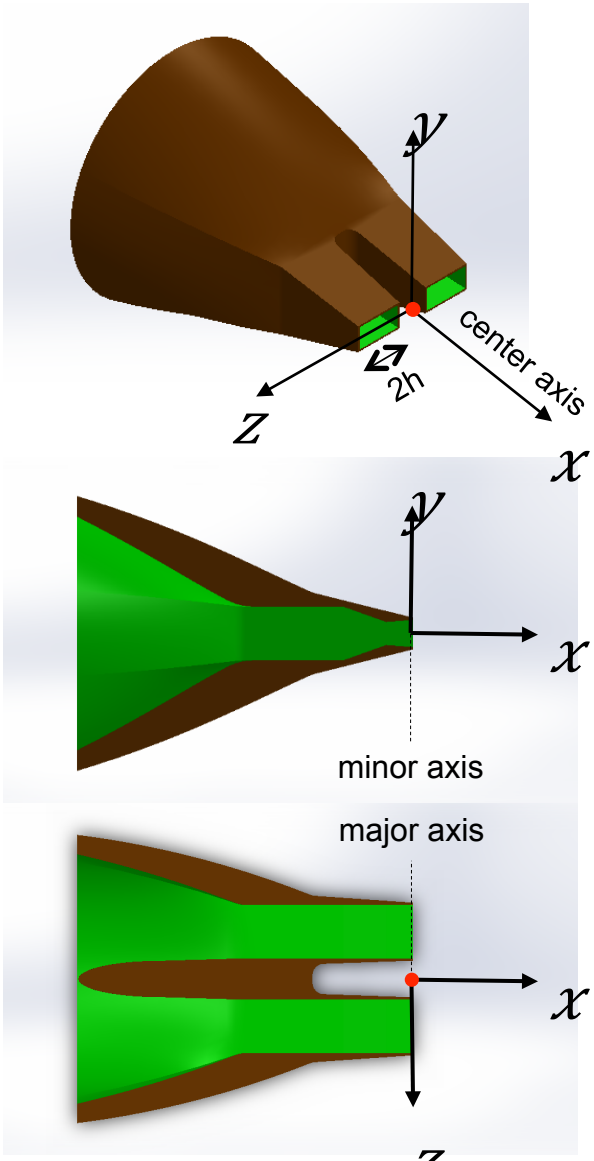
Problem Setup (cont.)

Twin Jet Nozzle Geometry

- Twin rectangular exit, 1:2 aspect ratio
- Circular cross section transitioning to rectangular
- Sharp converging-diverging sections
- M_d = 1.5, NPR_{design} = 3.67
- **Experiments done at U of Cincinnati (Prof. E. Gutmark)**

Operating points (thus far)

Case 1: NPR = 2.5, M_j = 1.22 (Over-expanded)
Case 2: NPR = 3, M_j = 1.36 (Over-expanded)
Case 3: NPR = 3.67, M_j = 1.5 (Design Condition)

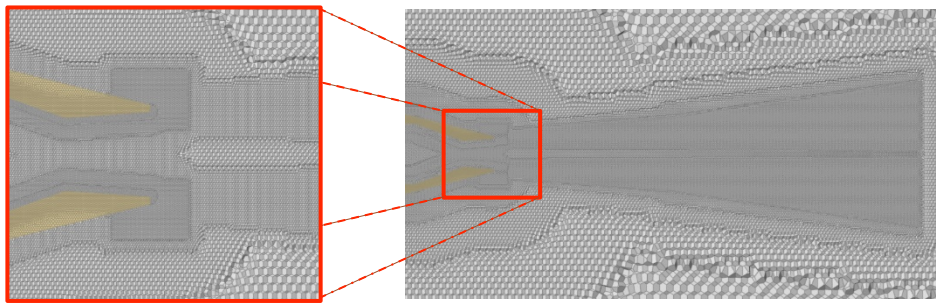


(Figures not drawn to scale)

Mesh Summary

Main Design Consideration

- Refinement windows at nozzle wall, exit, jet shear layers, potential core, and in between the twin plumes
- Avoid sharp grid transition in critical regions, which increases numerical dissipation



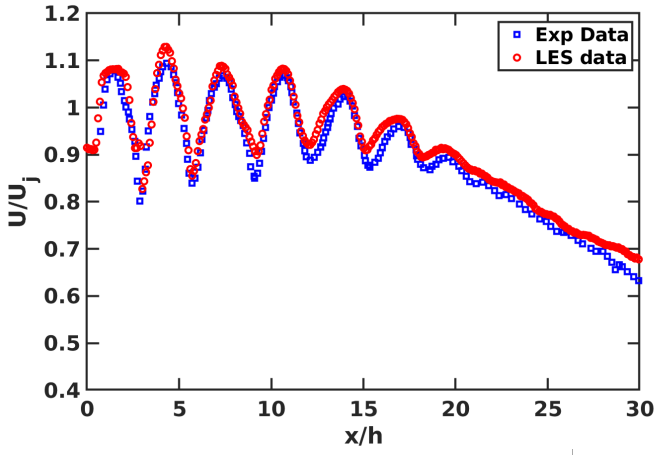
Screech Case	Mesh Size	Internal Nozzle Wall Resolution	Potential Core Resolution	Jet Plume Resolution	Time step	Sampling step	Avg. Time
Single Jet	140M	0.01 – 0.02h	0.02-0.04h (0 ≤ x/h ≤ 30)	0.08 – 0.16 (30 ≤ x/h ≤ 150)	0.002	0.1	700-1400
Twin Jet	190M-210M	0.005-0.01h	0.01-0.04h (0 ≤ x/h ≤ 24)	0.04-0.08h (up to 50h)	0.001	0.05	500-1000

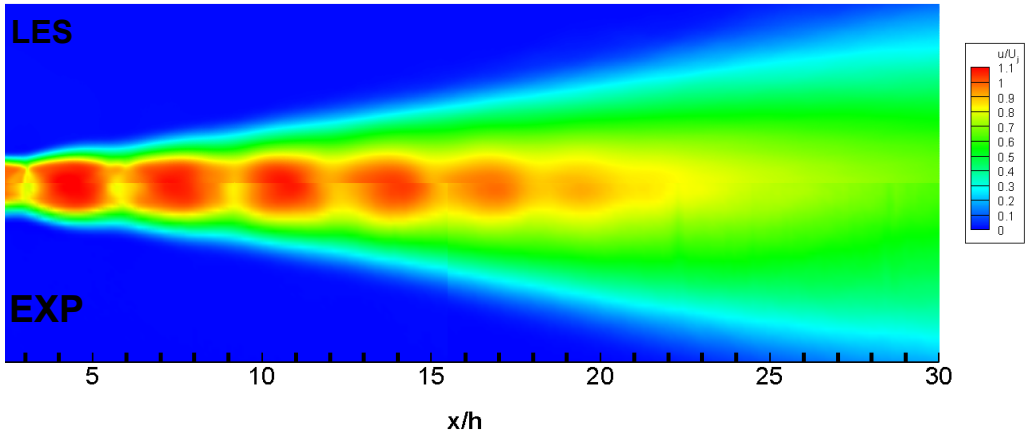
Single Jet Screech Results

Velocity Profiles along Jet Centerline

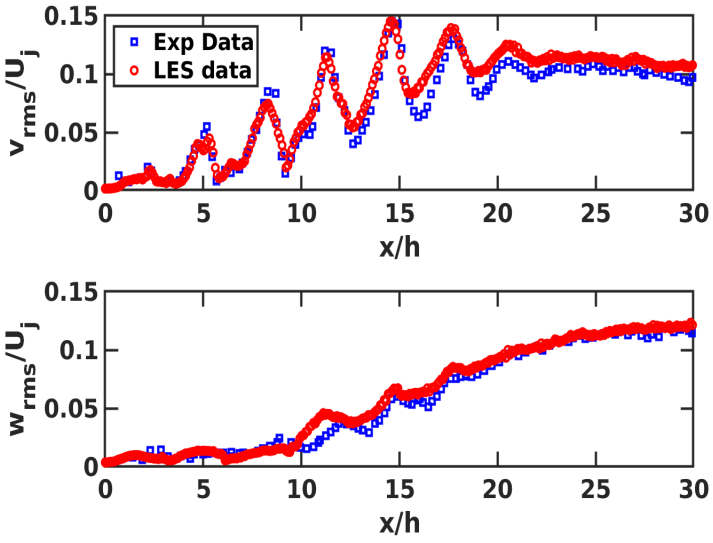
- NPR = 4.86, $M_j = 1.69$
- Max Screech

