Large Eddy Simulations and Computational Aeroacoustics of Supersonic Jets

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Outline

- ❑ Motivation and Objectives
- ❑ Research tools
    - ○ *Compressible flow solver, finite-volume based; LES approach*
- ❑ Fluidic Injection in supersonic round jets
- ❑ Temperature effects in supersonic rectangular jets
- ❑ Twin nozzle configurations
- ❑ Summary and Outlook

Background

- Supersonic jets & Aerospace applications
- Generate thrust for civil / military aircrafts
- Acoustic radiation: powerful excitation
  - Supersonic Jet Noise → Community noise
  - Stressful stimulus for the crew, wildlife, and those in the vicinity during take-off / lift-off / vertical rocket landing
  - Undesirable stresses on nearby structures & aircraft's components
- Nozzle configurations & integration aspects
  - Tight integration with airframe (e.g. rectangular nozzles)
  - Potential of ***reducing noise signature***; developing noise suppression technologies
  - Thrust vector control potential
  - Interactions (ground effects & adjacent / twin jets)

SpaceX starship,
Reuters, news18.com

Lockheed Martin X-59 QueSST
https://en.wikipedia.org/wiki/Lockheed_Martin_X-59_QueSST

Space tourism: Virgin Galactic spaceship www.cnn.com

Installation configurations for a Silent Aircraft; Hall & Crichton www.acoustics.org

Motivation and Objective

- Supersonic jet noise reduction technologies are mainly developed based on laboratory-scale data and relatively low-temperature flows
    - Challenges with measuring flow inside the nozzle and the dynamics associated with supersonic & high-temperature flows (e.g. quantifying temperature/density fluctuations).
    - Short-test duration (mass flow limitations).
    - Temperature limitations with the test rig.
- Practical high-performance jets are highly-heated ($T_t > 2000$ K)
    - Limited understanding of noise generation process in real scale, highly-heated jets.
- *Supersonic Jet – airframe / ground / deck / nozzle to nozzle* interactions
- **Objective**: to gain insights on the noise generation mechanisms in highly-heated supersonic jets
    - Use of LES approach for a physics-based understanding of flow-acoustics interactions.
    - Develop jet noise suppression technologies to ***mitigate jet-noise signature***.

Research tools and focus areas

Research Tools

- Validated “in-house” compressible finite-volume based flow solver (e.g., M-Edge).
- High-fidelity Large Eddy Simulation (LES) calculations for physics-based understanding of phenomena.
- Acoustic analogies for far-field noise prediction using a Ffowcs Williams-Hawkings porous open surface.
- Fast Reynolds averaged Navier-Stokes (RANS) based formulations for geometry optimization purposes.
- Data-driven methods and Advanced post-processing, including e.g., Proper Orthogonal Decomposition, Dynamic Mode Decomposition, Fourier surface decomposition.

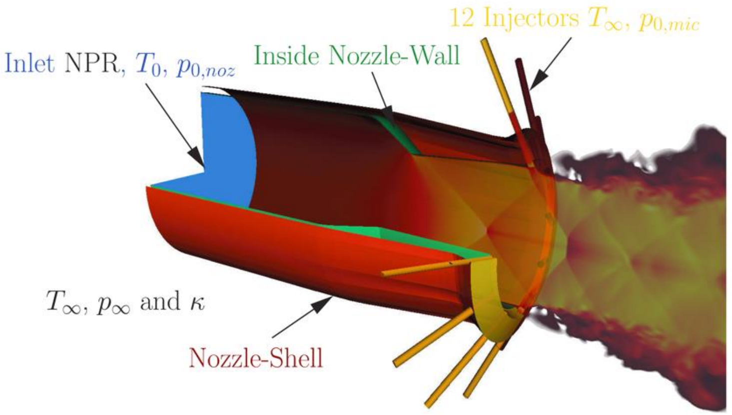
Focus Areas

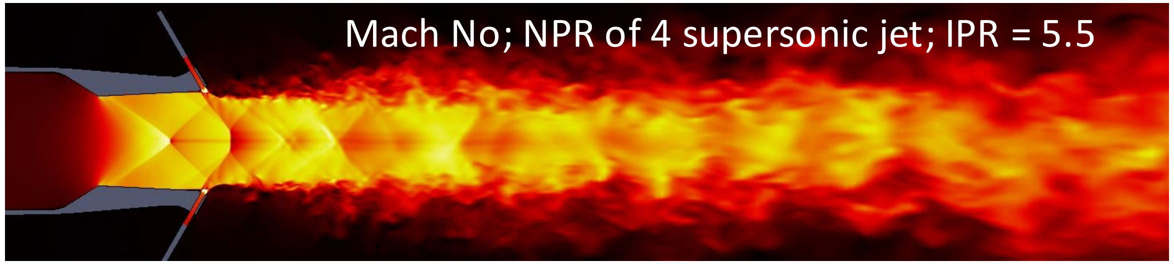
- More efficient & silent propulsion systems.
- Circular / rectangular convergent-divergent nozzles under realistic operating conditions, i.e., including *real* temperature ratios TR~7 (2100K).
- Runway surface effects on noise generation and propagation; *vertical lift-off and landing*.
- Consider installation effects, embedded rectangular nozzles into the aircraft structure.
- Flow control for noise suppression technologies (e.g. fluidics, vortex generators).

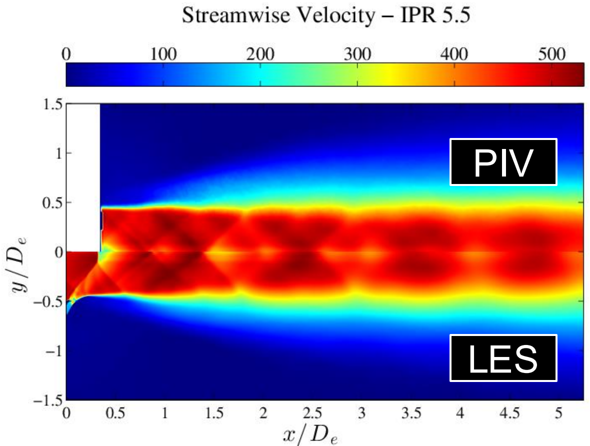
Fluidic injection in supersonic non-ideally expanded round jets

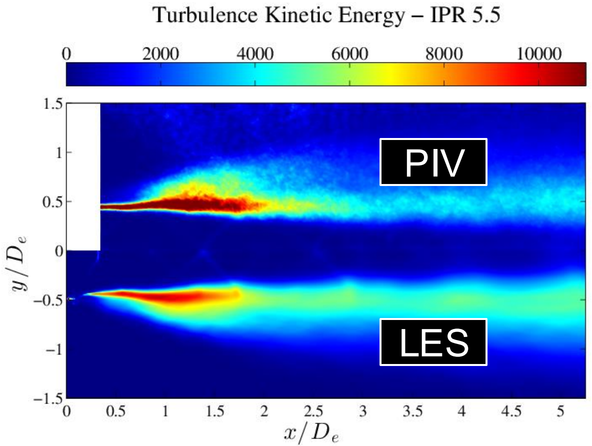
- Compressible “in-house” finite volume-based flow solver
  - Turbulence by means of implicit LES approach, with Jameson-type artificial dissipation mechanism
  - Assessment of Noise suppression technologies
- Computational grid
  - Sponge zone + non-reflecting boundaries; 160 M cells → 1000 CPUs
- Aeroacoustics: Ffowcs Williams-Hawkings (FW-H) acoustic analogy

Fluidic injection impact on the **circular supersonic jet** (NPR=4); Comparisons LES vs. PIV experiments




Mach No; NPR of 4 supersonic jet; IPR = 5.5


Streamwise Velocity – IPR 5.5

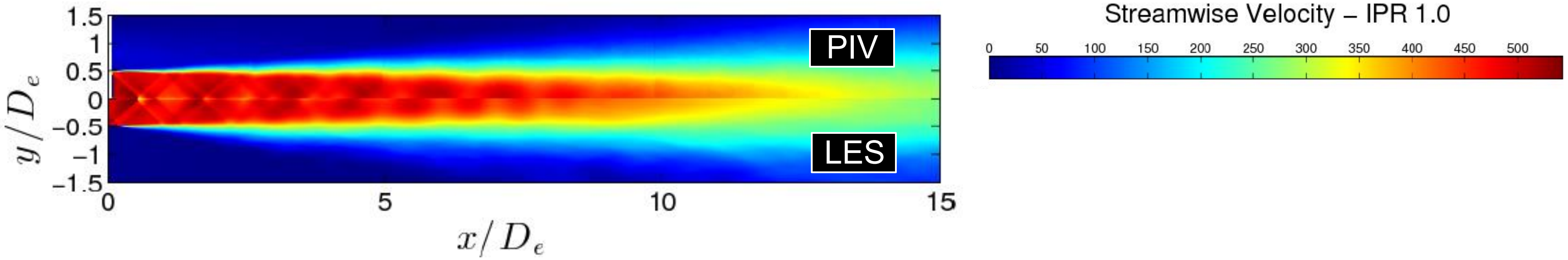

Turbulence Kinetic Energy – IPR 5.5

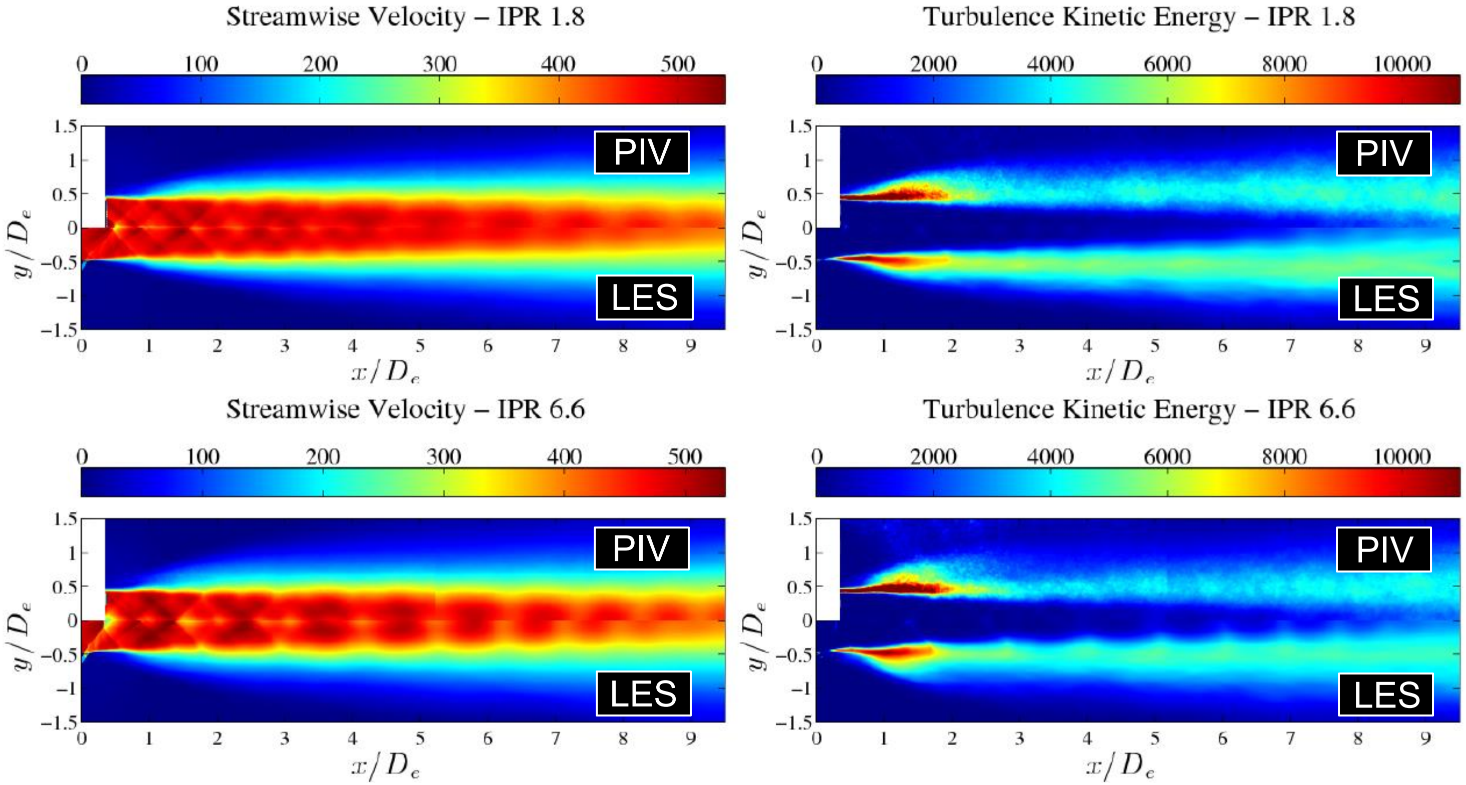
Semlitsch B, Mihăescu M. (2021) Evaluation of Injection Strategies in Supersonic Nozzle Flow. *Aerospace.* 8(12):369. https://doi.org/10.3390/aerospace8120369

Semlitsch B., Cuppoletti D., Gutmark, E.J., & Mihăescu M., (2019), Transforming the Shock Pattern of Supersonic Jets Using Fluidic Injection, *AIAA Journal,* 57(5):1851-1861. https://doi.org/10.2514/1.J057629

PIV experimental data courtesy of Prof. Ephraim Gutmark, University of Cincinnati

External fluidic injection effects: 12 injectors (60°)





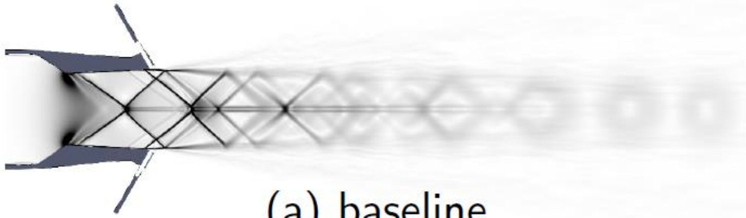
Good agreement between Simulations (LES) and Experimental data (PIV): Time-averaged axial velocity and Turbulence Kinetic Energy (TKE) for different Injection Pressure Ratios (IPR)

Semlitsch B., Cuppoletti D., Gutmark, E.J., & Mihaescu M., (2019), *AIAA Journal,* 57(5):1851-1861.