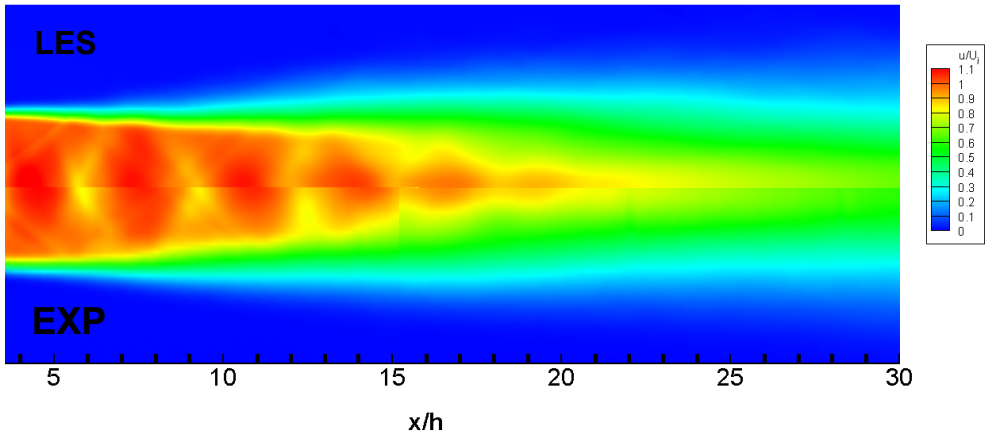
Mean Streamwise Velocity





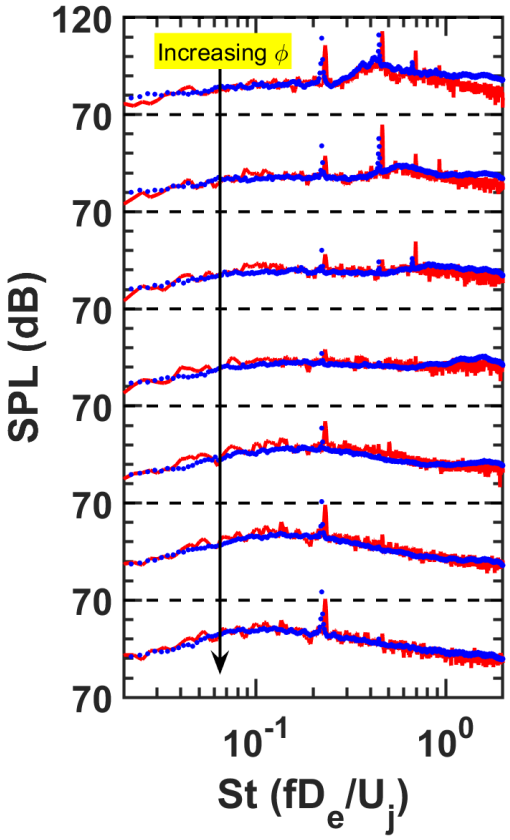
RMS of Spanwise Velocity Fluctuations



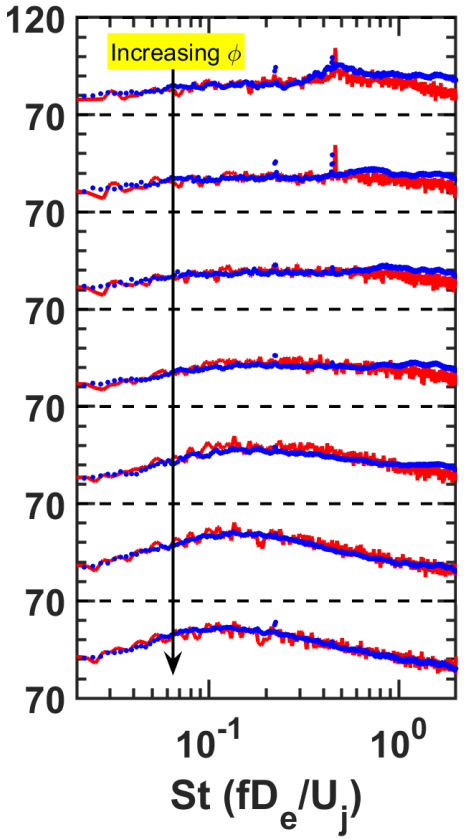


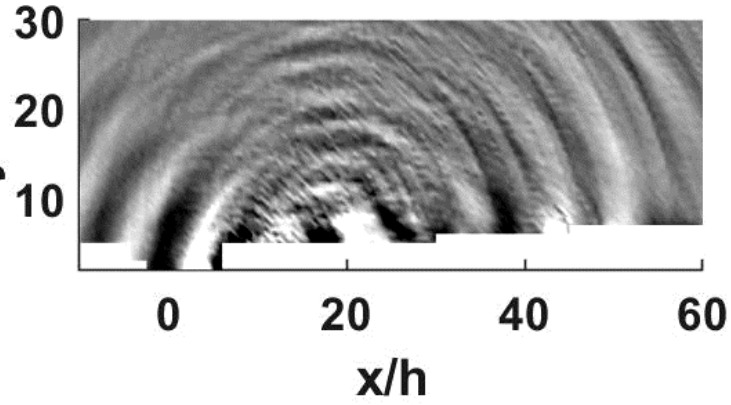
Acoustics

Minor-axis plane



Major-axis plane

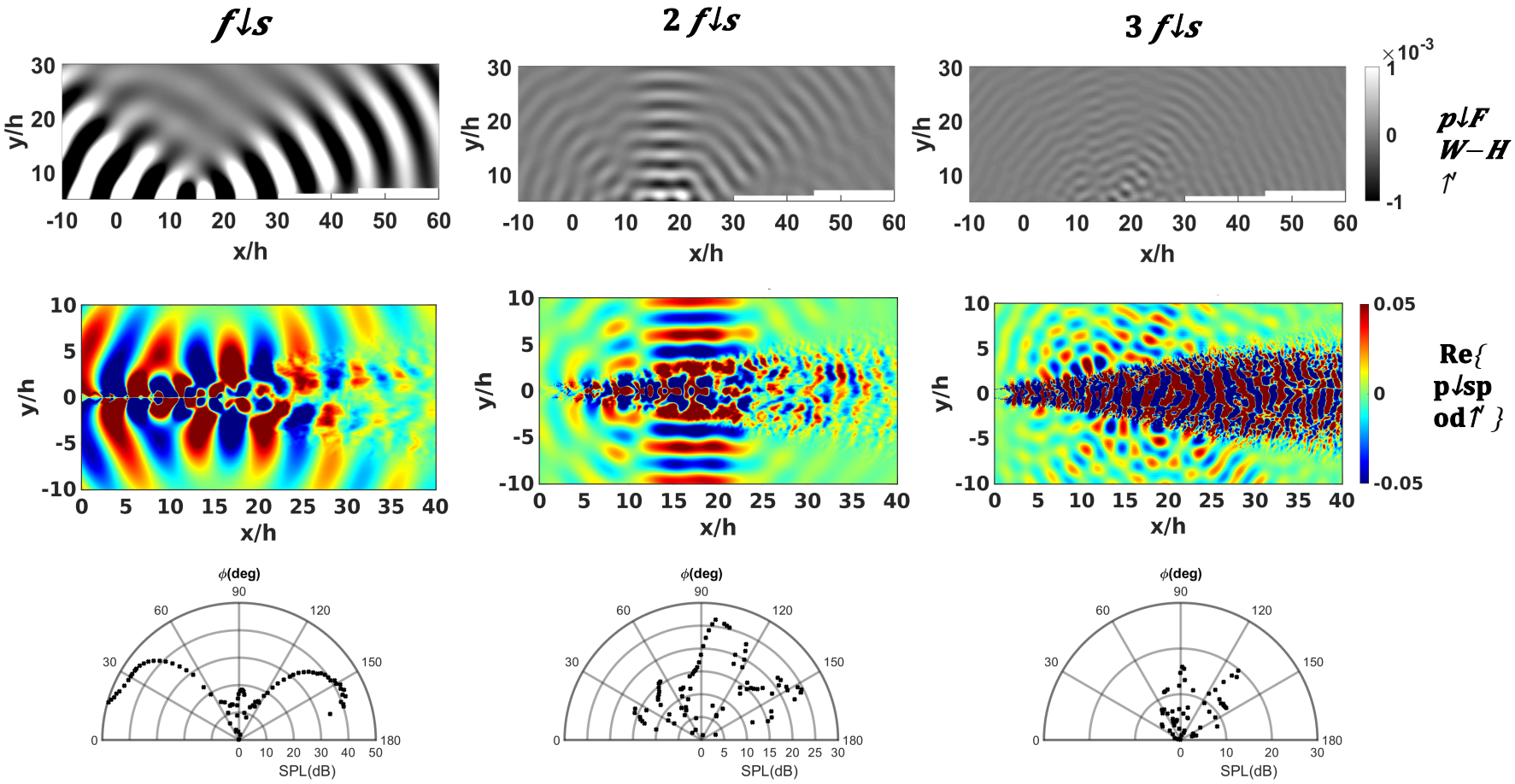




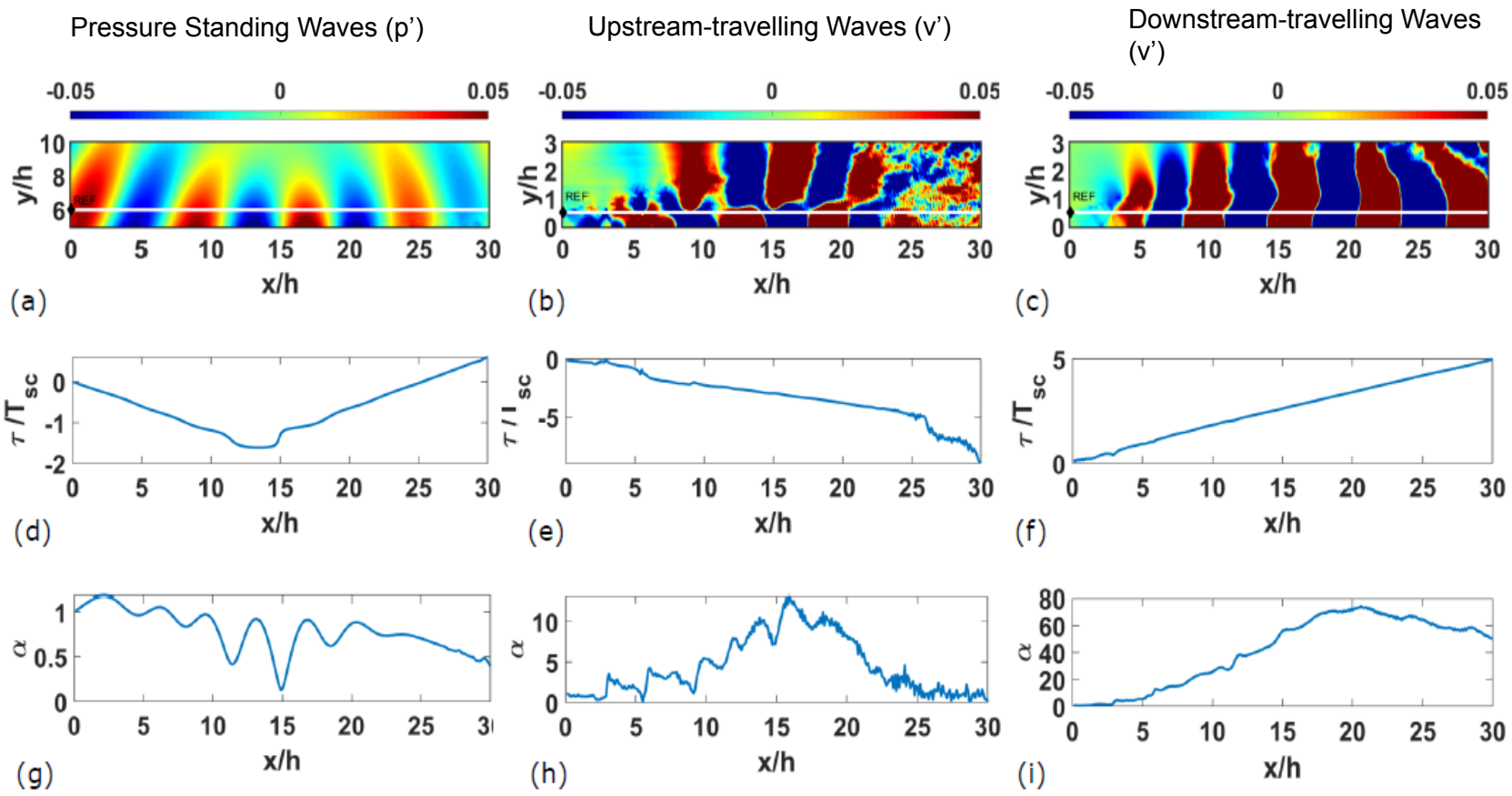
Blue: EXP, Red: LES

$r/h \approx 270$

Screech Tone and Associated SPOD Modes



Coherent Structures at Screech Fundamental Frequency



$$q\downarrow 1\ (t)=\alpha q\downarrow 2\ (t-\tau)+n(t)$$

Reference signal is taken at the nozzle exit

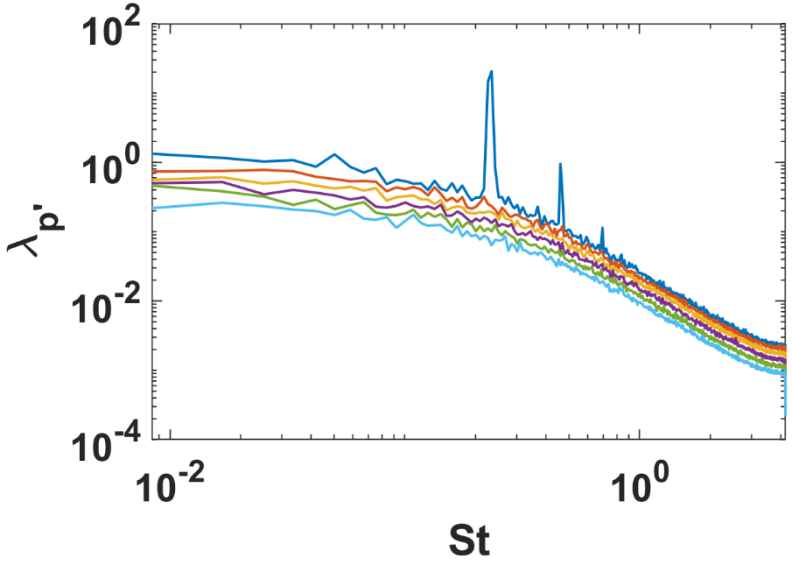
Quantification of Waves – Key Observations

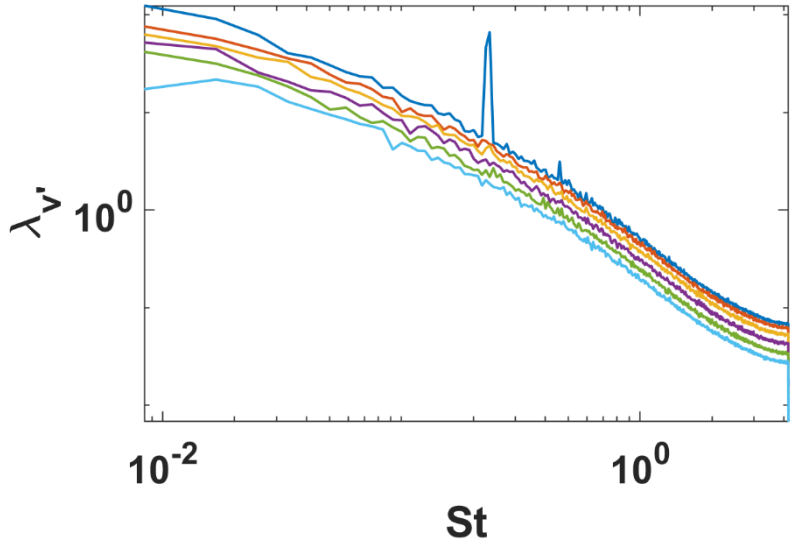
- External acoustic waves originate from spatially distributed phased array of sources
- Internal upstream acoustic mode is modulated by shock structures and reaches maximum amplitude at the end of jet supersonic core
- K-H wave is non-modulated by shock (Edgington-Mitchell *et.al.* 2019) and peaks at the end of the potential core
- Average streamwise phase velocity is related to $U\downarrow j$ by a relatively constant factor across the 3 cases considered