PIV experimental data courtesy of Prof. Ephraim Gutmark, University of Cincinnati

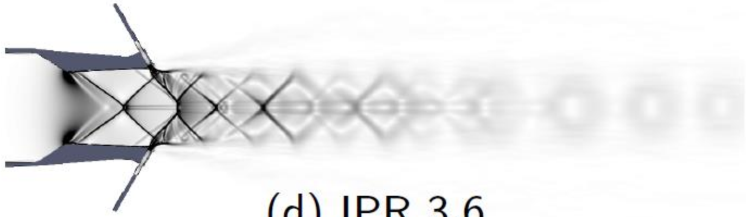
External fluidic injection effects, 12 injectors (60^o)

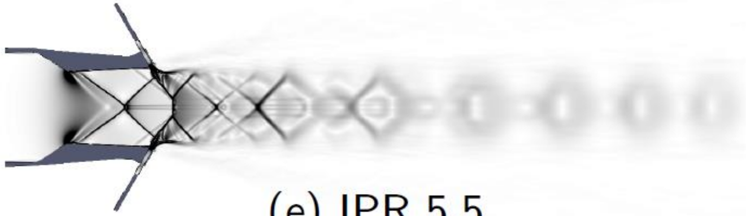
Numerical Schlieren; LES data: normalized density gradients


(a) baseline


(b) IPR 1.8


(c) IPR 2.4


(d) IPR 3.6


(e) IPR 5.5


(f) IPR 7.8

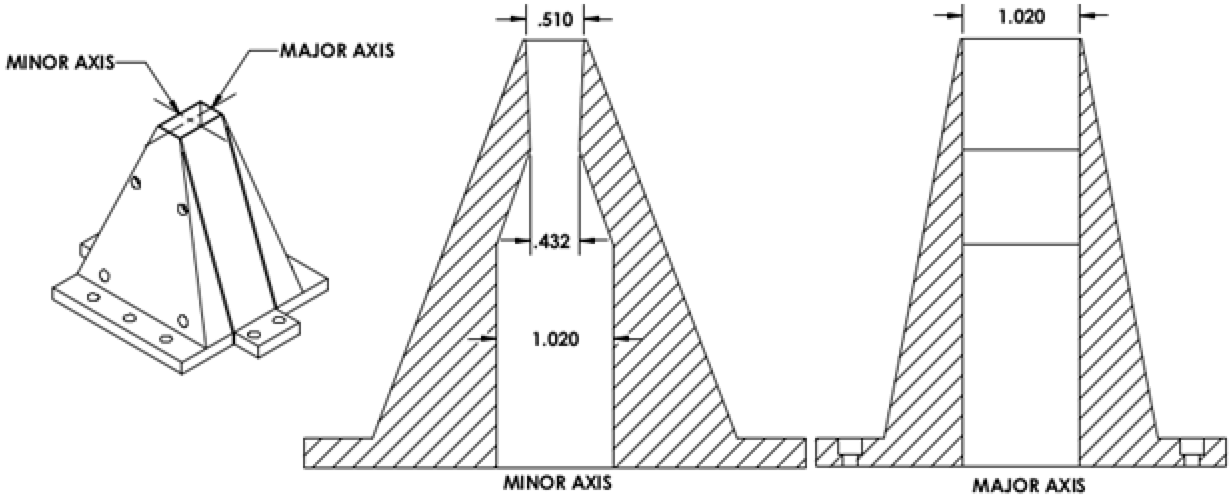
- ☐ Possibility to control the shock structures (e.g., position, strength and dynamics) downstream with using flow control (fluidic injection) → lower jet-noise signature

Semlitsch B., Cuppoletti D., Gutmark, E.J., & Mihaescu M., (2019), *AIAA Journal,* 57(5):1851-1861.

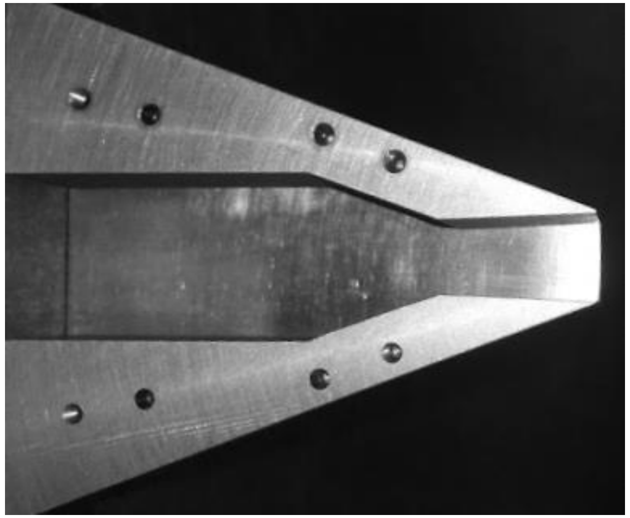
Flow and aeroacoustics of a Supersonic rectangular jet: Temperature effects

- University of Cincinnati rectangular nozzle
    - *Rectangular shape with an aspect ratio 2:1, sharp throat*
    - *Lab scale: height in the minor axis plane is 12.95 mm*
    - *Design Mach 1.5 at NPR 3.67 and TR 1.0*
- Nozzle pressure ratio (*NPR*) and temperature ratio (*TR*)

$$NPR = P_t/P_\infty \qquad TR = T_t/T_\infty$$



Rectangular Nozzle used in the experimental set-up at Univ. of Cincinnati

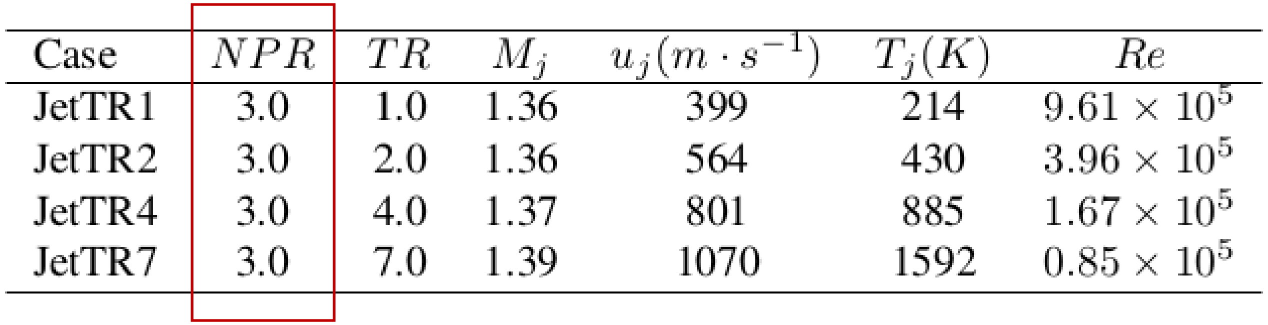


Mora, P., Baier, F., Kailasanath, K., & Gutmark, E. J., Acoustics from a rectangular supersonic nozzle exhausting over a flat surface, JASA, 140(6), 4130-4141, (2016).

Courtesy of Prof. Ephraim Gutmark, the Gas Dynamic and Propulsion Lab, University of Cincinnati, USA

Operating conditions for the supersonic rectangular jet

- Effects of temperature ratio (TR)
  - *Nozzle pressure ratio (NPR) 3.0 → over-expanded*
  - *Nozzle temperature ratio (TR) 1.0, 2.0, 4.0, 7.0 → Max* T_t *~ 2100 K*
  - *Air dissociation → air properties change (e.g. gamma)*
  - *Ideally expanded Mach number* M_j *and velocity* u_j *increase with TR*
  - *Reynolds number → one order of magnitude decrease*



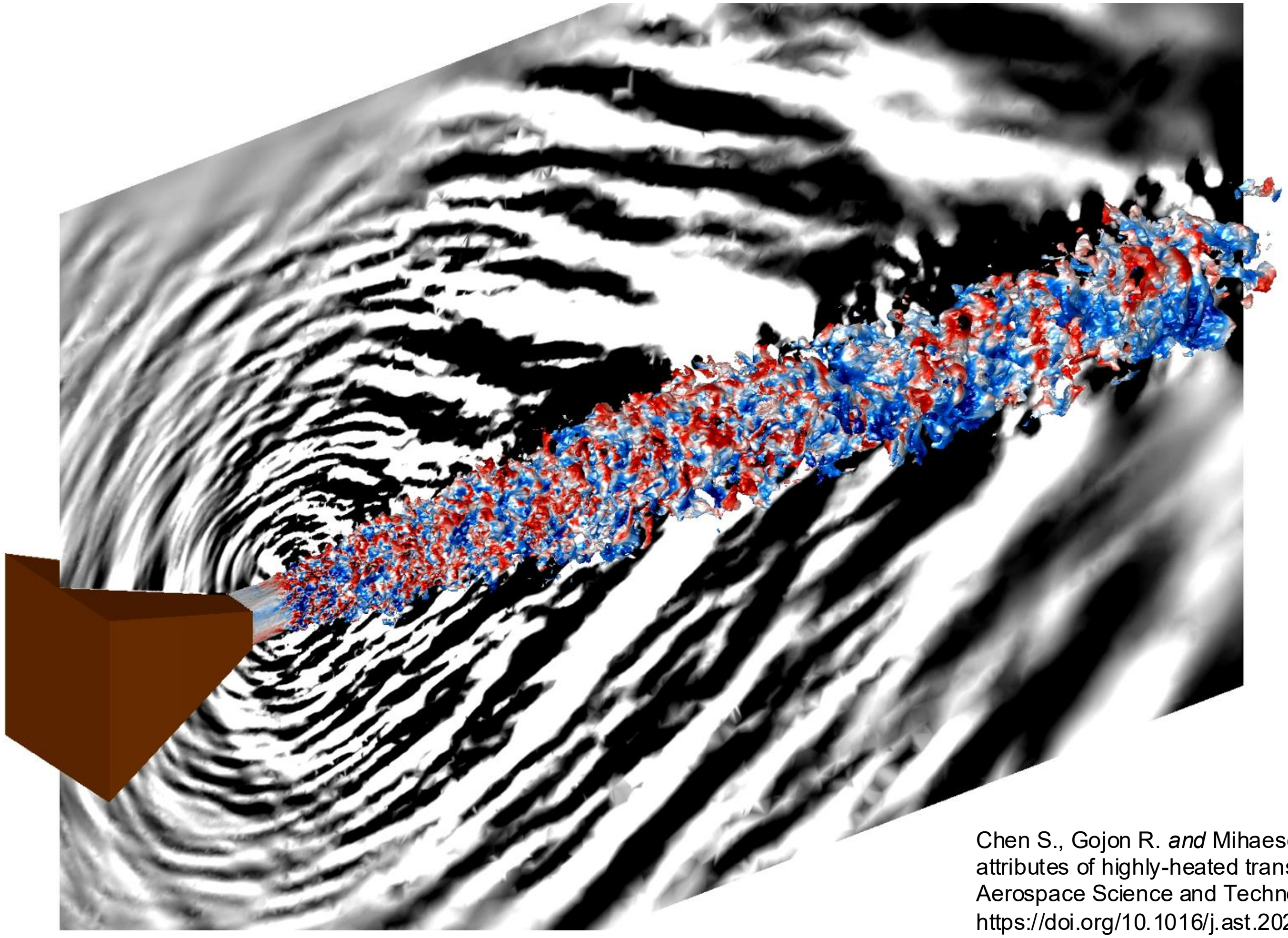
Case	NPR	TR	M_j	$u_j(m \cdot s^{-1})$	$T_j(K)$	Re
JetTR1	3.0	1.0	1.36	399	214	9.61×10^5
JetTR2	3.0	2.0	1.36	564	430	3.96×10^5
JetTR4	3.0	4.0	1.37	801	885	1.67×10^5
JetTR7	3.0	7.0	1.39	1070	1592	0.85×10^5

$$Re = \frac{\rho u_j D_{eq}}{\mu} = \frac{u_j D_{eq}}{\upsilon}$$

Chen S., Gojon R. *and* Mihaescu M. (2021) Flow and aeroacoustic attributes of highly-heated transitional rectangular supersonic jets, Aerospace Science and Technology, 114, https://doi.org/10.1016/j.ast.2021.106747.

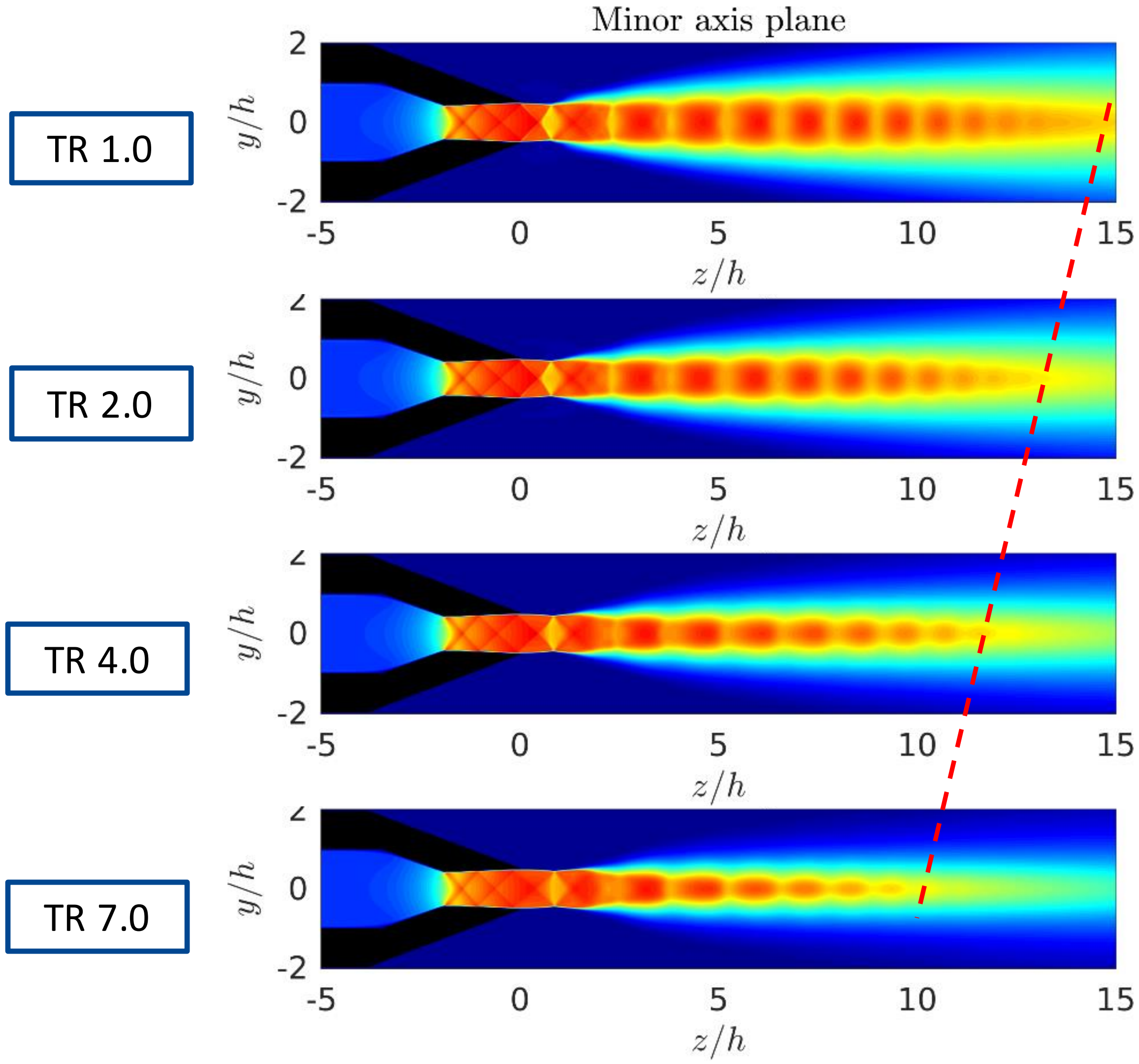
Dynamics of the highly-heated jet: TR 7.0