M_j	U_j/c_∞	U_+/U_j	U_-/U_j
1.56	1.28	0.62	-0.55
1.69	1.35	0.65	-0.56
1.78	1.39	0.67	-0.54

- On-going Works:
  - Quantification of screech feedback mechanisms
  - Acoustic source modelling for screech tones

SPOD Energy Spectra

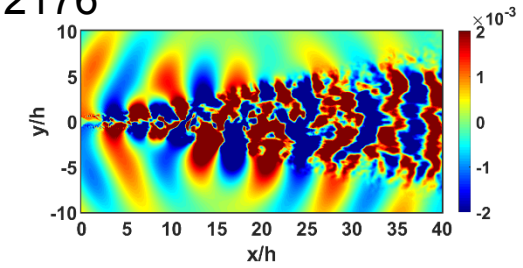




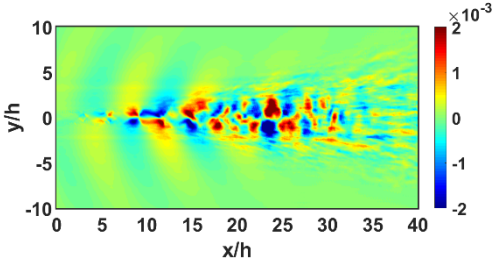
Variable	St = 0.2176	St = 0.2343	St = 0.2511
p’	0.41956	20.6033	0.31105
v’	5.7415	66.2296	4.7791

p’ SPOD

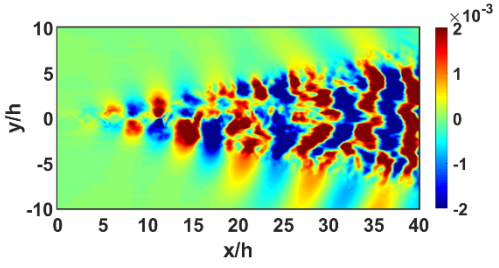
St = 0.2176



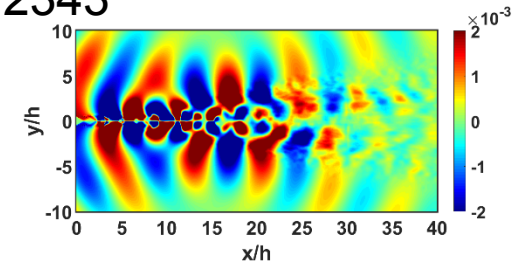
Upstream-travelling

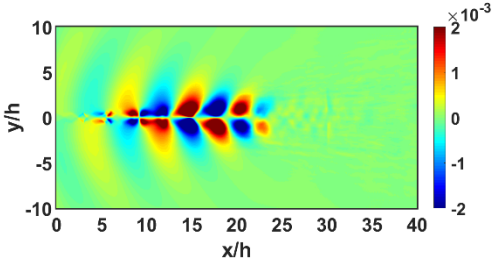


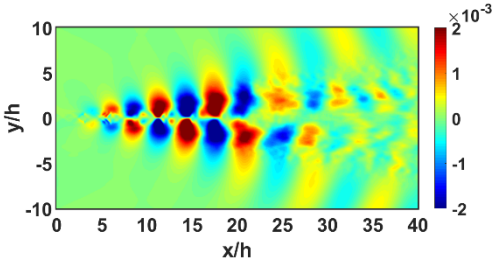
Downstream-travelling



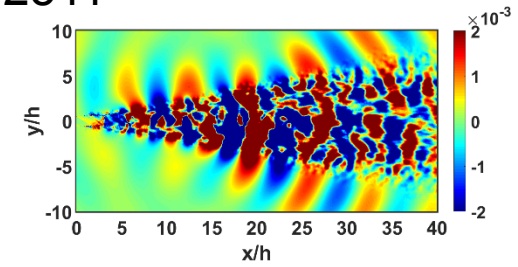
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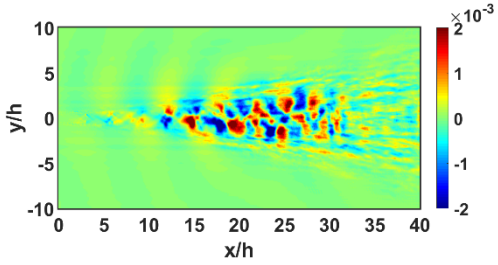


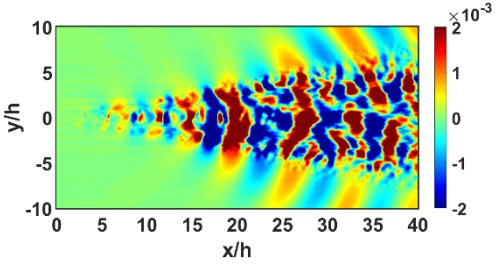




St = 0.2511

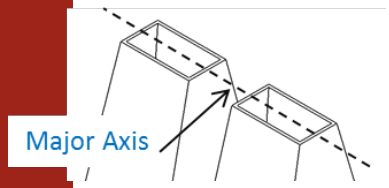


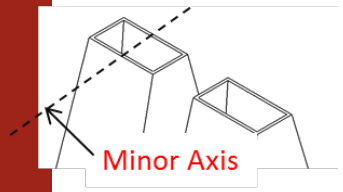


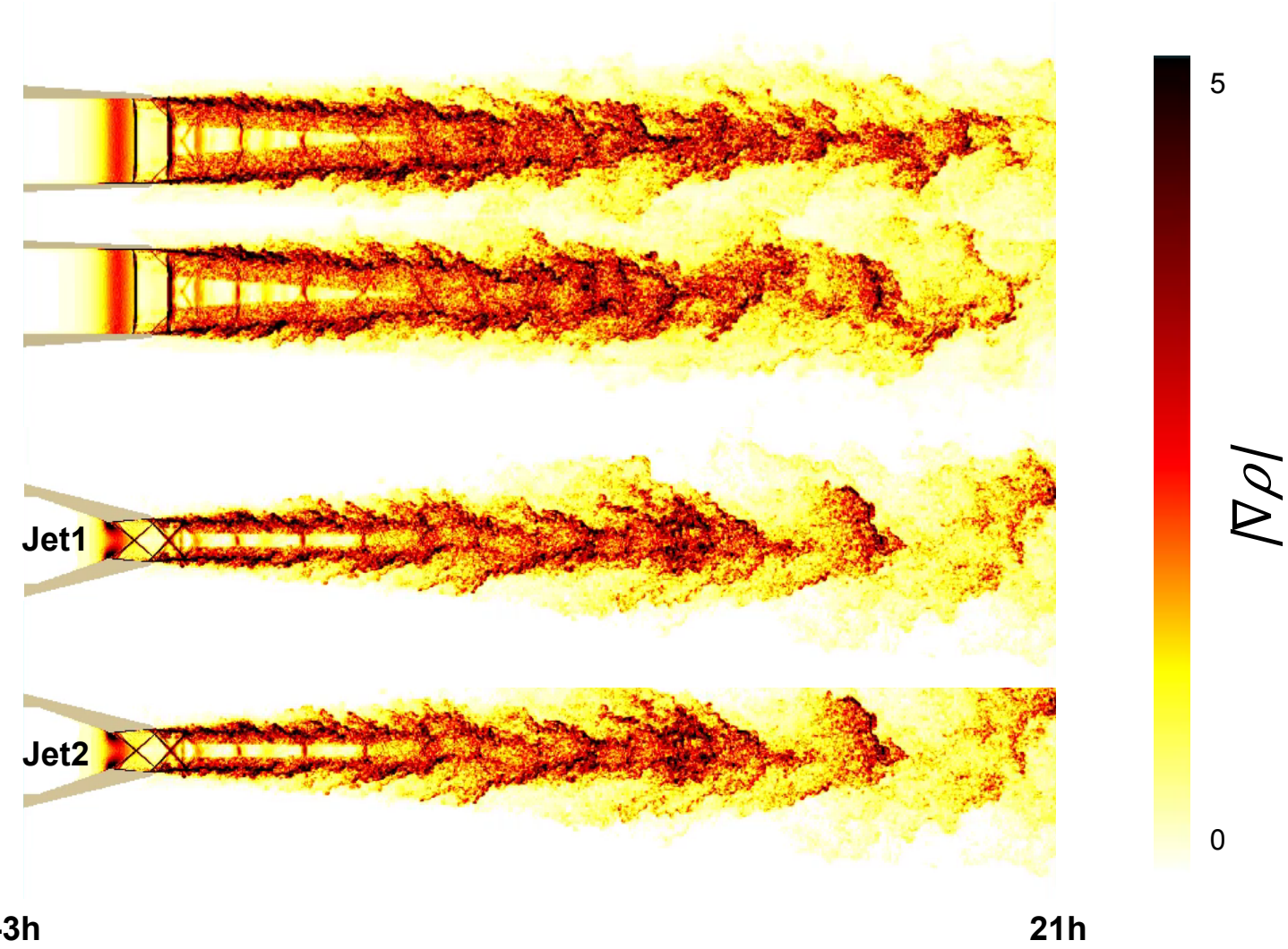


Twin Jet Screech Results

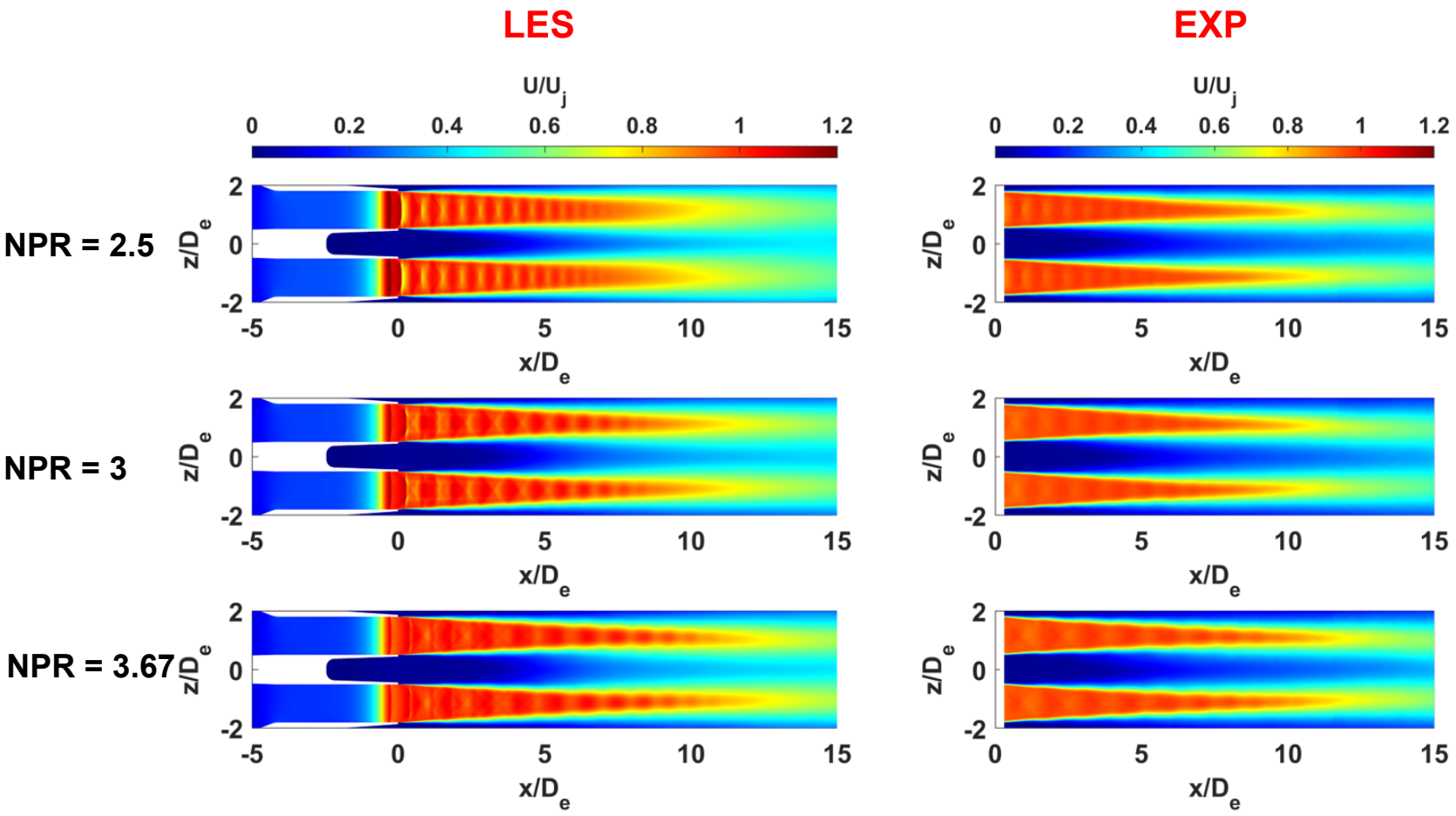
Instantaneous Velocity Field (NPR = 3)



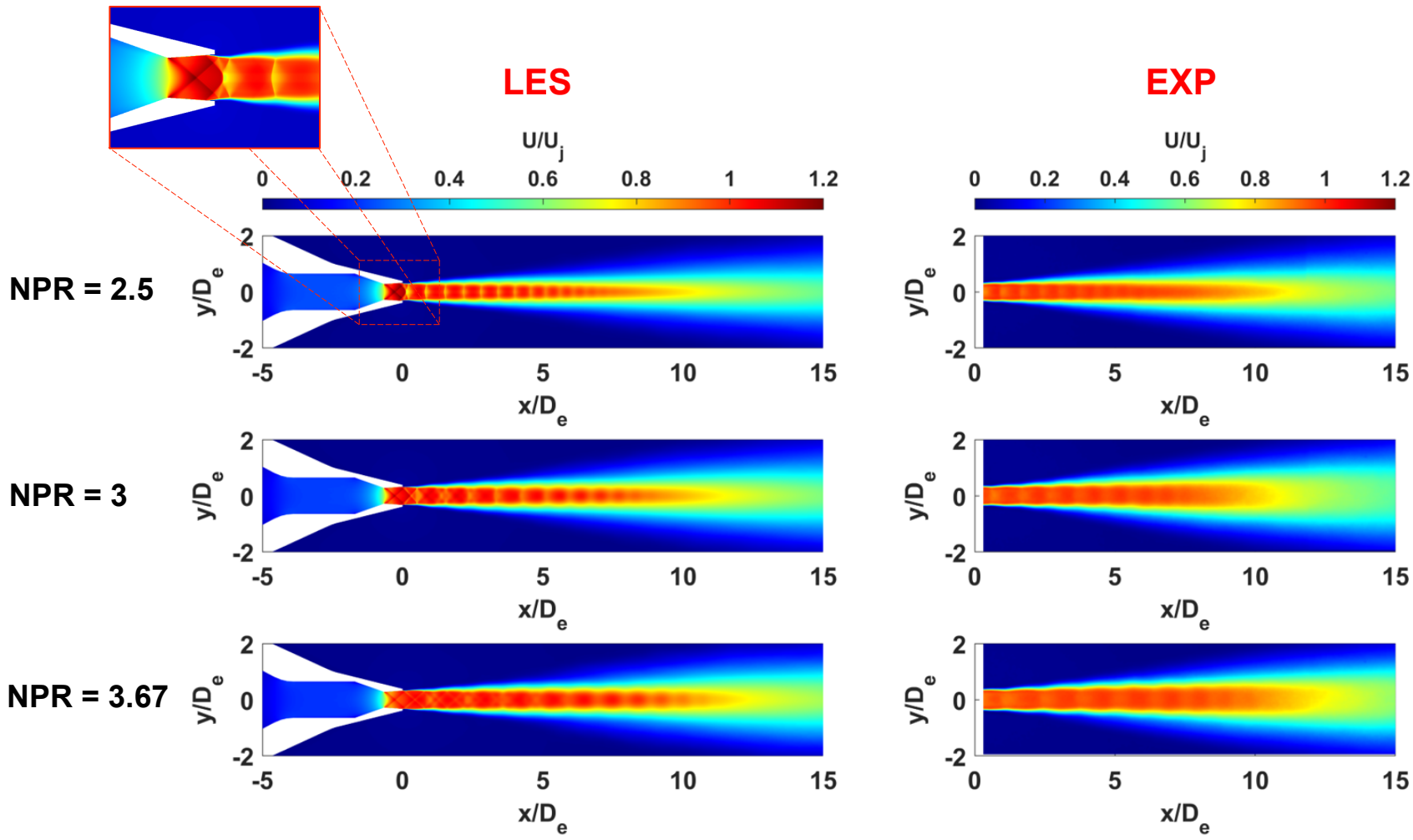




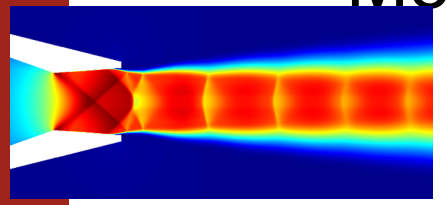
Mean Axial Velocity Field – Major Axis



Mean Axial Velocity Field – Minor Axis

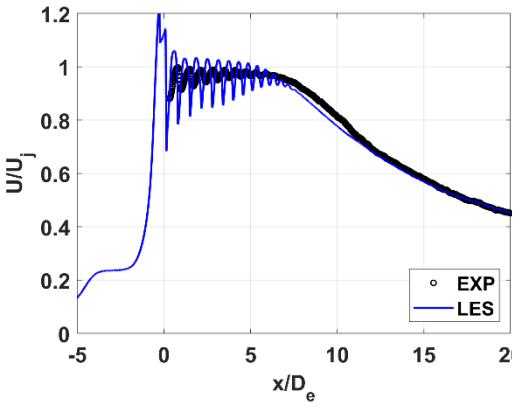


Mean Axial Velocity Profiles

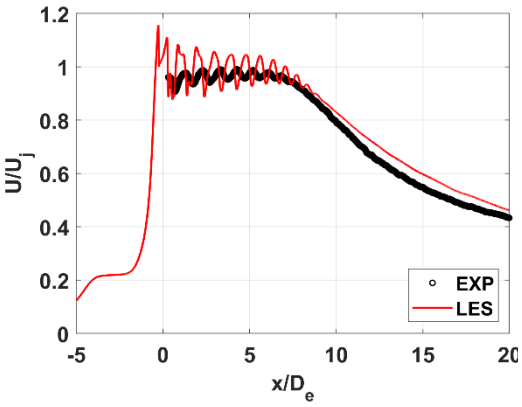




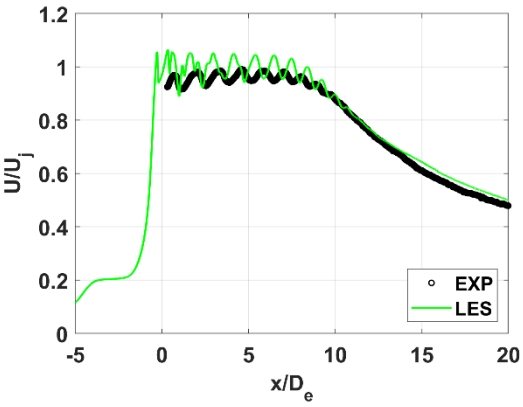
NPR = 2.5



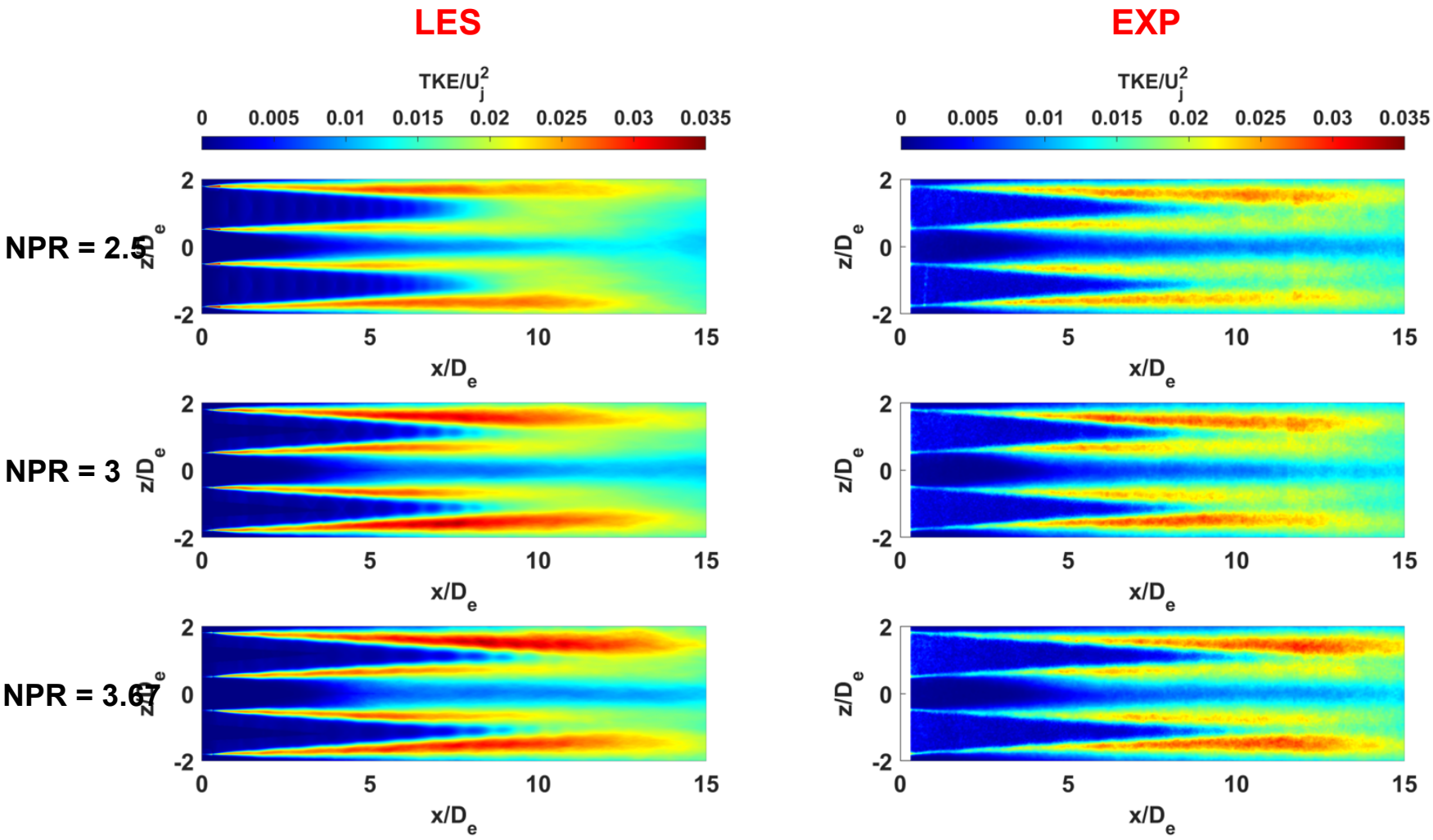
NPR = 3



NPR = 3.67

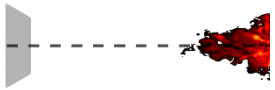


Turbulent Kinetic Energy – Major Axis

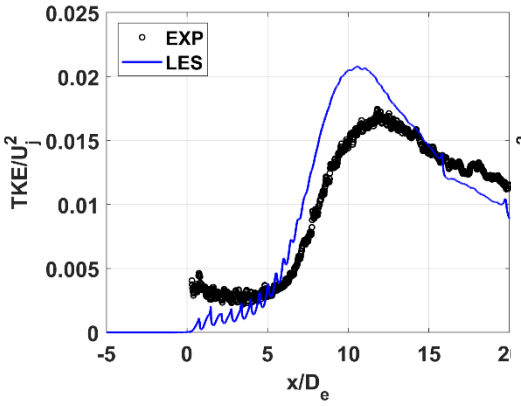


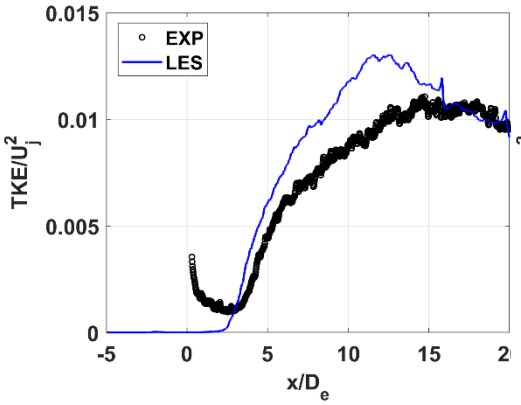
Turbulent Kinetic Energy Profiles



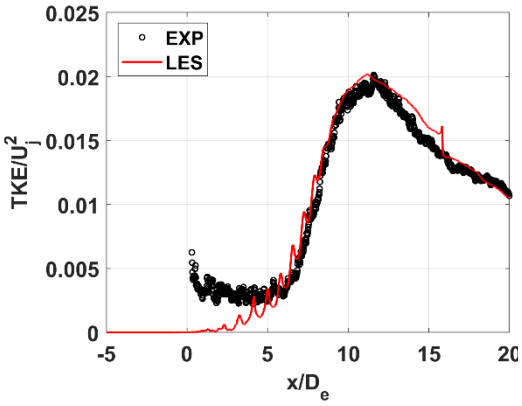


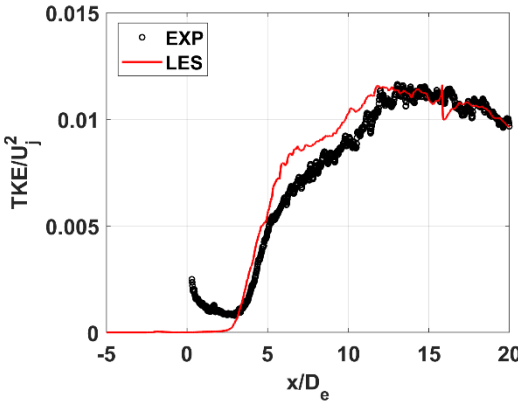
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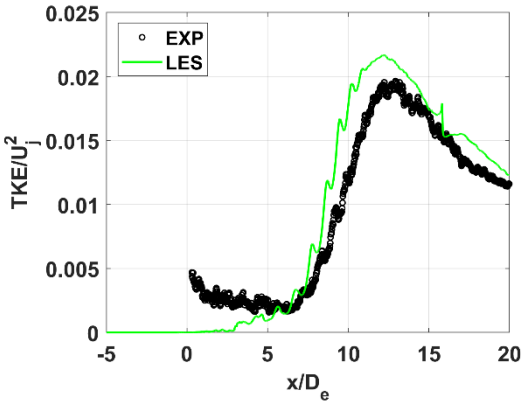