3-D: isosurfaces of density + acoustic



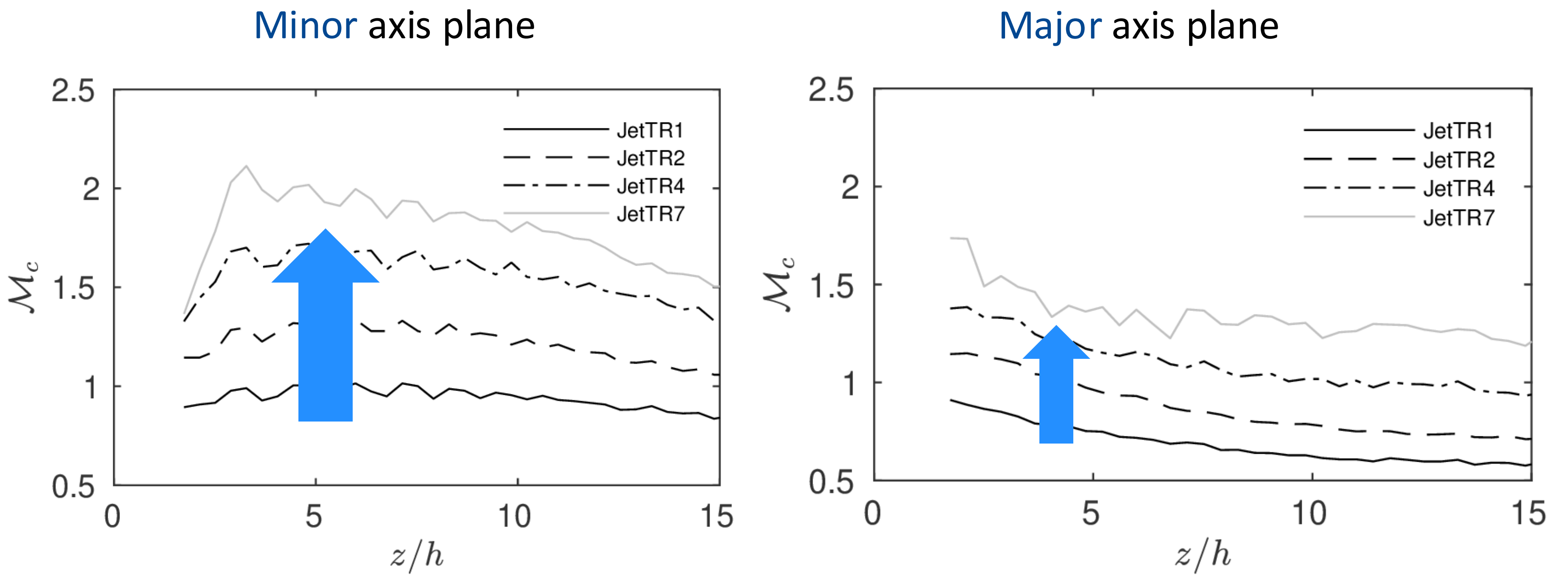
Chen S., Gojon R. *and* Mihaescu M. (2021) Flow and aeroacoustic attributes of highly-heated transitional rectangular supersonic jets, Aerospace Science and Technology, 114, https://doi.org/10.1016/j.ast.2021.106747.

Time-averaged normalized axial velocity (NPR=3)



Chen S., Gojon R. *and* Mihaescu M. (2021) Flow and aeroacoustic attributes of highly-heated transitional rectangular supersonic jets, Aerospace Science and Technology, 114, https://doi.org/10.1016/j.ast.2021.106747.

Jet shear layer: convection Mach number



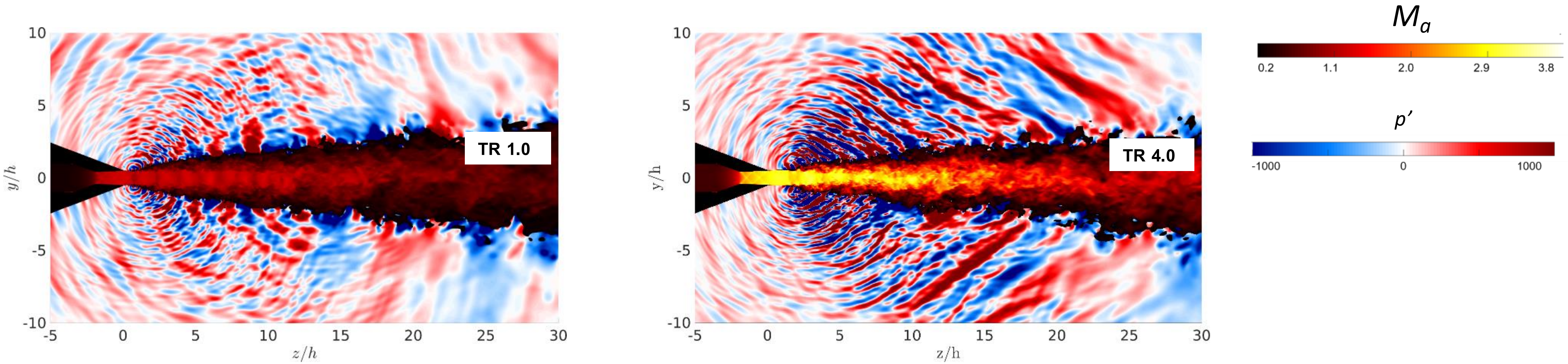
Averaged convection Mach number (U_c / c_o)

Subsonic → supersonic

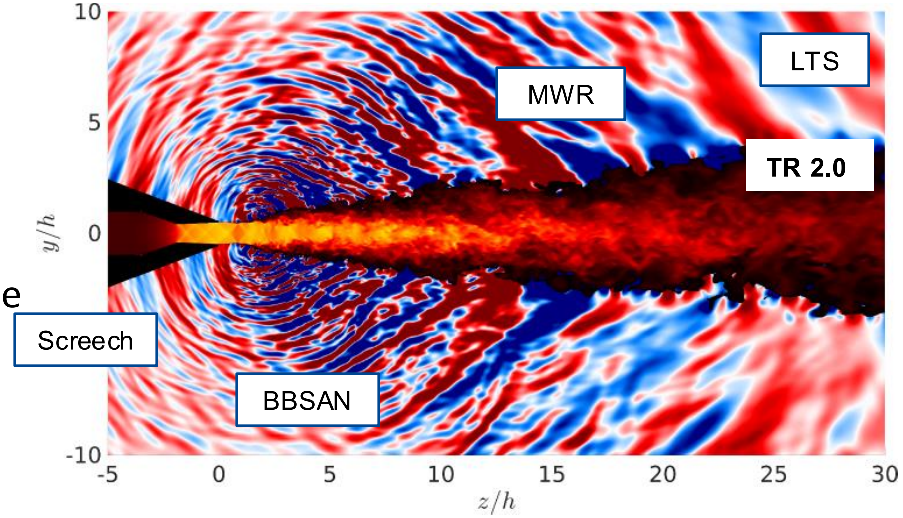
0.95(TR1) → 1.24(TR2) → 1.6(TR4) → 1.88(TR7)

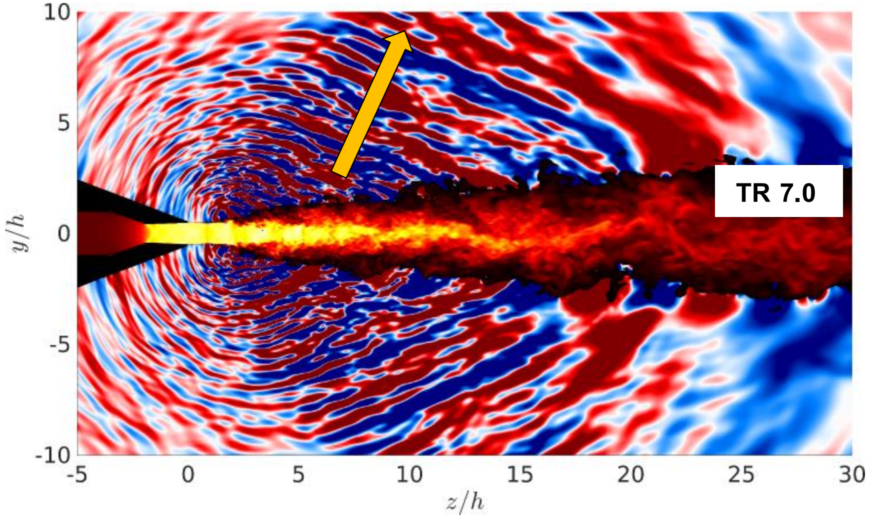
The increasing temperatures result in supersonic shear-layer convection Mach numbers and consequently Mach Wave Radiation (MWR) in far-field.

Instantaneous near field acoustics: M_a & pressure fluctuation



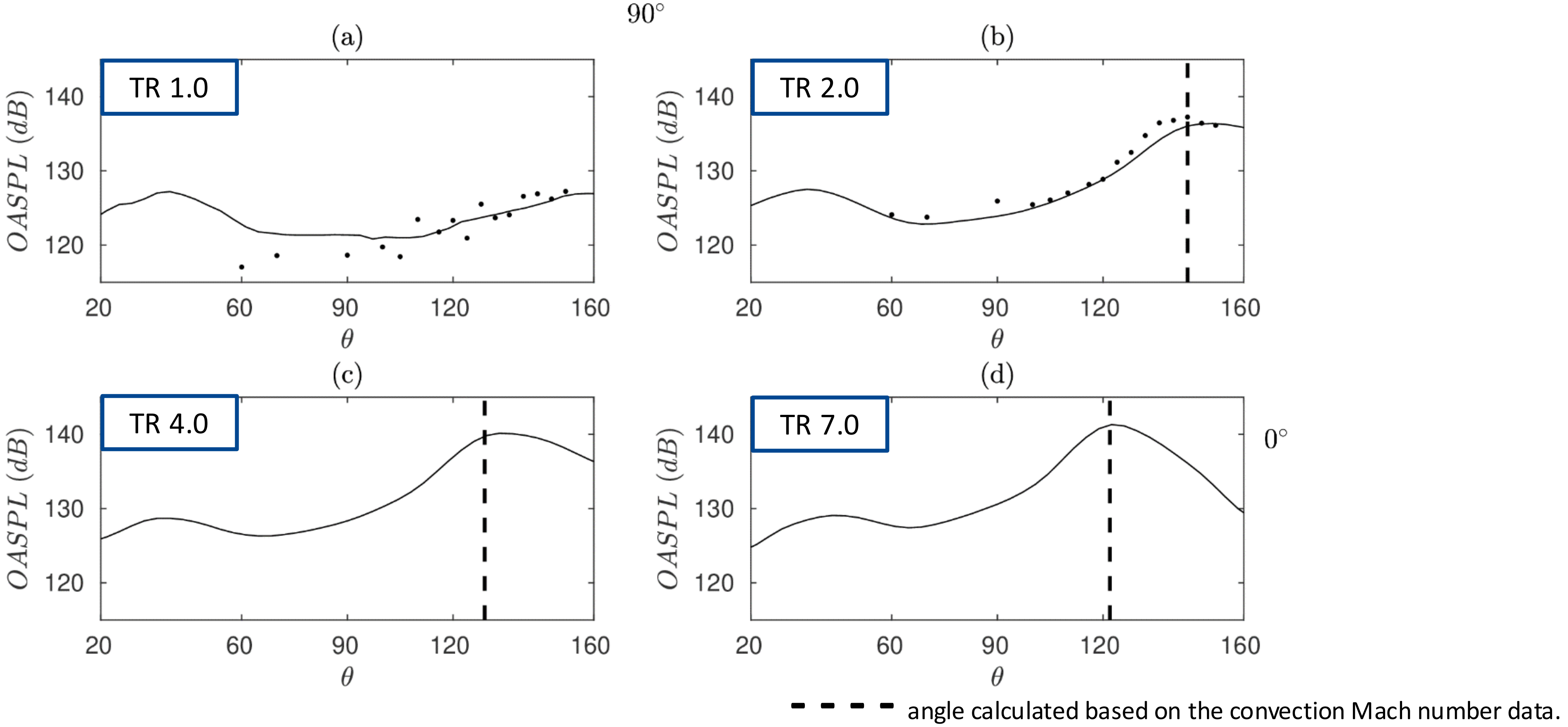
- Large turbulent structure (LTS) noise (mixing noise)
- Mach wave radiation (MWR)
- Screech tones
- Broadband shock associate noise (BBSAN)





Chen S., Gojon R. *and* Mihaescu M. (2021). Aerospace Science and Technology, 114, https://doi.org/10.1016/j.ast.2021.106747.

Far field OASPL: FW-H eq.



angle calculated based on the convection Mach number data.

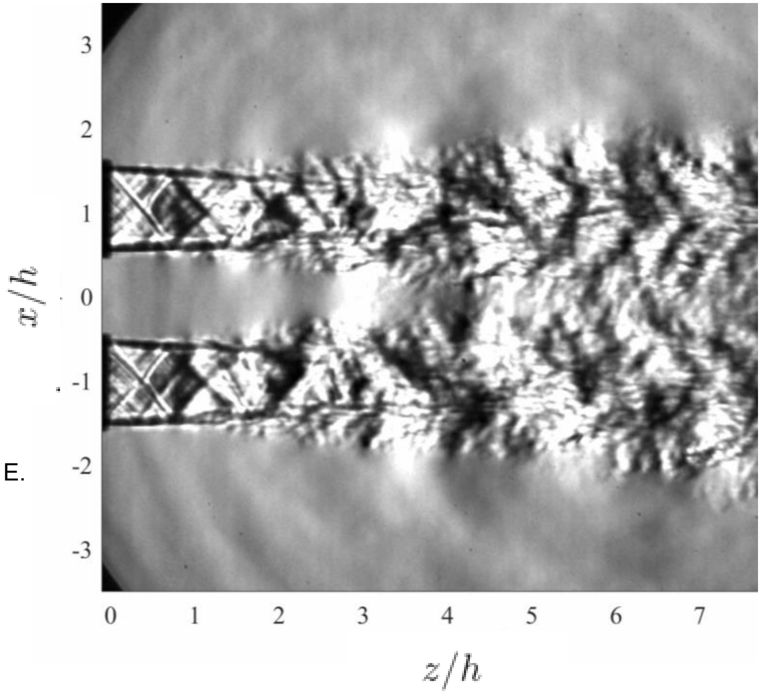
Chen S., Gojon R. *and* Mihaescu M. (2021). Aerospace Science and Technology, 114, https://doi.org/10.1016/j.ast.2021.106747.

Experimental data courtesy of Prof. Ephraim Gutmark, University of Cincinnati

Flow and Aeroacoustics of Twin Supersonic square jets

- Twin nozzles to generate thrust for civil / military aircrafts
- Rectangular/square twin nozzles can have a simplified airframe integration and thrust vectoring ability
- Operated at non-ideal conditions: generation of a shock cell structure
- Understand coupling motion of the twin jets for flow control

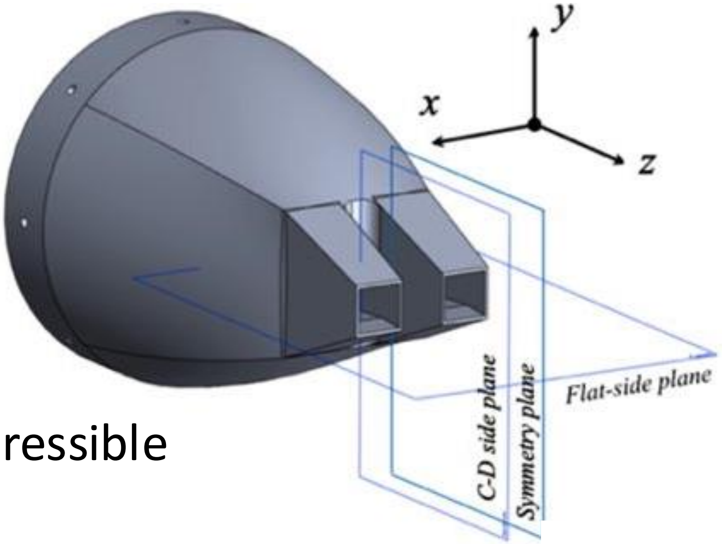
Rolls-Royce/Snecma Olympus 593
https://www.reddit.com/



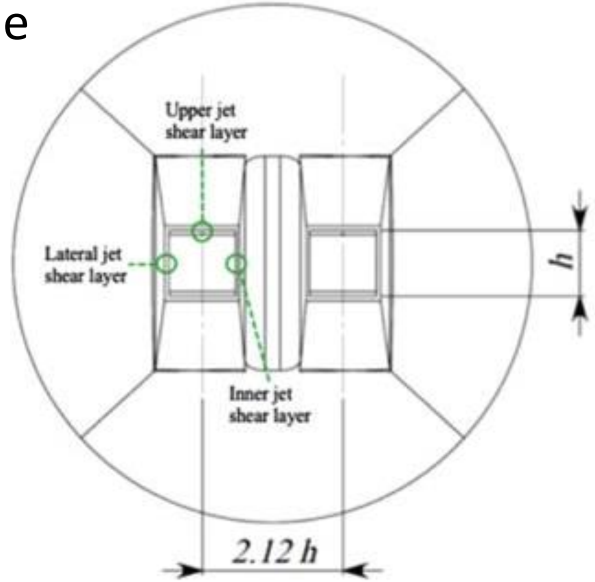
Karnam A, Ahn M, Mihaescu M, Saleem M, Gutmark E. Insights into instability modes of supersonic square jets. *Journal of Fluid Mechanics*. 2025;1009:A13. doi:10.1017/jfm.2025.101

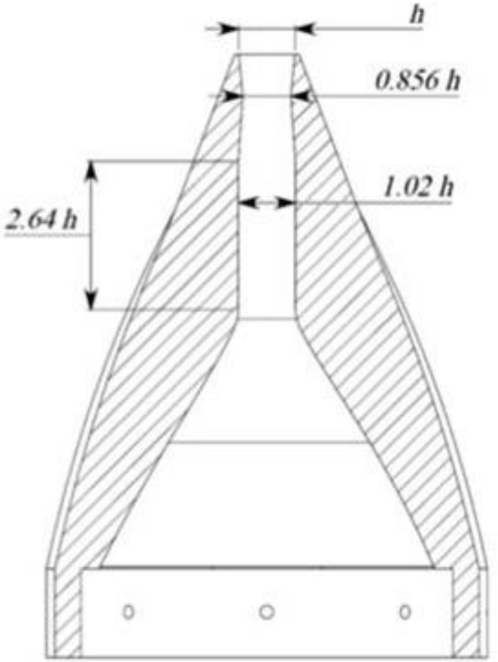
Boom Supersonic
https://www.revolution.aero

Geometry & Numerical Setup



- Twin nozzle, channel height $h = 0.01661\ m$
- Implicit Large Eddy Simulations (**LES**) with finite-volume compressible flow solver M-Edge[1]
  - 2nd-order CD-scheme in space, 4th-order RK in time
  - Viscous flux terms calculated with a 4th-order CD scheme
  - Artificial dissipation to avoid grid-to-grid oscillation[2,3]
- Validated for various supersonic flow configurations, nozzle geometries, and BC[4]
- Boundary conditions: cold case ($TR = 1$), $NPR = 3$
- Characteristic BCs at the surrounding boundaries
- Validation with Schlieren, PIV measurements and acoustic measurements from Univ. of Cincinnati





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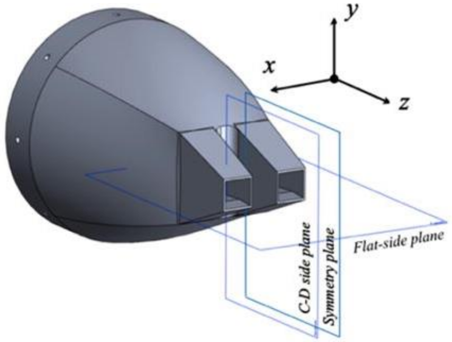
[1] *EDGE, a Navier-Stokes solver for unstructured grids*, Eliasson P., 2001. https://foi.se/rapporter/rapportsammanfattning.html?reportNo=FOI-R--0298--SE

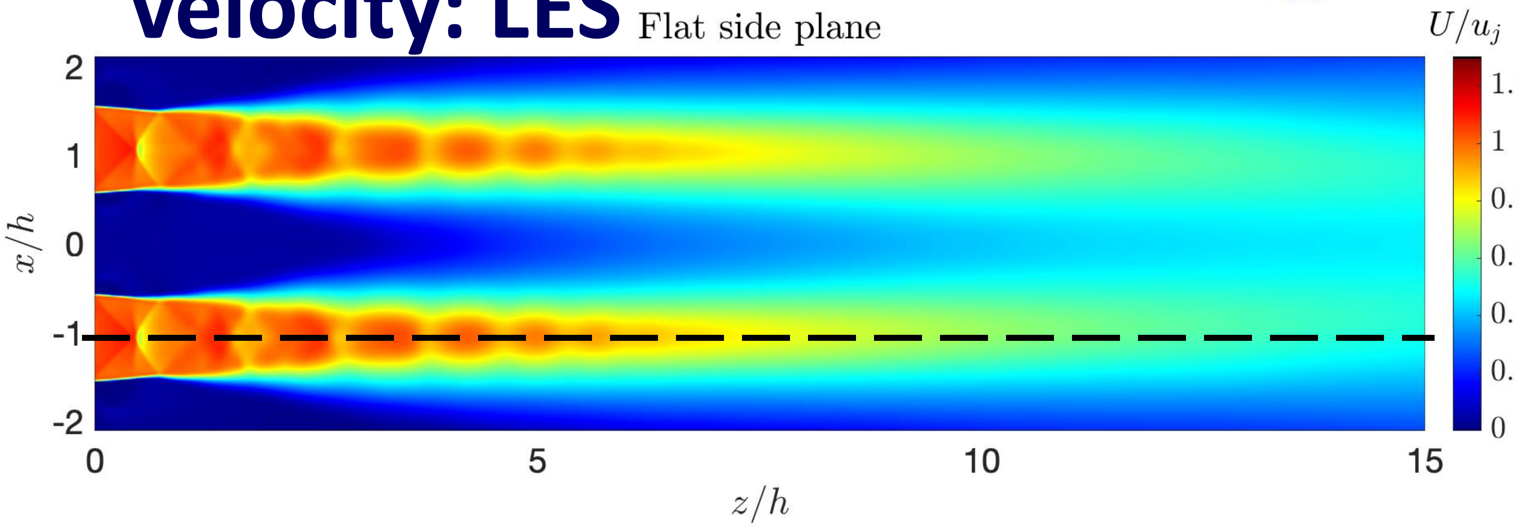
[2] *Temperature effects on the aerodynamic and acoustic fields of a rectangular supersonic jet*, Gojon R., Gutmark E. & Mihaescu M., M. *AIAA Paper* (2017) DOI:10.2514/6.2017-0002.

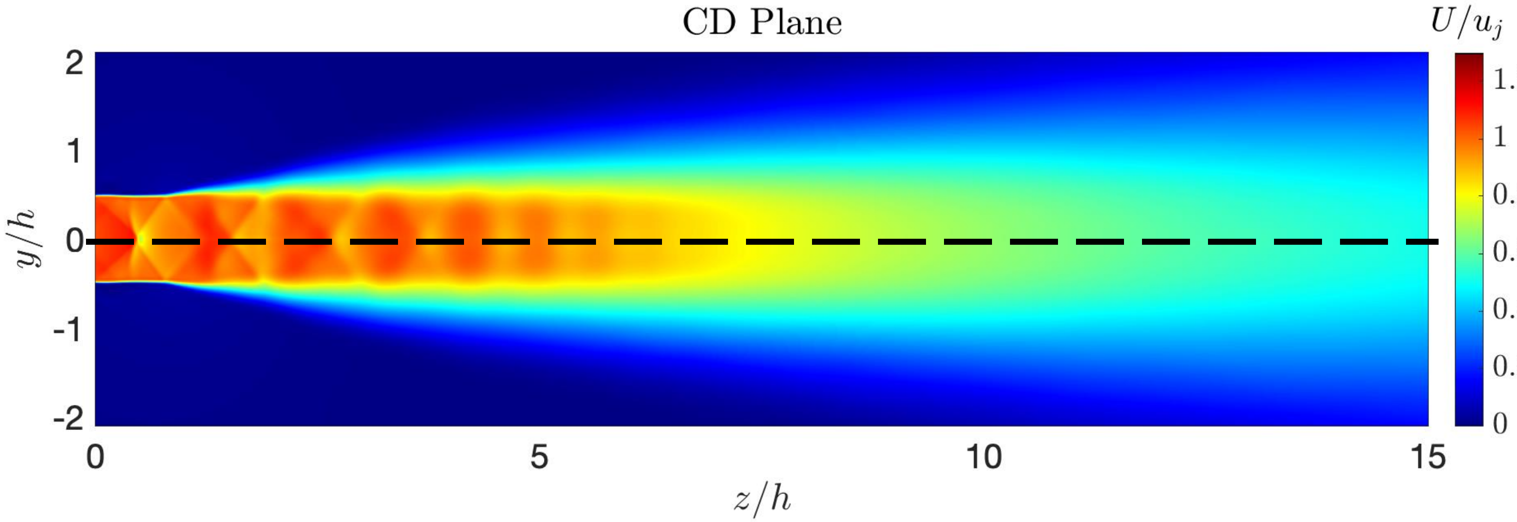
[3] *Large-eddy simulations of flow and aeroacoustics of twin square jets including turbulence tripping*, Ahn M-H., Mihaescu M., Karnam A. & Gutmark E., *Physics of Fluids.* Vol. 35(6) (2023). DOI:10.1063/5.0147295.

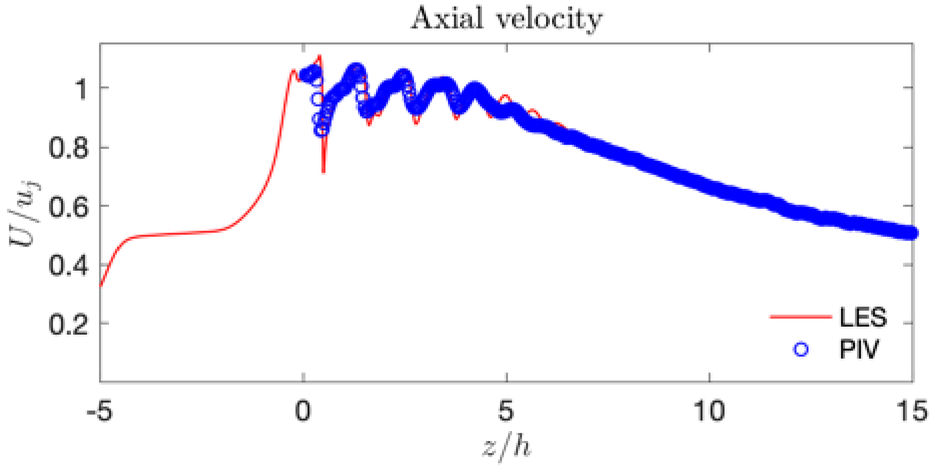
[4] *Transforming the Shock Pattern of Supersonic Jets using fluidic injection*, Semlitsch et al, AIAA Journal, Vol. 57(5), pp.1851-1861, 2019. DOI: 10.2514/1.J057629