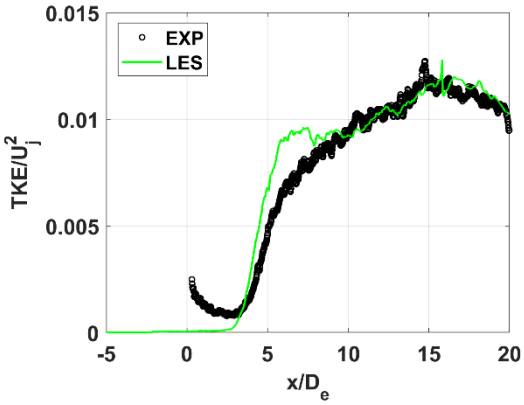
NPR = 3



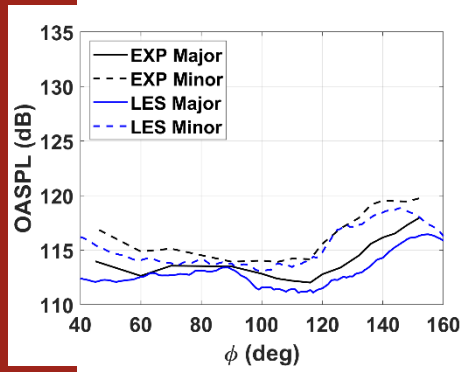


NPR = 3.67

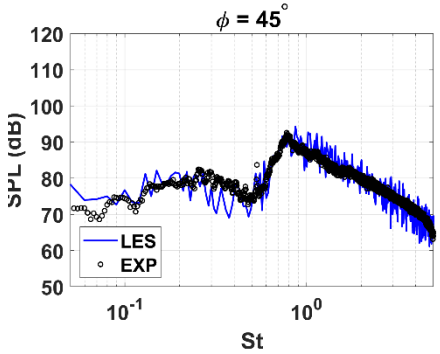


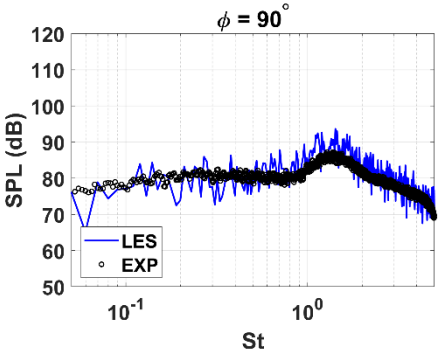


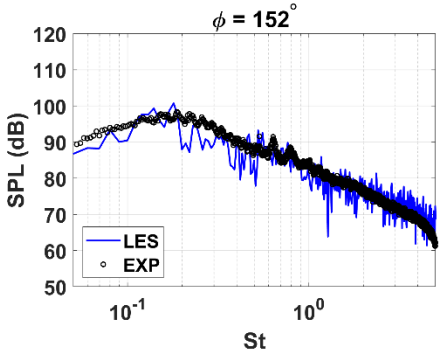
Far-field Spectra: NPR = 2.5



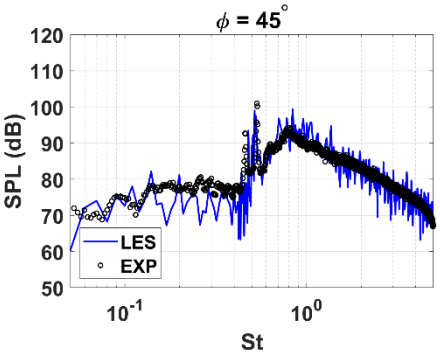
Major axis

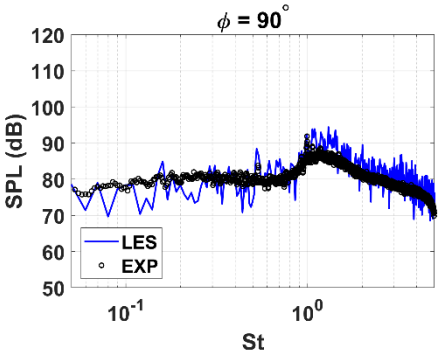


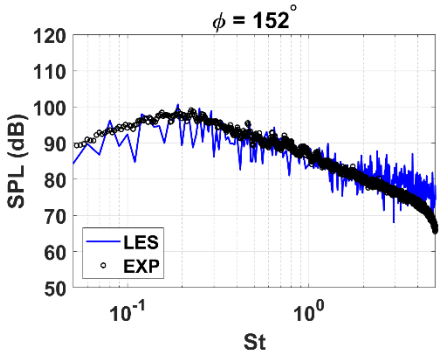




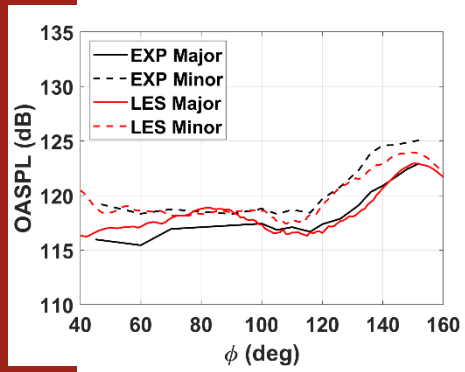
Minor axis



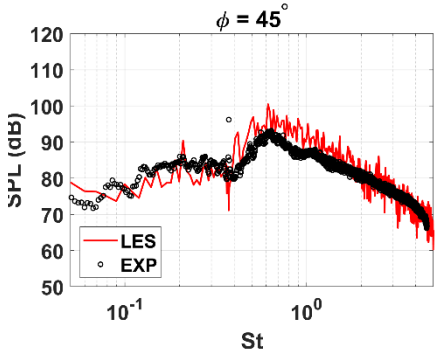


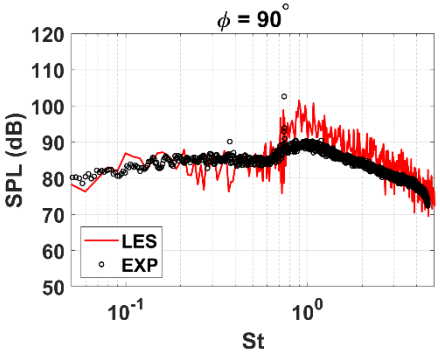


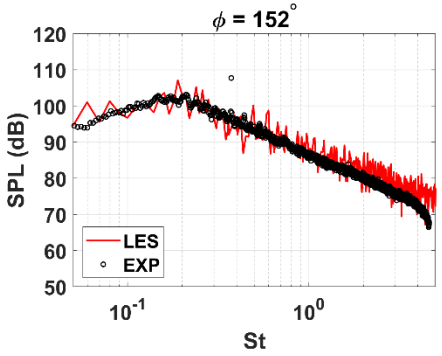
Far-field Spectra: NPR = 3



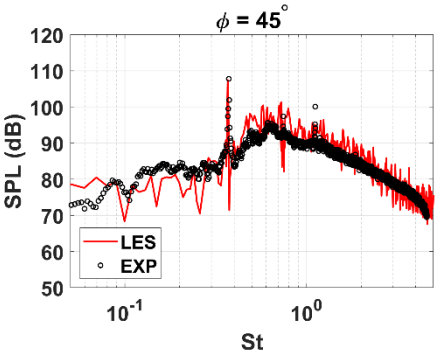
Major axis

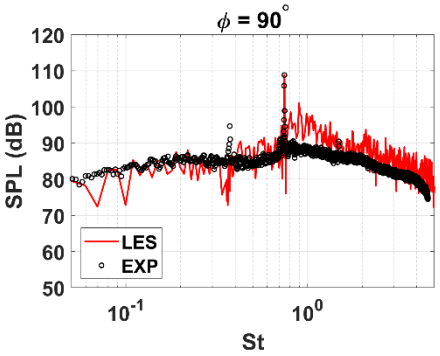


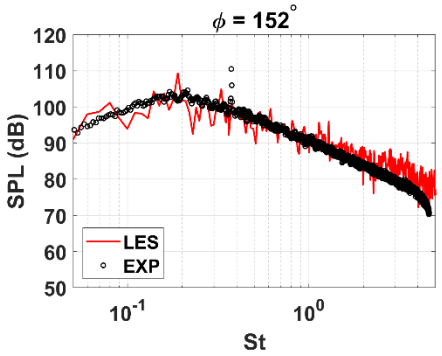




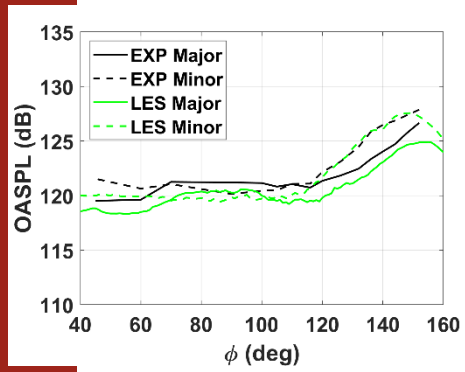
Minor axis



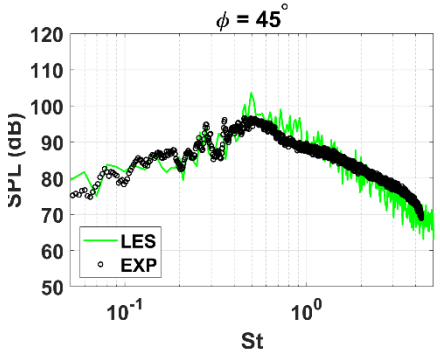


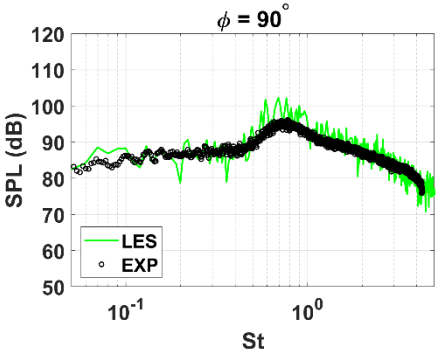


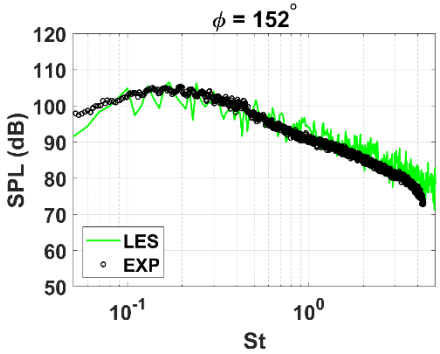
Far-field Spectra: NPR = 3.67



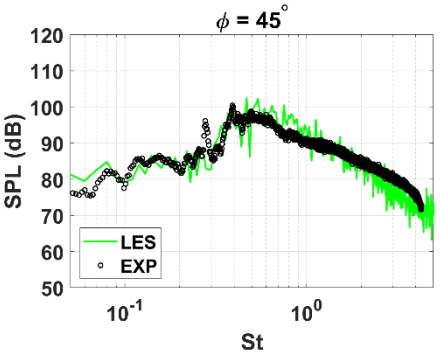
Major axis

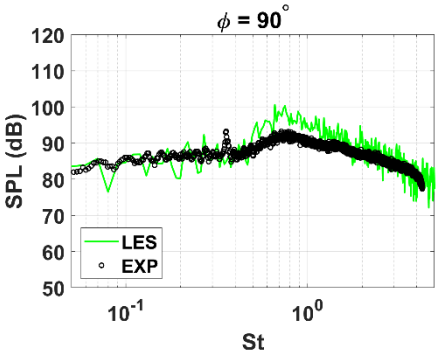


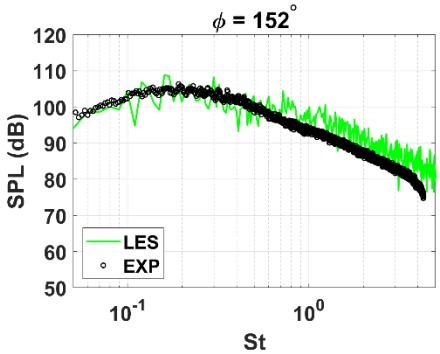




Minor axis



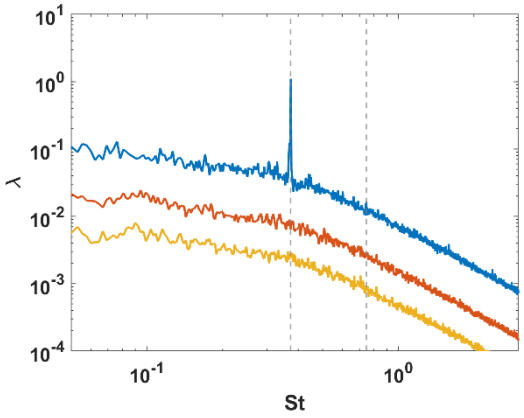


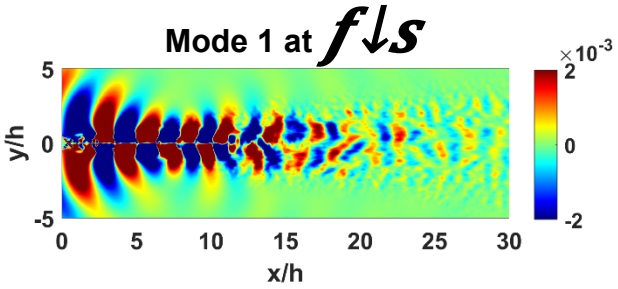


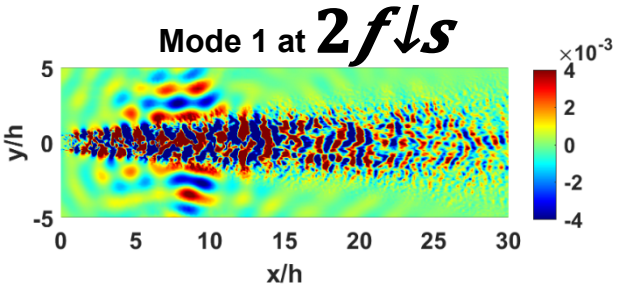
*For NPR = 3.67, FW-H data are collected over 500 acoustic times (Jeun et al., AIAA Paper 2021-1290)

Twin Jet Interaction – SPOD-p'

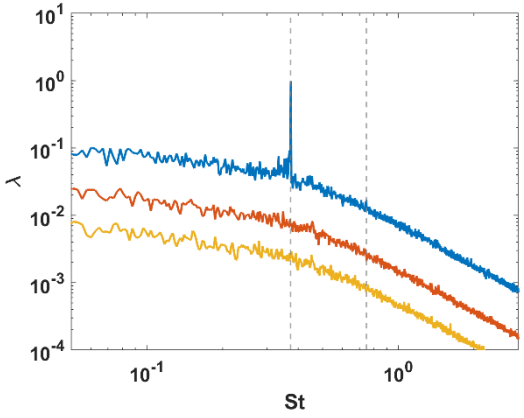
Jet 1

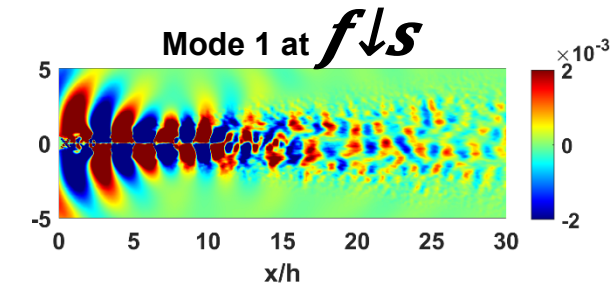


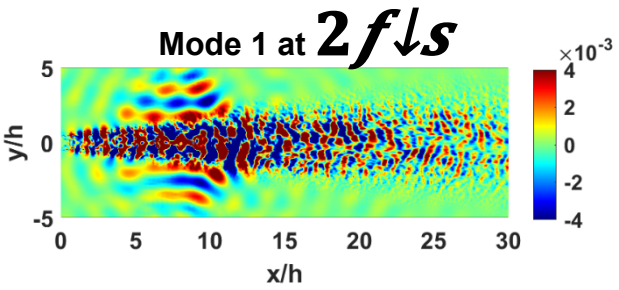