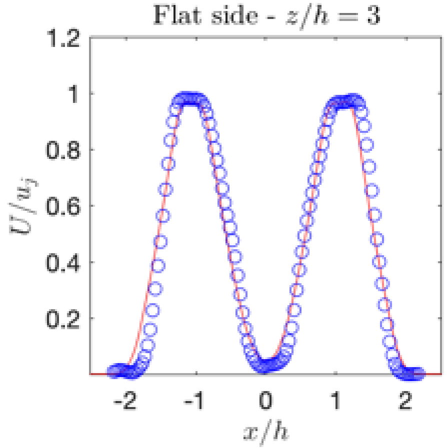
Time-averaged axial velocity: LES

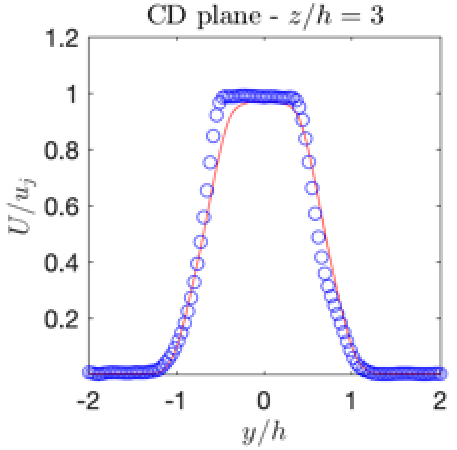


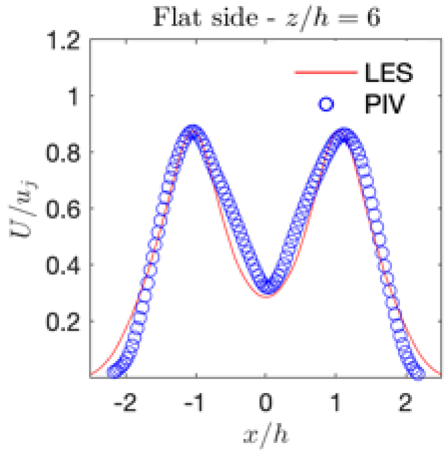


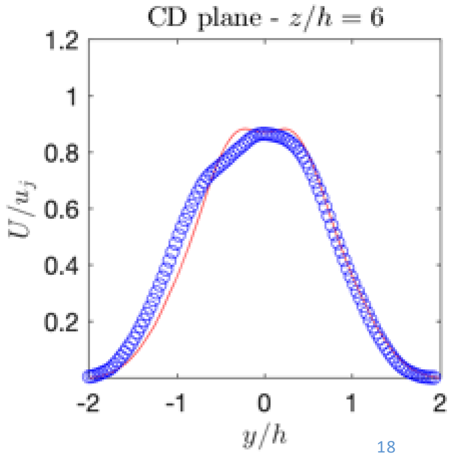




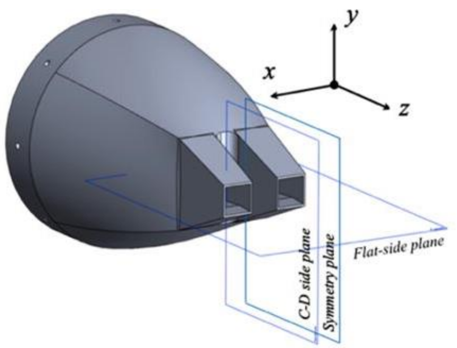


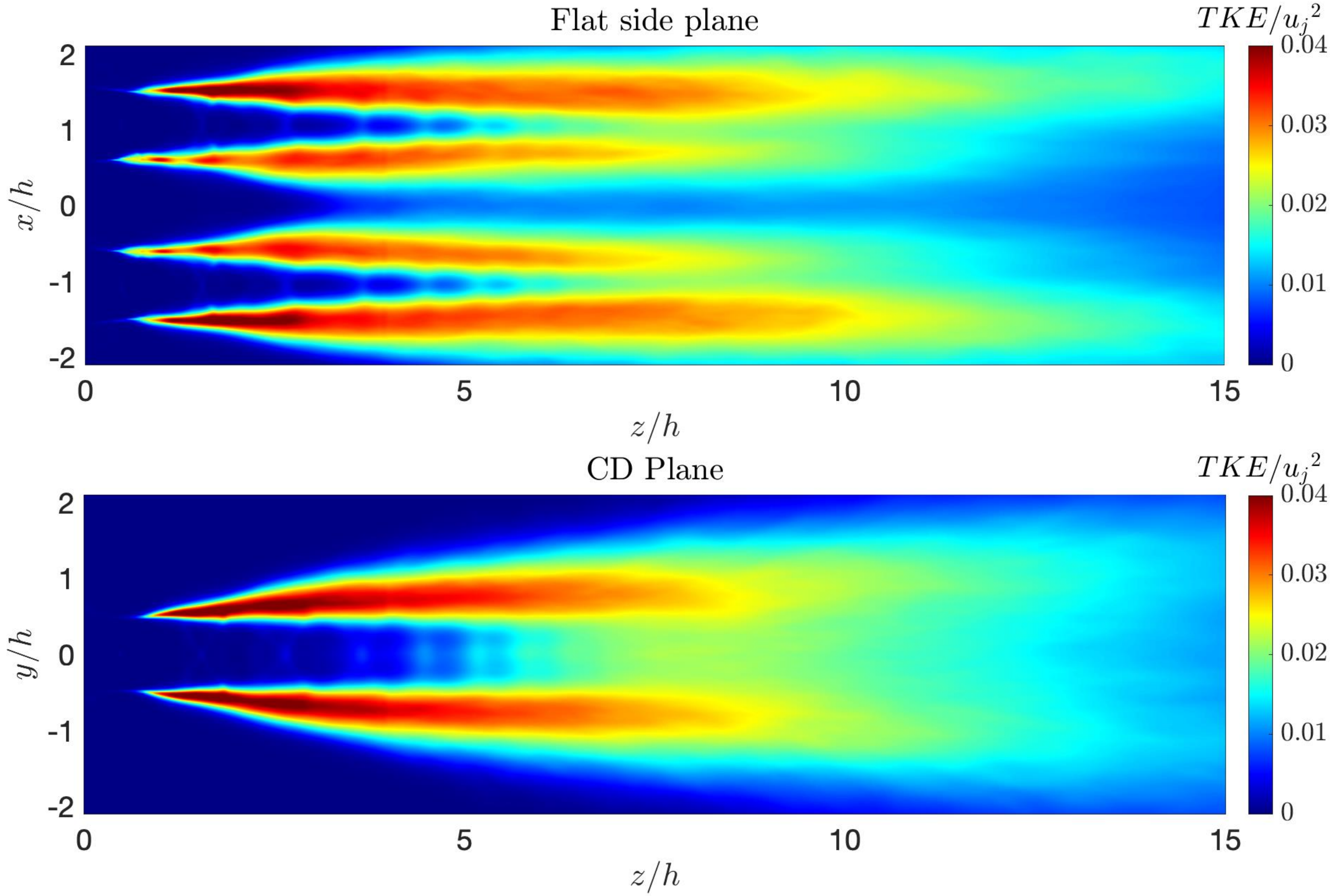


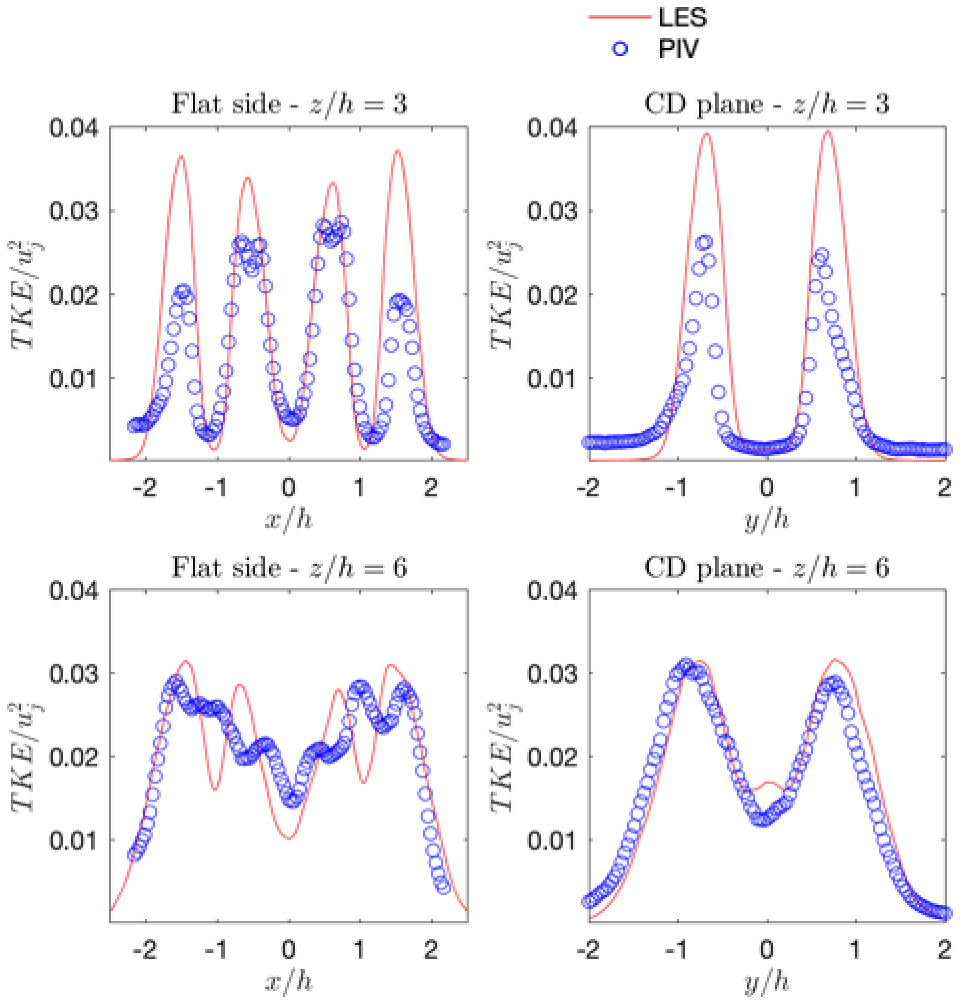




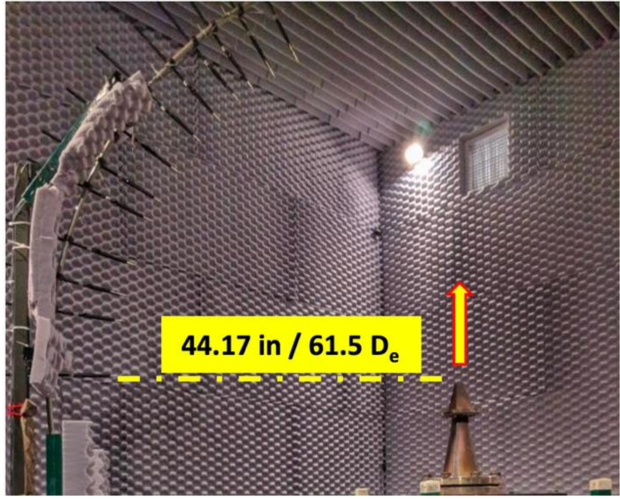
Turbulent kinetic energy: LES



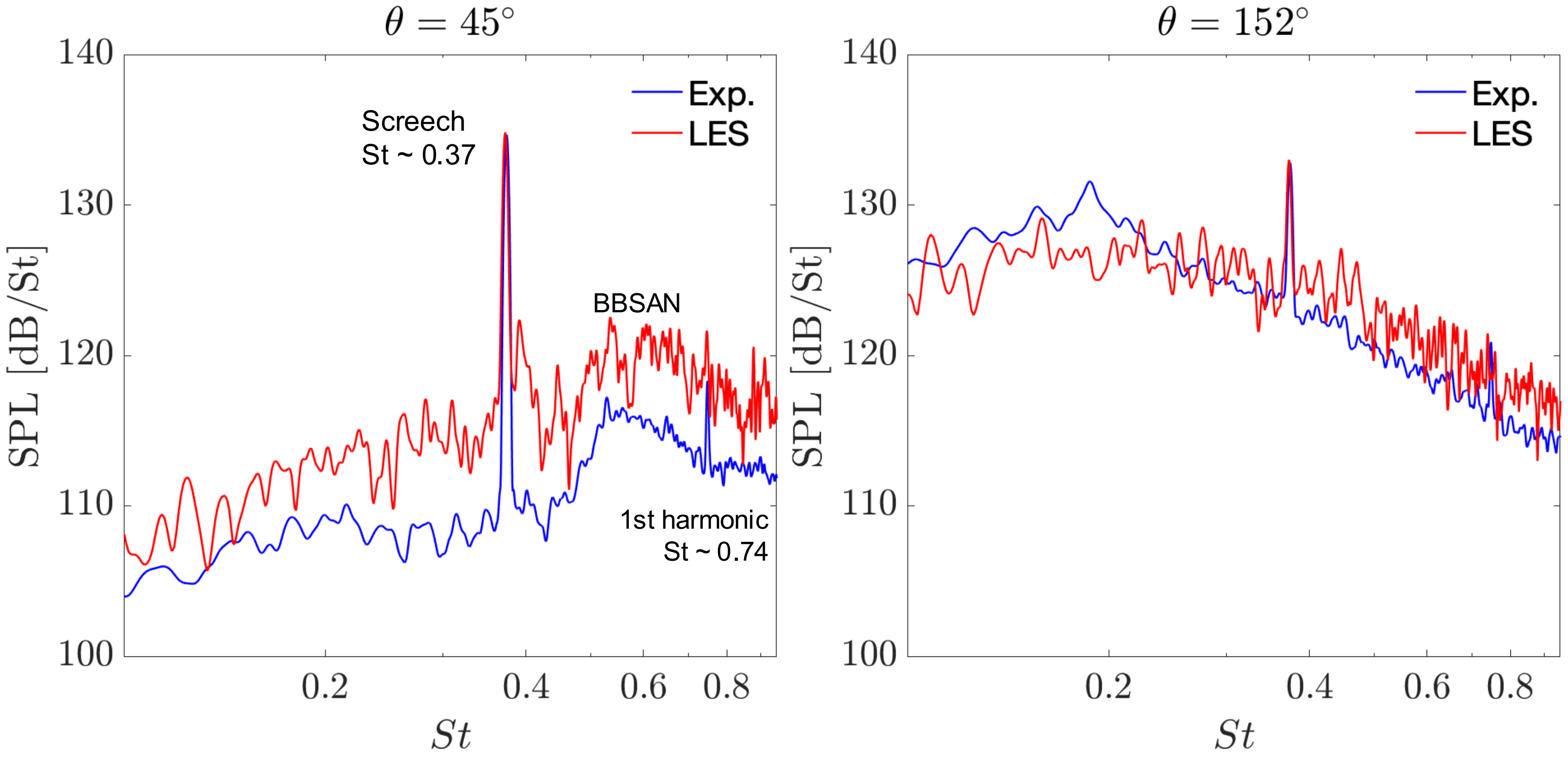


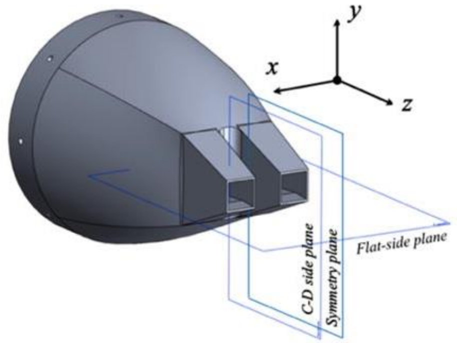


Far-field aeroacoustic signature: Flat side



Solution of the Ffowcs Williams Hawkings (FWH[1]) equation in the far-field at $67.2h$





$$St = fD_e/u_j$$

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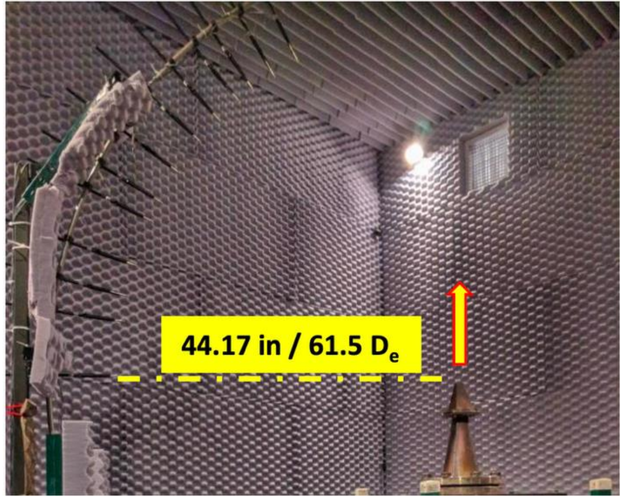
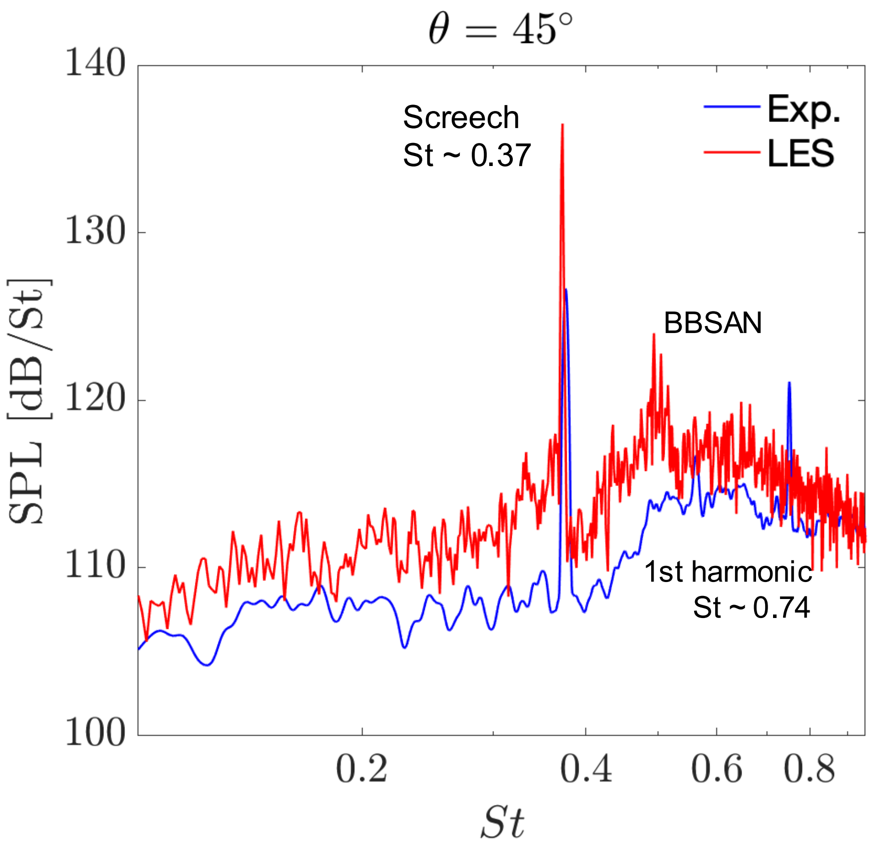
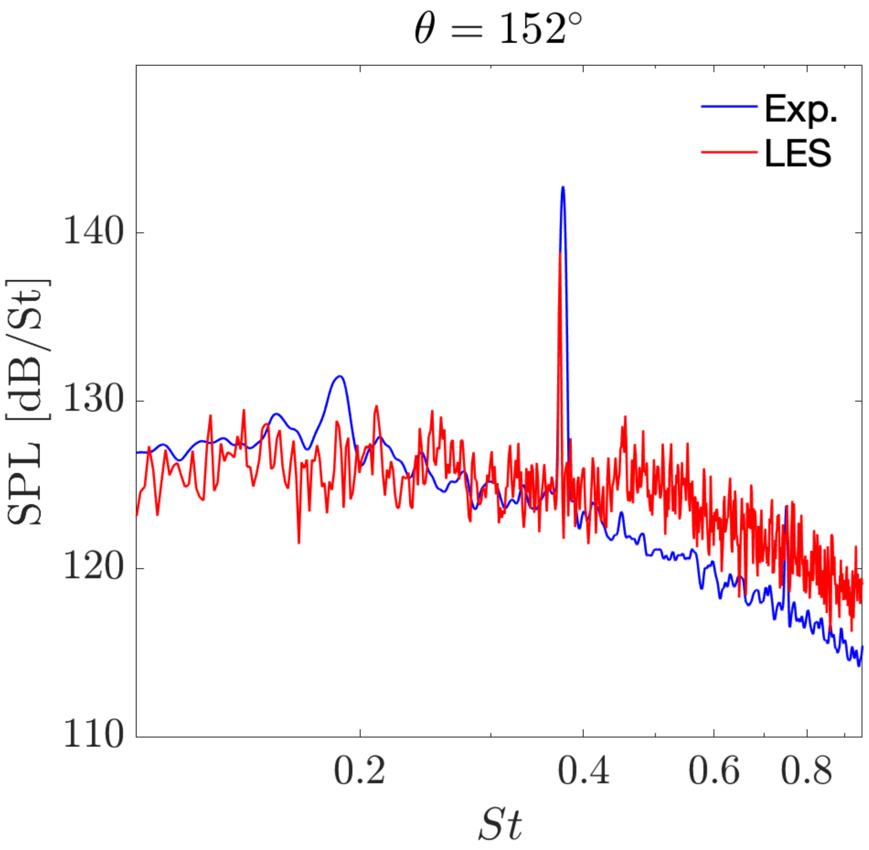
[1] *Sound generated by turbulence and surfaces in arbitrary motion*, Ffowcs Williams J.E. and Hawkings D.L., *Philosophical Transaction of the Royal Society A*, Vol. 264, Issue 1151, 1969. DOI: 10.1098/rsta.1969.0031.

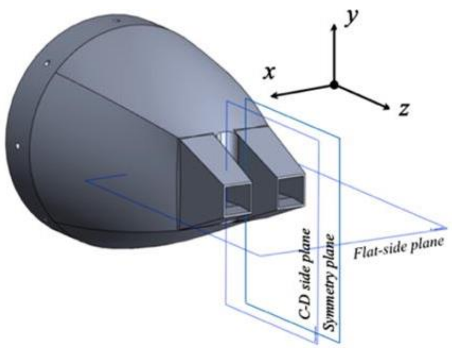


Far-field aeroacoustic signature: Symmetry

Solution of the Ffowcs Williams Hawkings (FWH[1]) equation in the far-field at $67.2h$







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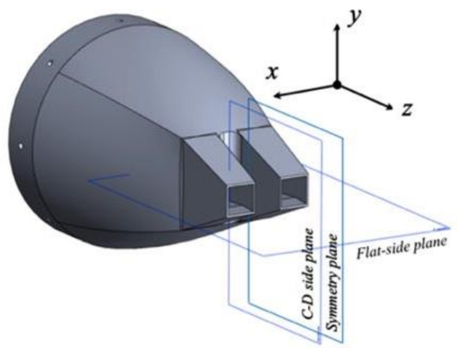
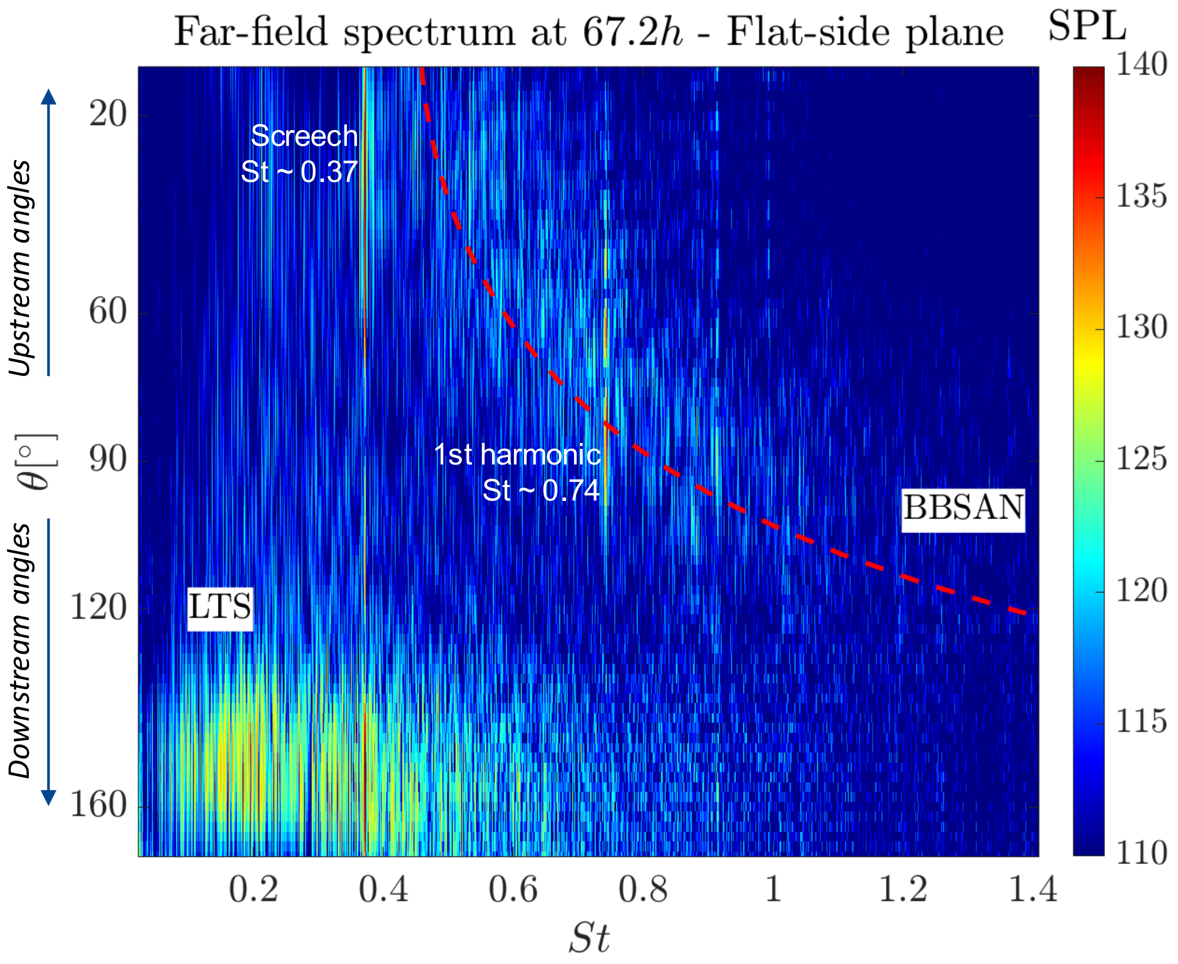
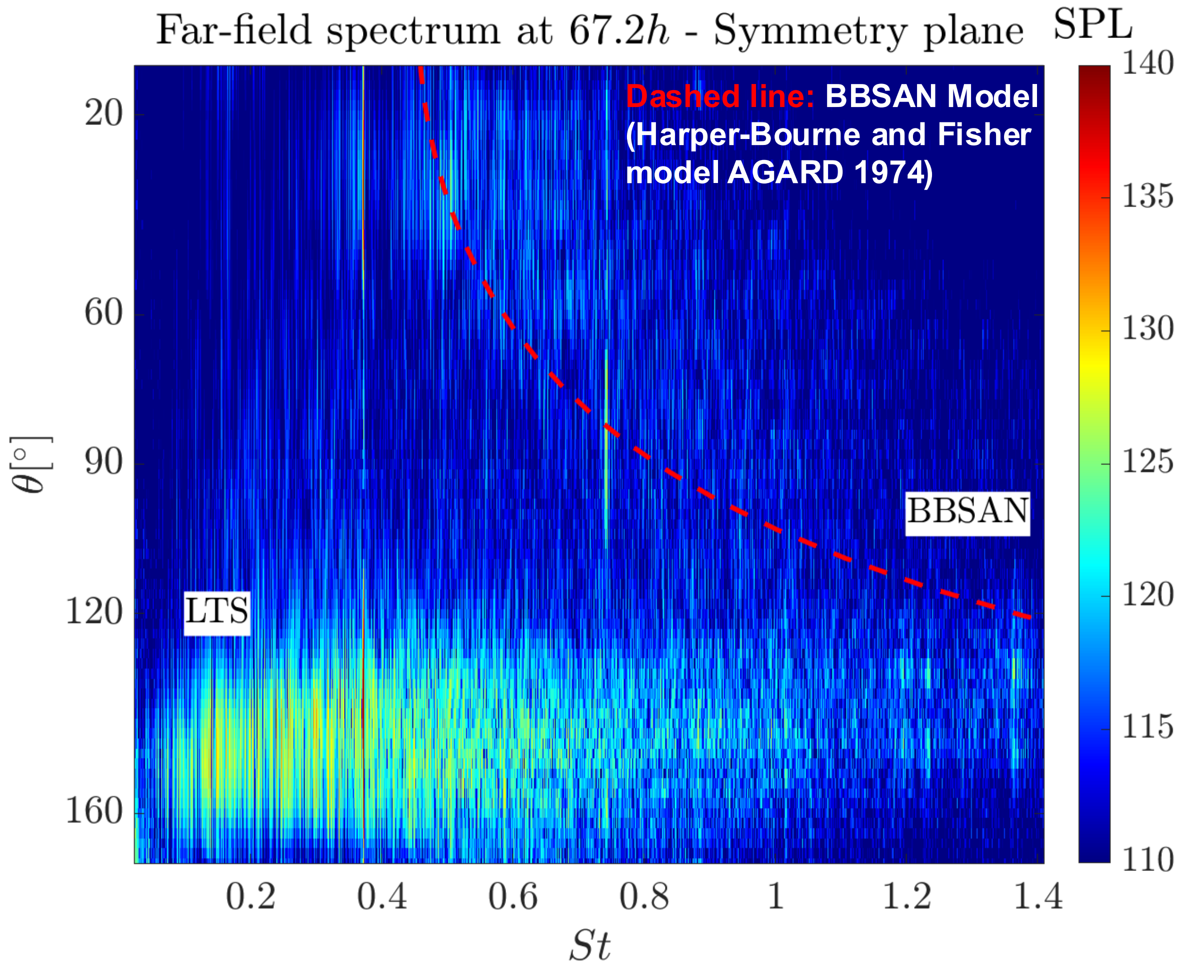