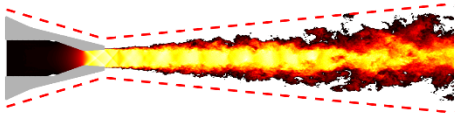
Jet 2



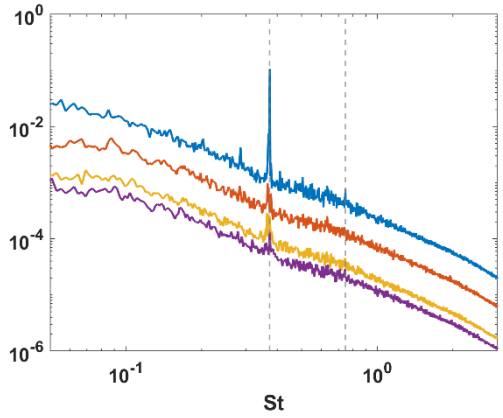


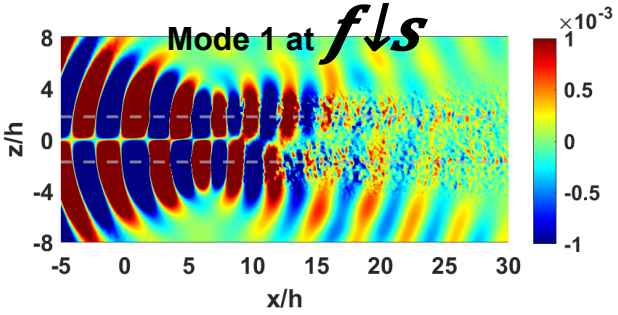


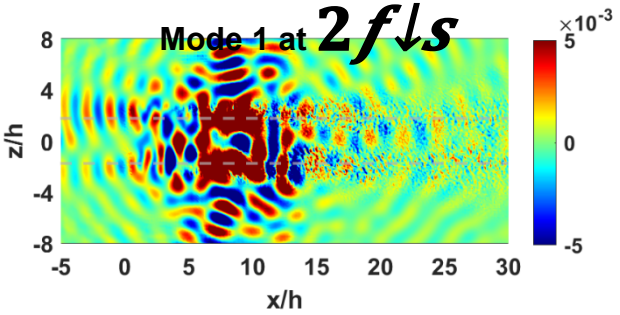
Twin Jet Interaction – SPOD-p'



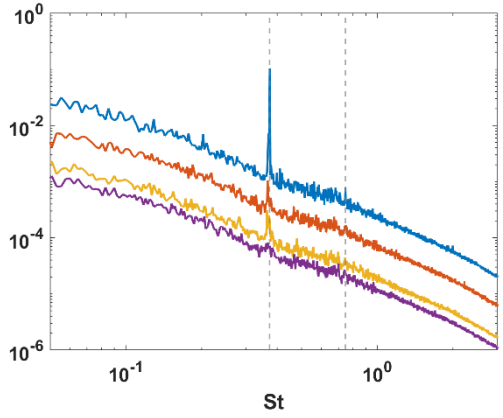
$y>0$

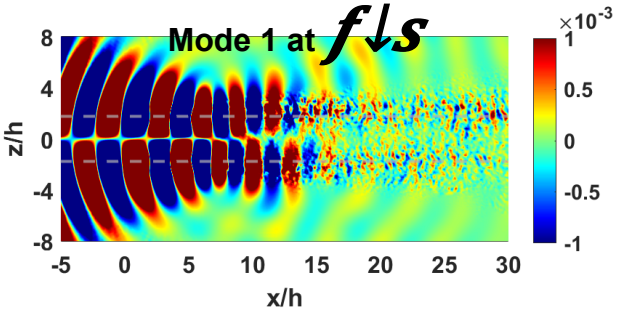


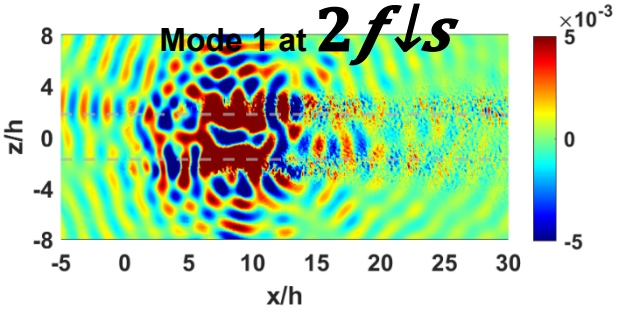




$y<0$







Findings and Conclusions

Single Jet Screech Case

- Further validated LES data with newer EXP measurements of flow velocity and acoustics
- Modal analysis reveals dominant coherent structures producing screech
- Internal mode appears to play an important role in screech feedback

Twin Jet Screech Case

- LES database of 3 different cold jets involving screech are obtained
- Basic statistical quantities (near/far fields) agree favorably with U. Cincinnati experiments
- Over-expanded jets present anti-symmetric twin-jet coupling in the minor direction that is aligned with intense jet flapping motions in this direction
- Flapping in the major direction is not obvious
- Over-expanded jet screech tones are intermittent

Summary

- Two examples of ongoing research
  on high speed shear layer turbulence and
  Jet aeroacoustics (screech and twin jet coupling)

- Turbulence resolving simulations are being used in many ways
  - Fundamental understanding
  - Engineering modeling improvements and reduced order modeling
  - Multi-fidelity approaches for analysis, design and optimization
  - Noise mitigation concepts
  - Team efforts – Experiments + Modeling + High Fidelity Simulations

Thank you!

Any questions, comments?

Flow Physics of Supersonic Mixing -- Observations II

Explanations/Hypotheses:

Dilatational/Shocklet dissipation Zeman (1990), Sarkar et al (1991)

Damping via Acoustic Radiation

Suppression of linear instability
Sandham & Reynolds (1990), Ragab & Wu (1989), Grosch & Jackson (1989), Lu & Lele (1993)

Turbulence structure change Vreman et al (1996), Pantano & Sarkar (2002)

Sonic Eddy Hypothesis Briedenthal (1992) AIAA J.

Compressible shear layer mixing

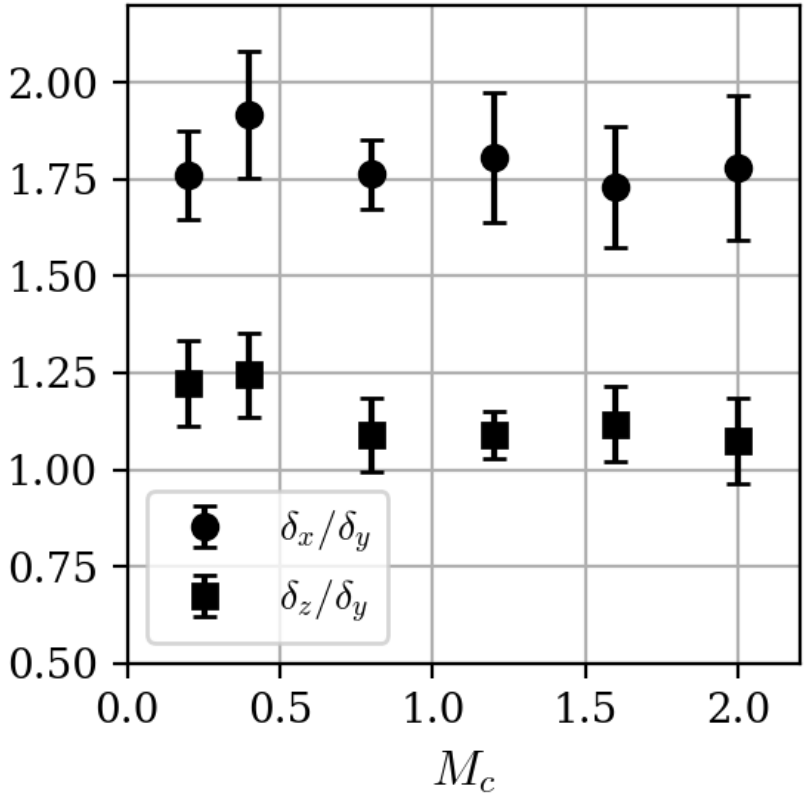
Kristen Matsuno & SKL

Working hypothesis:

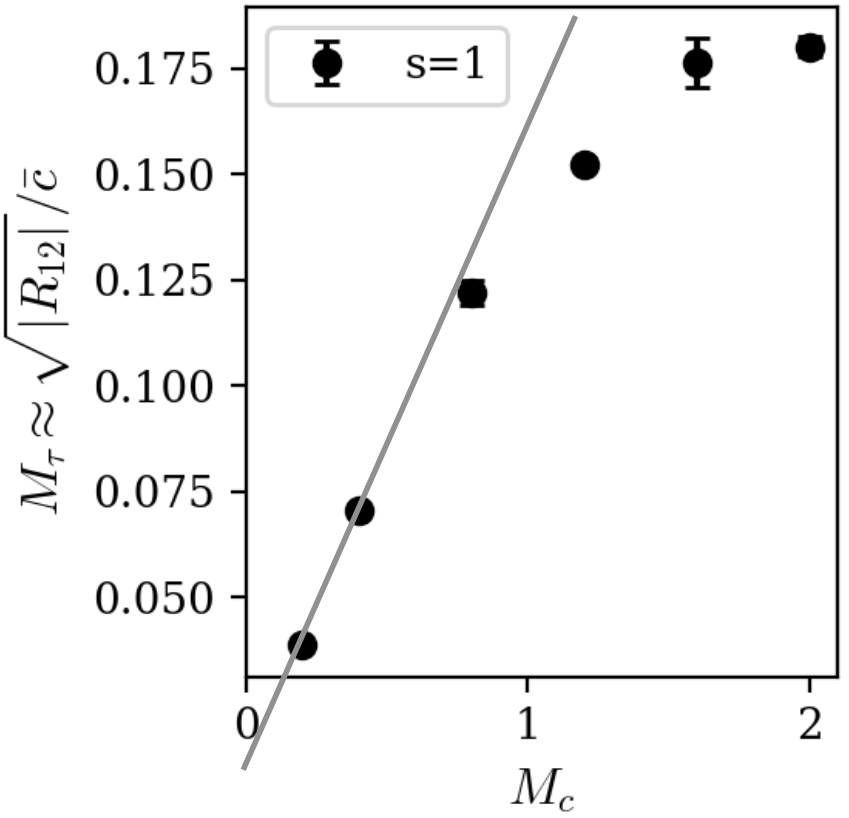
Acoustic communication limits the eddy scales (internal regulation)

Supporting evidence for internal regulation

Ratio of correlation scales



Shear stress regulation



$M_c = \Delta U/(C_1 + C_2)$

$\rho_2/\rho_1 = s$

Compressible shear layer mixing

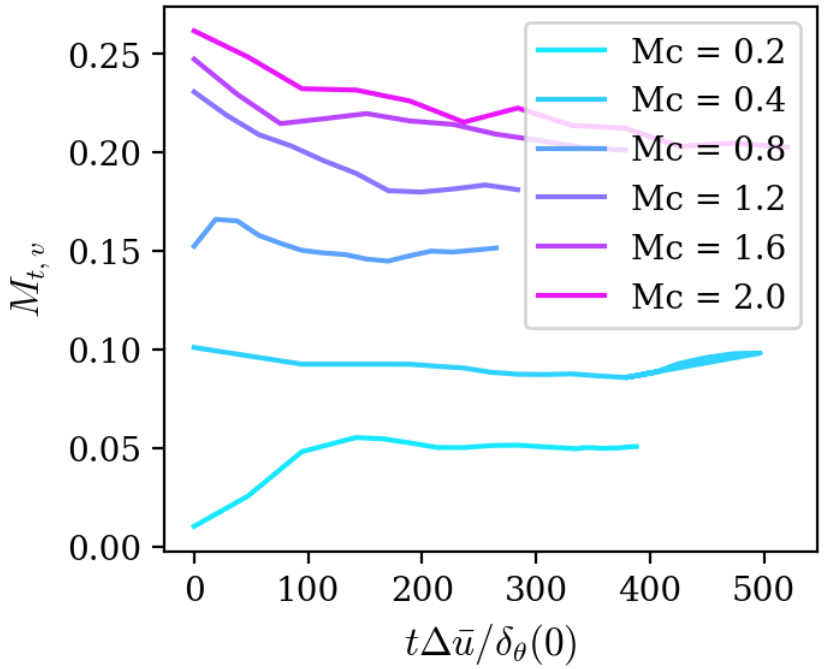
Kristen Matsuno & SKL

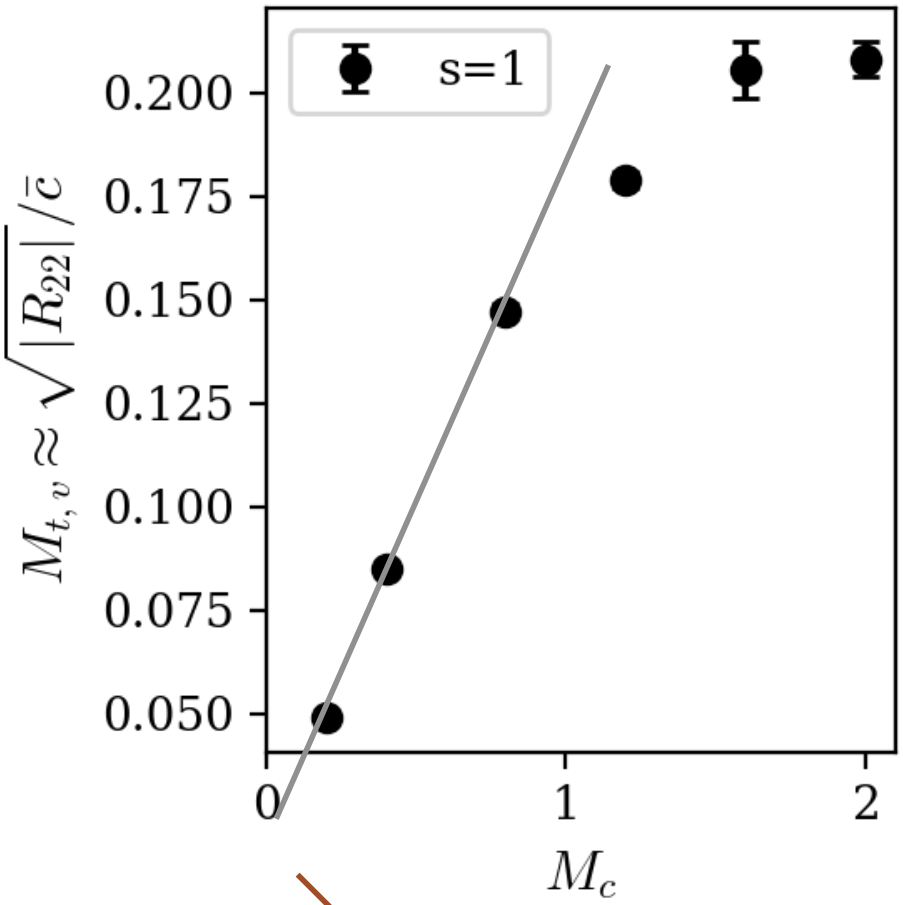
Working hypothesis:

Acoustic communication limits the eddy scales (internal regulation)