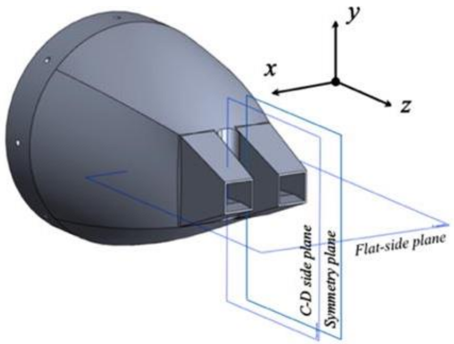
Far-field aeroacoustic signature

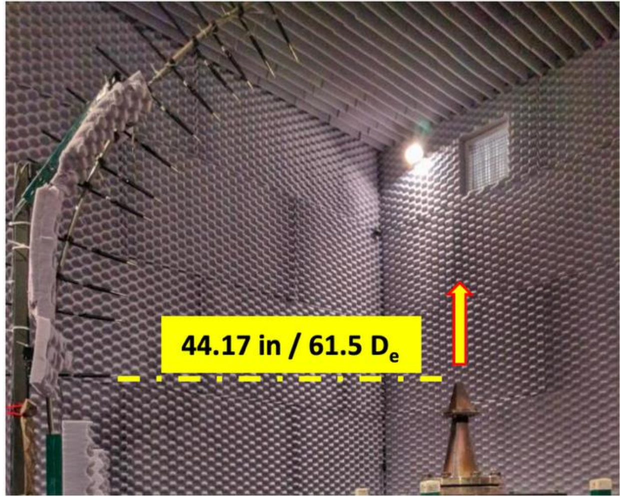

Far-field spectrum at 67.2h - Flat-side plane


Far-field spectrum at 67.2h - Symmetry plane

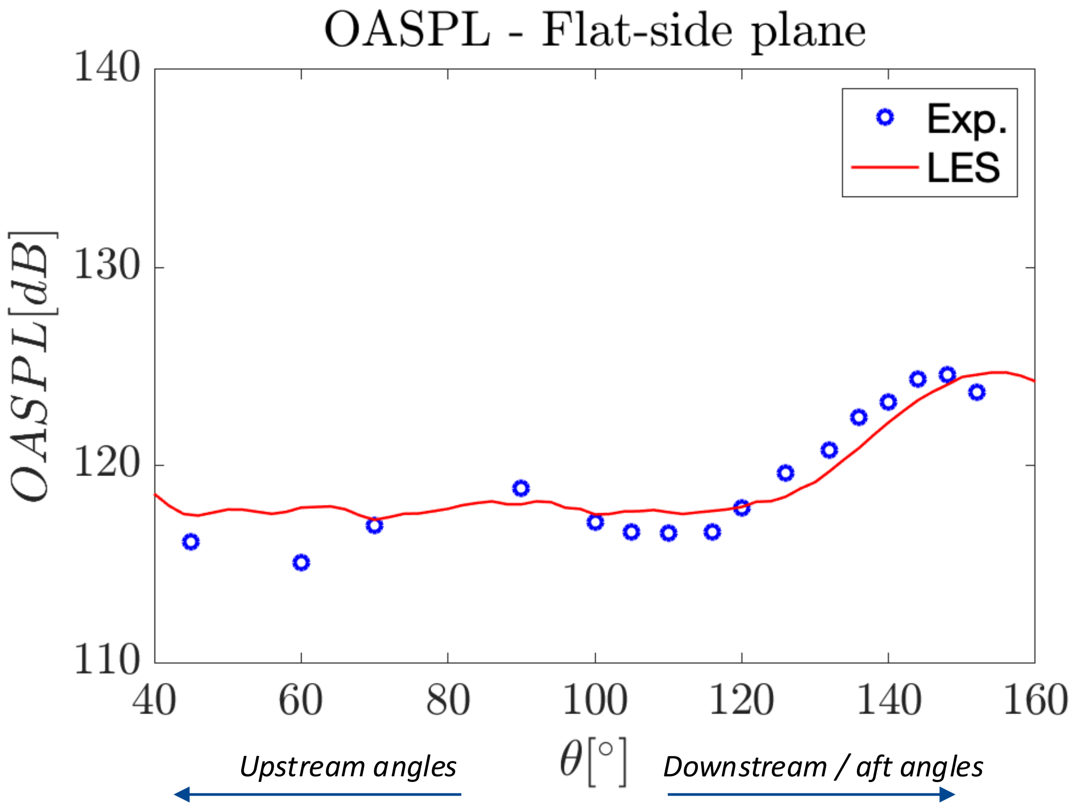
Dashed line: **BBSAN Model (Harper-Bourne and Fisher model AGARD 1974)**

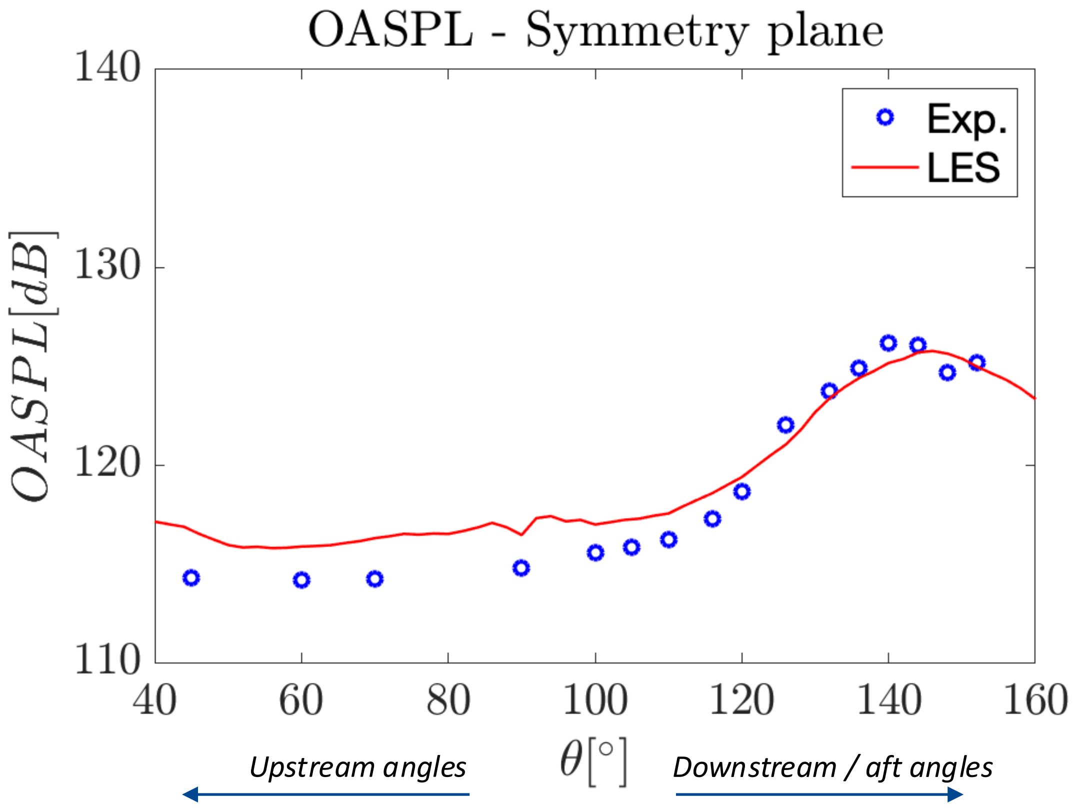
Far-field aeroacoustic signature





Solution of the Ffowcs Williams Hawkings (FWH[1]) equation in the far-field at $67.2h$





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[1] *Sound generated by turbulence and surfaces in arbitrary motion*, Ffowcs Williams J.E. and Hawkings D.L., *Philosophical Transaction of the Royal Society A*, Vol. 264, Issue 1151, 1969. DOI: 10.1098/rsta.1969.0031.

Summary & Outlook

- **LES & CAA** of circular, rectangular, and twin **supersonic jets**.
- **Good agreement with experimental data** in terms of flow fields (PIV), near-field and far-field acoustics (spectra & OASPL).

- **Efficientely addressing** the challenges associated with the **multiscale**, **highly compressible**, and **turbulent** nature of supersonic jet flows, combined with the need to accurately resolve **acoustics** (without excessive numerical damping).
- **Complex physics interplay**, e.g., compressibility effects, shocks and vortex-shock interaction, non-linearities, noise generation & acoustic radiation:
  - Temperature gradients and real gas effects;
  - Nozzle geometry & near-wall treatment, heat transfer, and chemistry (if afterburning).
- **Non-reflective boundary conditions** for acoustic waves.
- Developing **effective and efficient flow control / noise suppression** technologies.
- **Validation**: need for **benchmark experimental data at** high Mach number flows under **realistic temperature** conditions.

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<u>Euro HPC</u>
Leonardo, CINECA, Italy
Atos BullSequana XH2000 computer running Red Hat Enterprise Linux, close to 14 000 Nvidia Ampere GPUs

HPE Cray EX supercomputer, **Dardel @ KTH** (70,912 CPU cores) - Dec. 2021

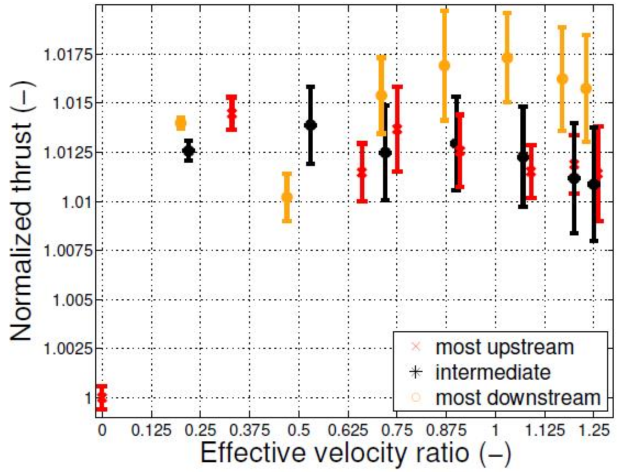
Appendix

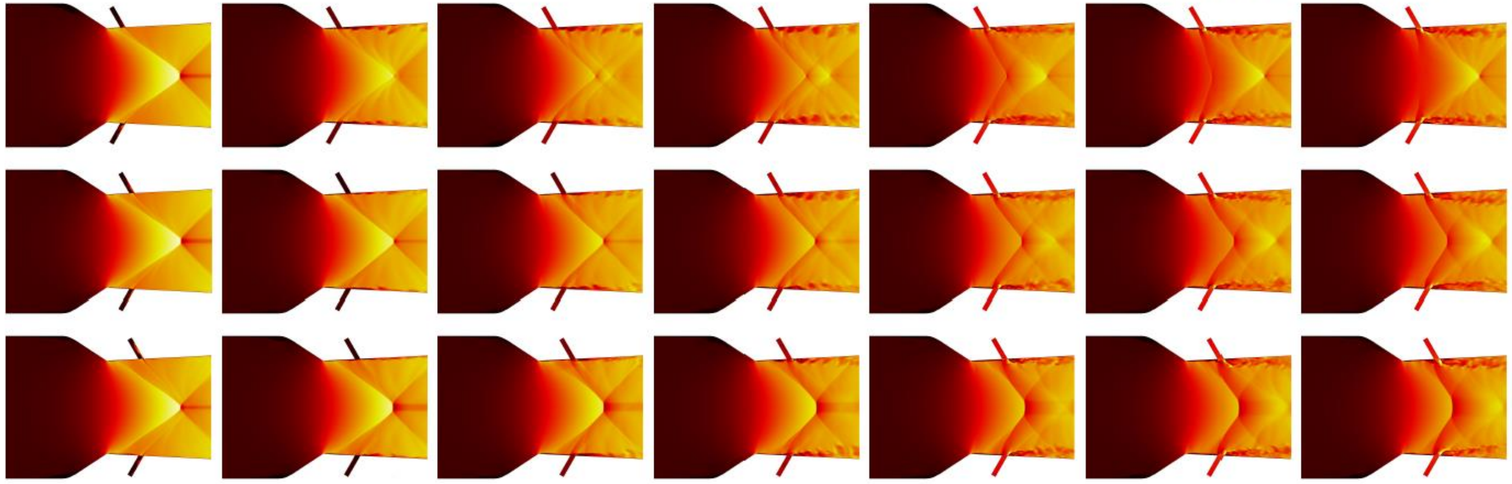
External fluidic injection effects: 12 injectiors at 60°

	IPR 1.8	IPR 2.4	IPR 3.6	IPR 5.5	IPR 6.6	IPR 7.8
$\mathbb{F}/\mathbb{F}_0$	99.7%	99.6%	99.4%	98.9%	98.8%	98.7%
$\dot{m}_j/\dot{m}_{noz}$	1.6%	2.2%	3.6%	5.0%	6.0%	7.1%

Thrust estimations for IPRs

- Increase with injection.
- Variance of thrust increases with injection.





$IPR = 1.0$ $IPR = 1.8$ $IPR = 2.4$ $IPR = 3.0$ $IPR = 4.4$ $IPR = 5.2$ $IPR = 5.6$

Far field pressure spectra

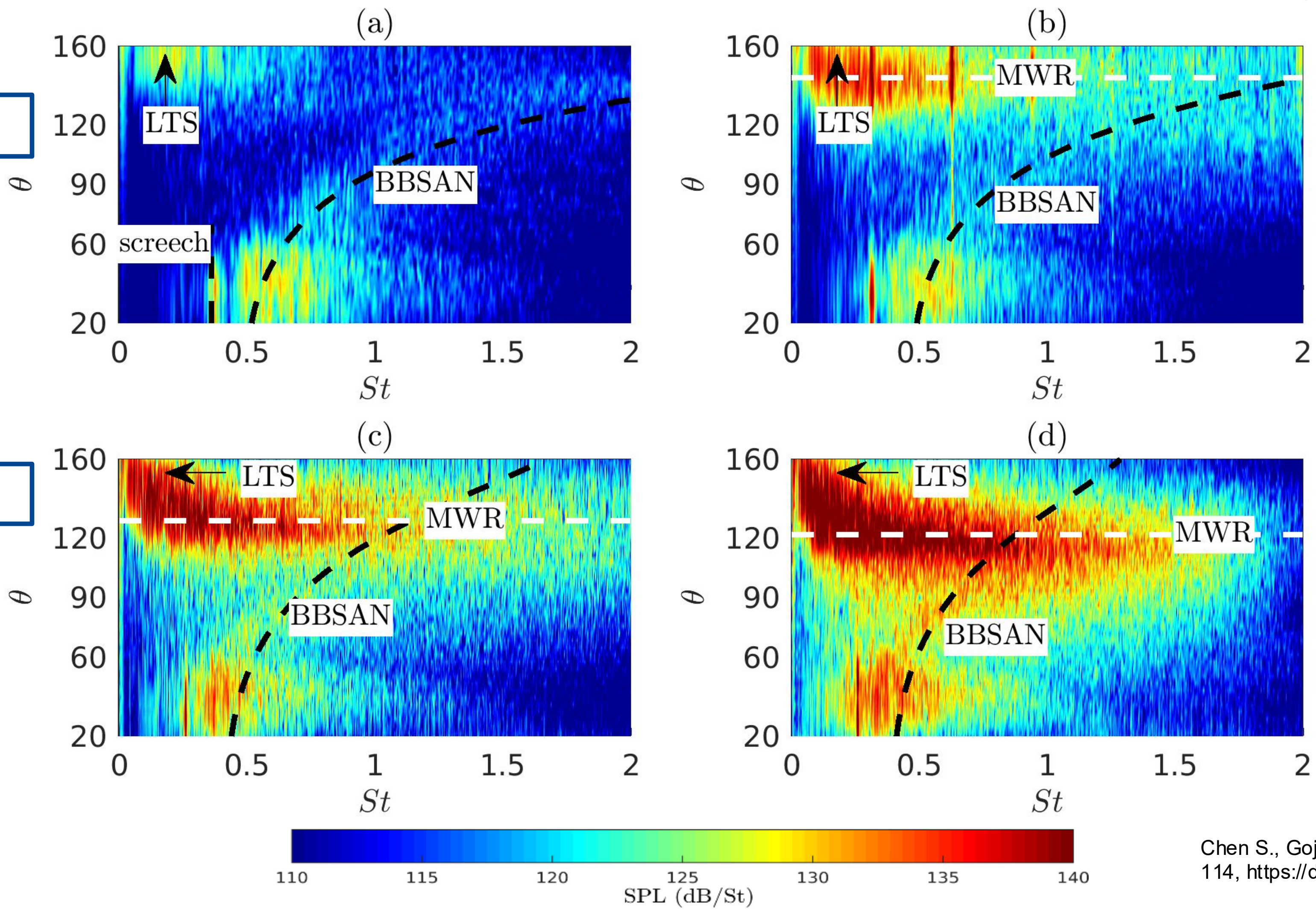
Dashed line: BBSAN Model (Harper-Bourne and Fisher model AGARD 1974)

TR 1.0

TR 2.0

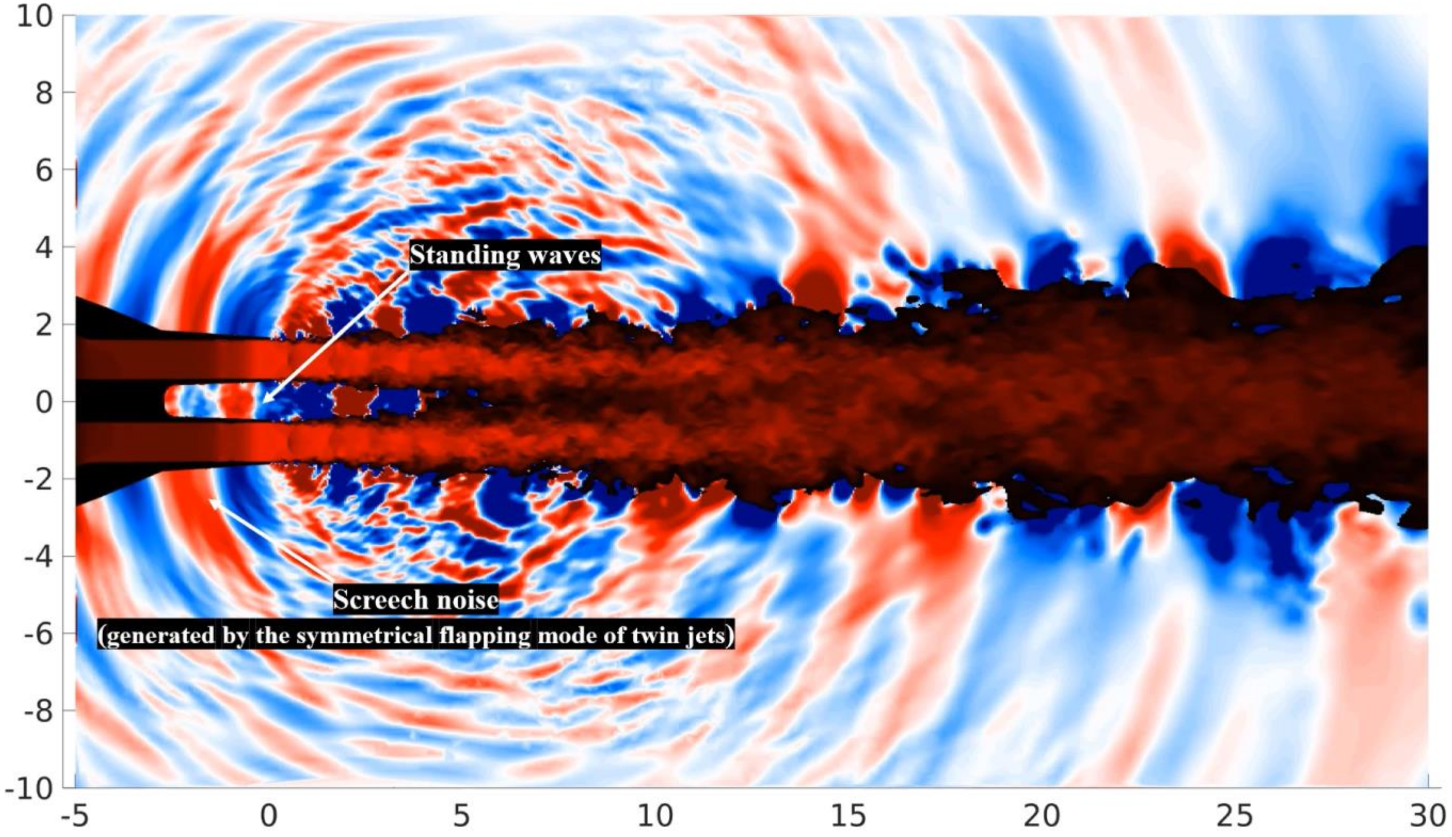
TR 4.0

TR 7.0



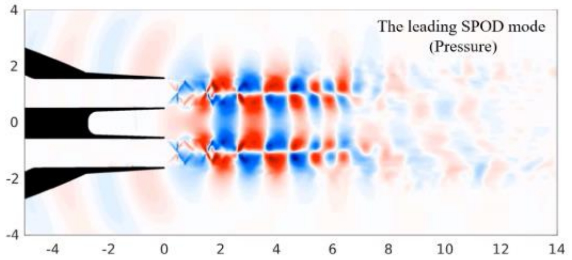
TR 7.0: Mach Wave Radiation is identified radiating noise at about 120 degrees, while the large turbulence structure noise at about 150 degrees.

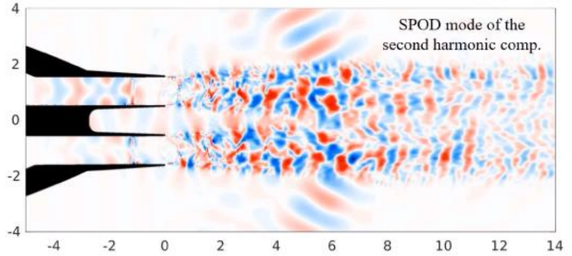
Chen S., Gojon R. *and* Mihaescu M. (2021). Aerospace Science and Technology, 114, https://doi.org/10.1016/j.ast.2021.106747.

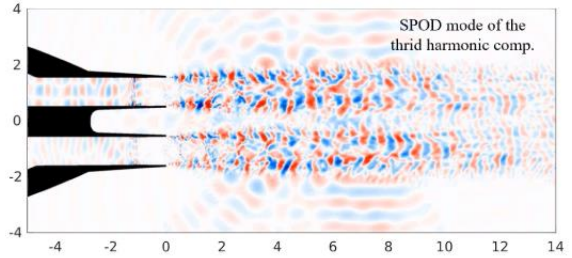


Standing waves

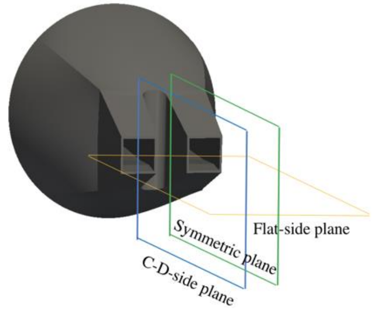
Screech noise
(generated by the symmetrical flapping mode of twin jets)


The leading SPOD mode
(Pressure)

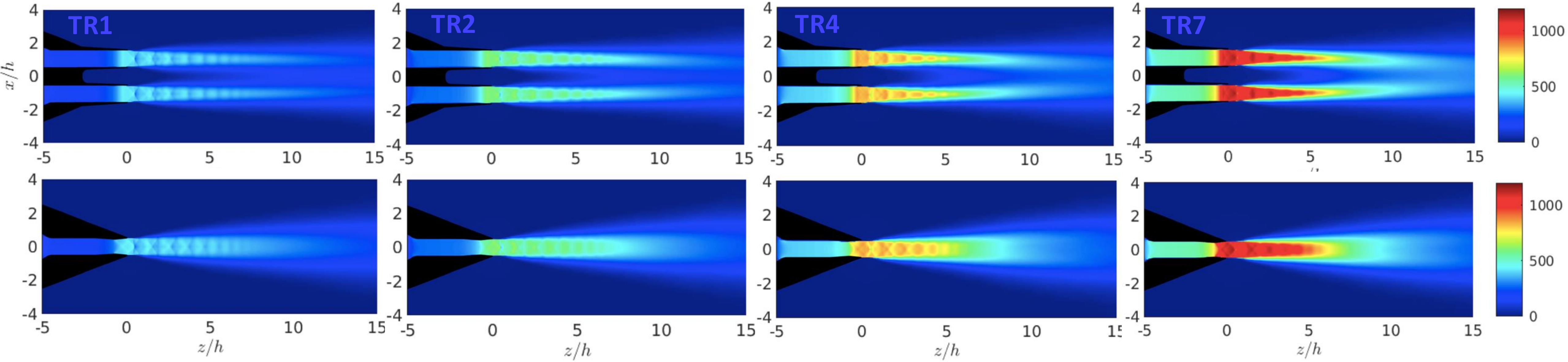

SPOD mode of the
second harmonic comp.

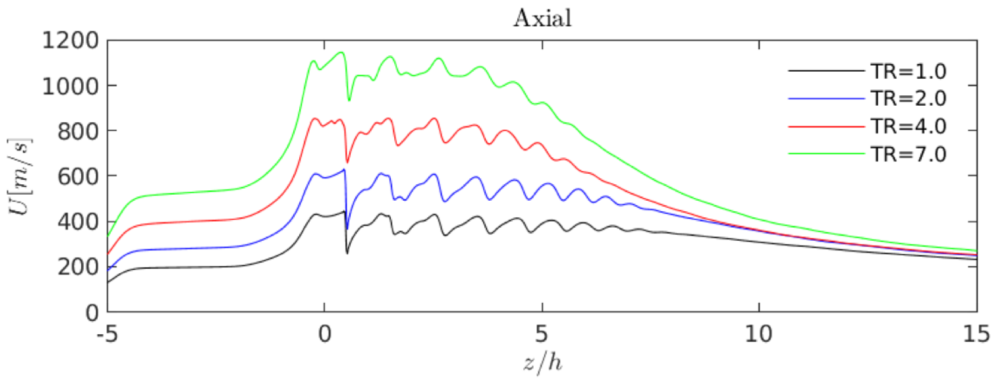

SPOD mode of the
thrid harmonic comp.

Time-averaged Flow Fields

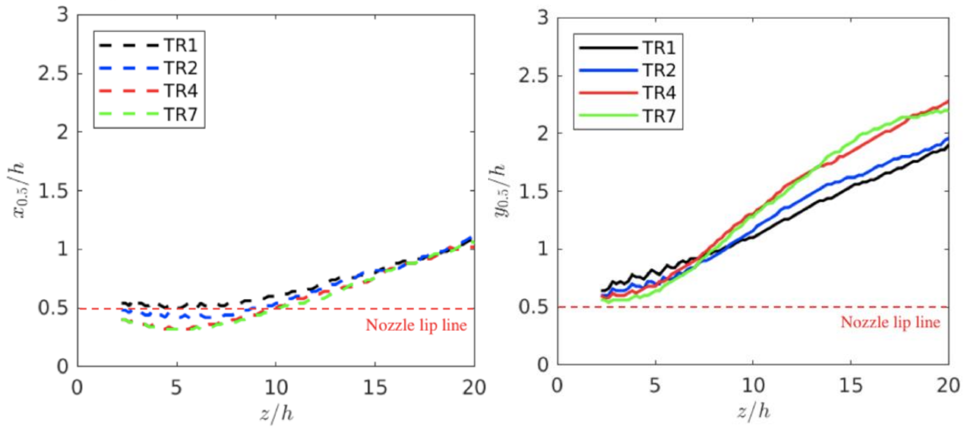


- *Time-averaged axial velocity and jet half velocity width*





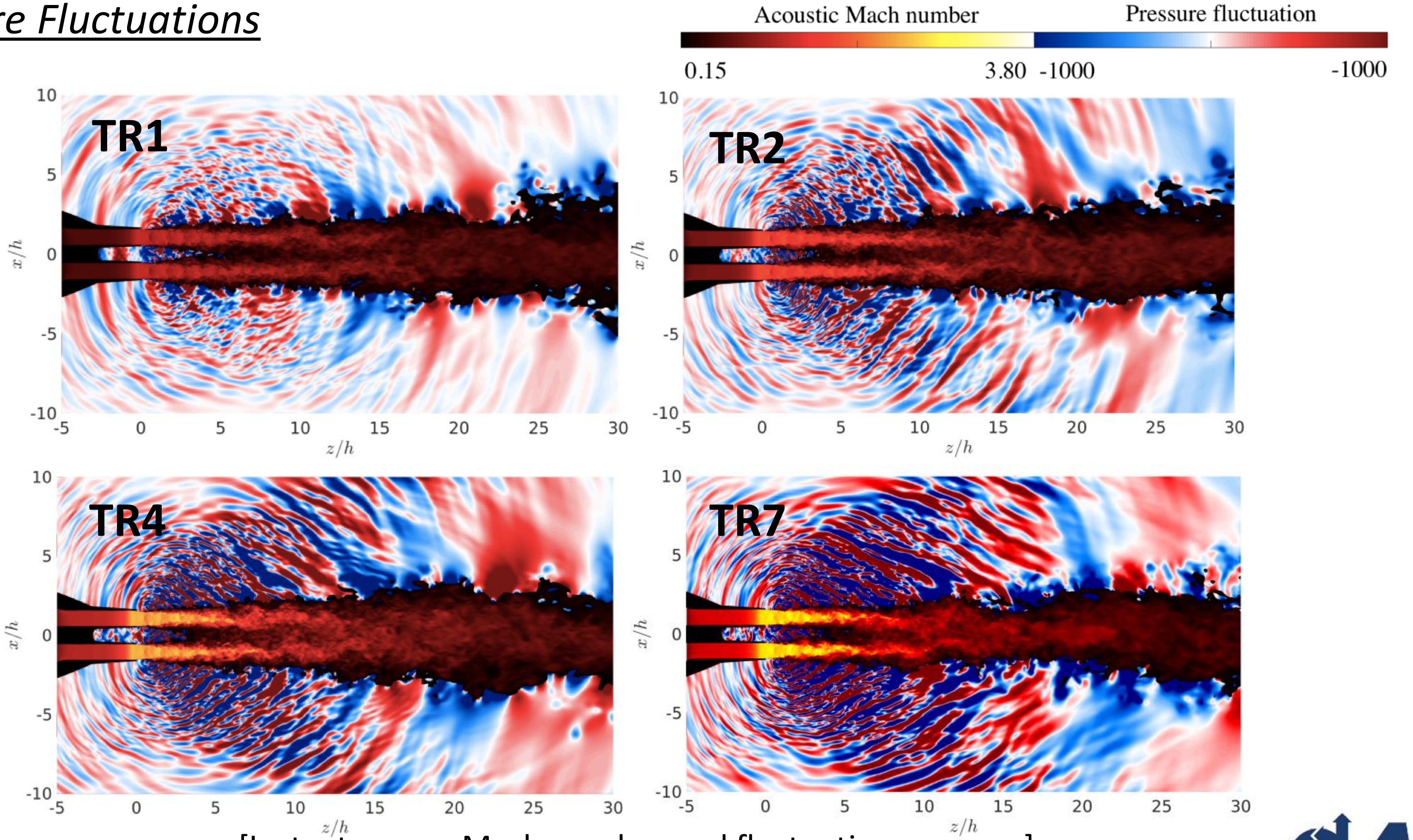
[Axial velocity along jet-center line]



[Jet half velocity along the (left) lateral and (right) upper shear layers]

Near-field Flow and Pressure Fluctuations

- ***Flow and Pressure Fluctuations***



Ahn M., Karnam A., Gutmark E., and M. Mihaescu, “Flow and near-field pressure fluctuations of twin square jets,” AIAA Paper No. 2021-3554, 2021.

[Instantaneous Mach number and fluctuating pressure]