Supporting evidence for internal regulation

Normal stress regulation





$M_c = \Delta U/(C_1 + C_2)$

$\rho_2/\rho_1 = s$

Stanford University

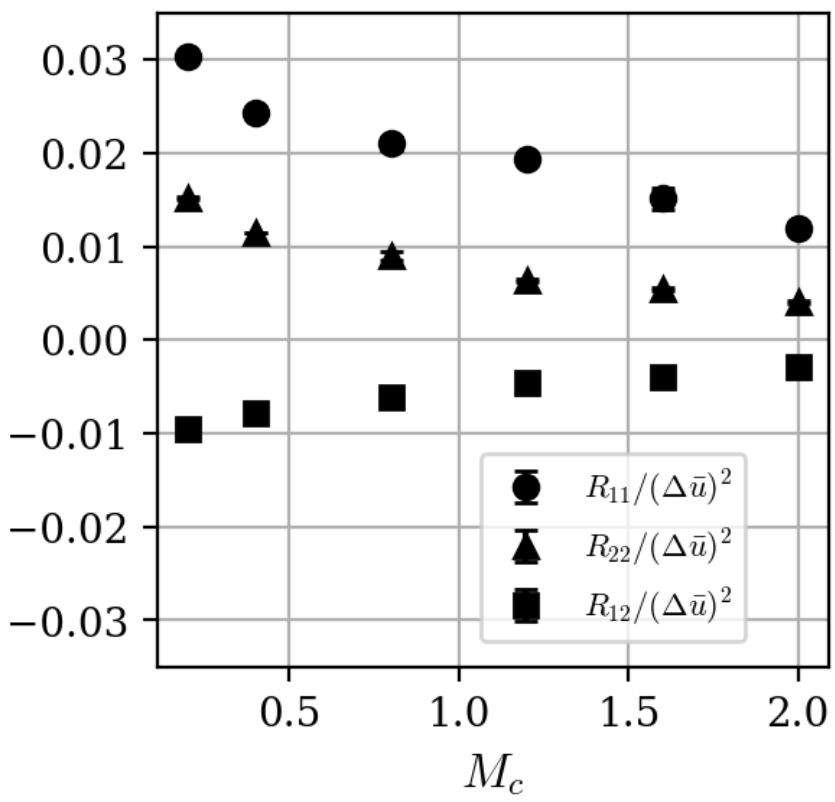
Compressible shear layer mixing

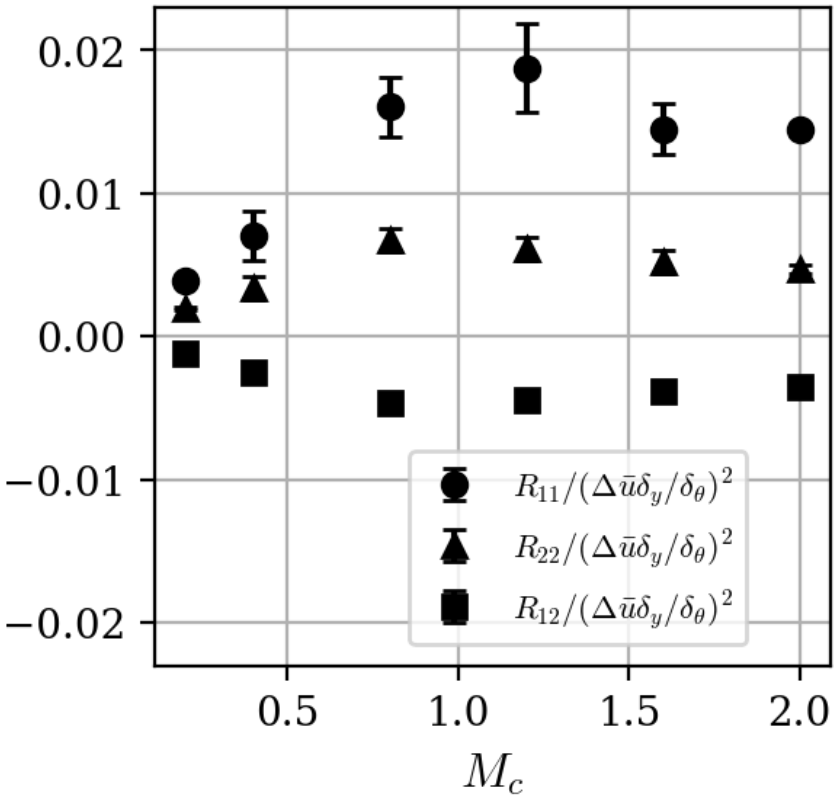
Kristen Matsuno & SKL

Working hypothesis:

Acoustic communication limits the eddy scales (internal regulation)

Supporting evidence for internal regulation





$M_c = \Delta U/(C_1 + C_2)$ $\rho_2/\rho_1 = s$

Compressible Turbulence - Fundamentals

Three Modes of fluctuations Yaglom (1948), Moyal (1952), Kovasznay (1953)

- **Vortical mode** or Gust Mode -- Solenoidal velocity, no pressure or density variations
- **Acoustic mode** – No vorticity, irrotational velocity, pressure, density fluctuation-isentropic
- **Entropic mode** – No velocity or pressure, density and temperature fluctuations

Linearized modes of uniform state
Evolve independently at first order in amplitude
mode coupling: due to mean gradients and nonlinearity

Incompressible turbulence – Nonlinearly interacting vortical modes
Not just gust modes; (incompressible) Pressure effects (non-locality) important

Variable density turbulence (low M reacting flow, low M mixing)
Compressible turbulence – density of fluid parcel changes in response to pressure
Low M_t -- Pseudo sound (Ristorcelli,1997) *Coerced* dilatational motions

Linearized modes of non-uniform state? Linear stability analysis; non-linear interactions
Primary Instability → Secondary Instability → Transition to turbulence
Useful framework but not well suited for broadband turbulence dynamics
Global modes/DMD/POD/Resolvents useful for modeling large-scale dynamics

Compressible Turbulence - Fundamentals

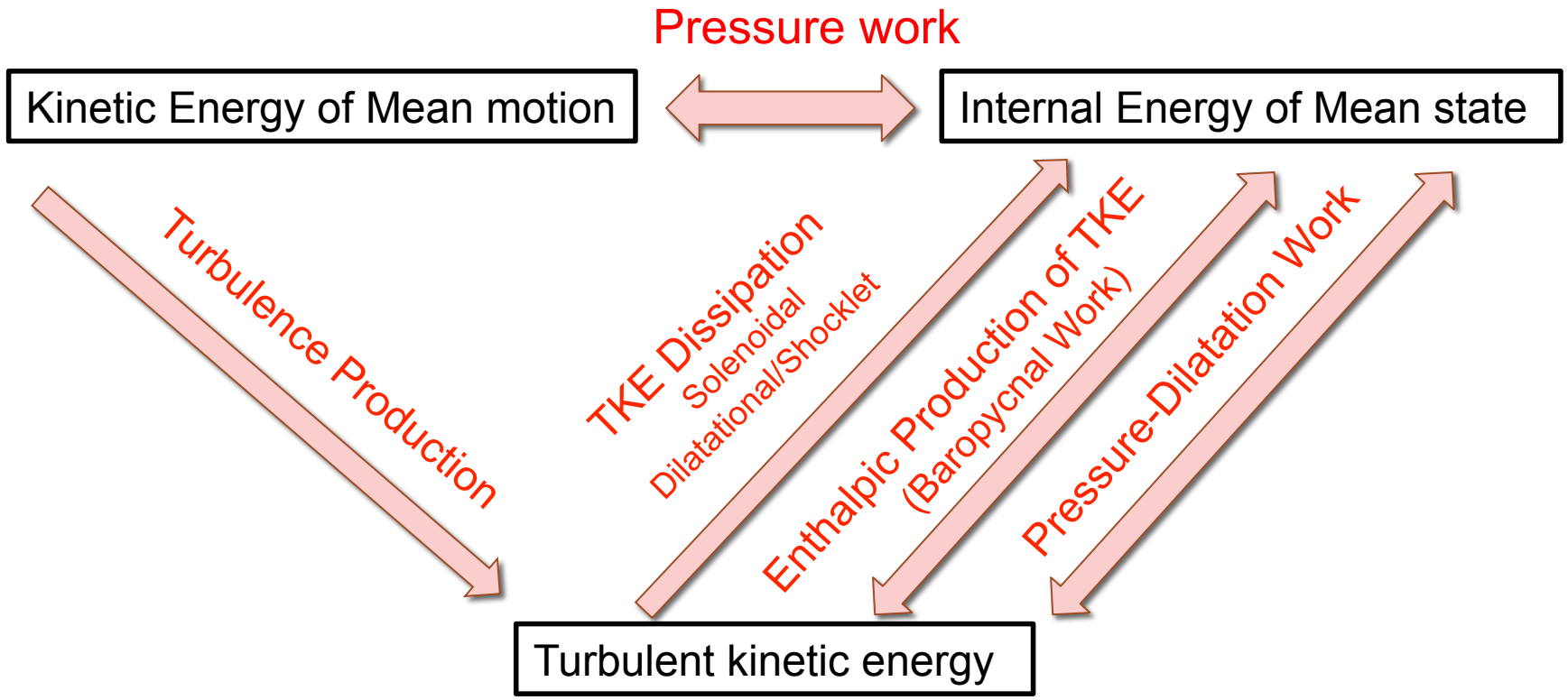
Decomposition of variables: **Favre decomposition** (mass weighted velocity)

$$u_i = \tilde{u}_i + u_i'' \; ; \quad \tilde{u}_i \equiv \frac{\langle \rho u_i \rangle}{\langle \rho \rangle}$$

Streamtubes based on $\tilde{u}_i$ maintain same mass flow

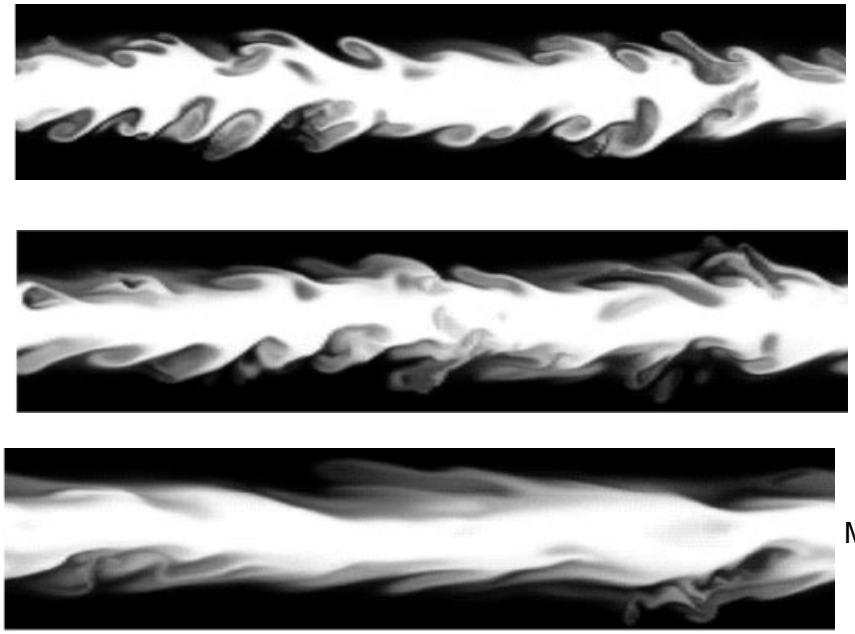
Energy Transfer pathways (coupling of momentum with thermodynamics)

Favre (1965), Huang et al (1995,JFM), …



Flow Physics of Supersonic Mixing -- Observations III

Freund, Lele & Moin, JFM (2003)



M_c = 0.2

M_c = 1.0

M_c = 1.9

Passive tracer cuts

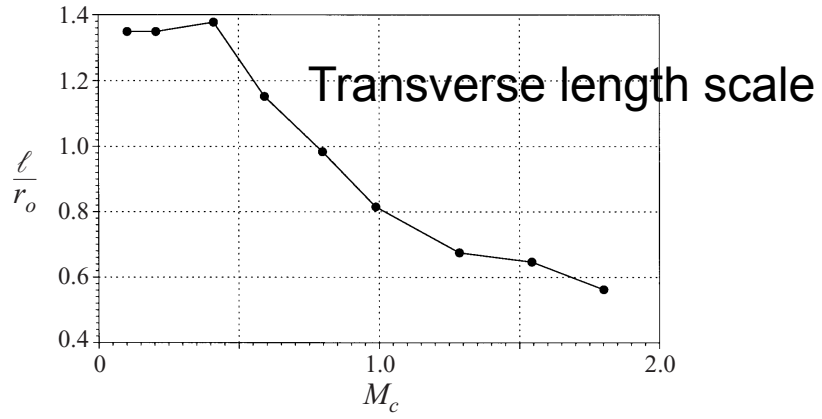


FIGURE 6. Transverse large-eddy lengthscale.

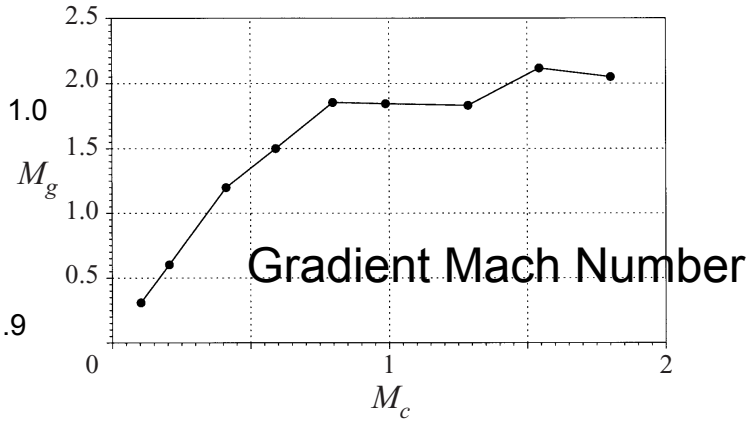


FIGURE 29. Gradient Mach number at $r = r_o$.