Aerodynamics and Aeroacoustics of Highly-Heated Rectangular Supersonic Jets

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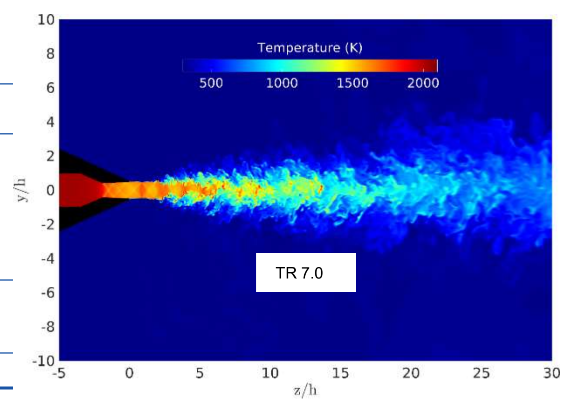
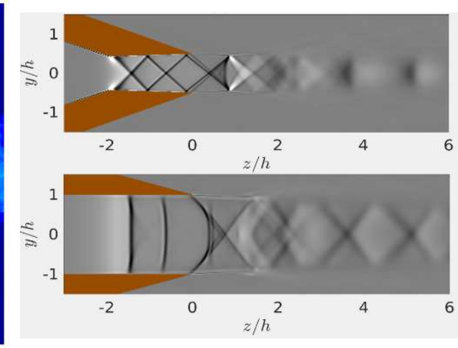




OUTLINE

- Background
- Motivation and Objectives
- Nozzle configuration & Operating conditions
- Numerical Method
  - Method and Computational set-up (LES & FW-H Acoustic Analogy)
  - Verification and Validation
- Temperature effects on near-field flow and far-field acoustics
- Summary and Conclusions
- Outlook

Background

- Supersonic jets & Aerospace applications
- Challenges with new supersonic civil & military aircrafts
  - *Sonic Boom & Supersonic Jet Noise*
  - *Community noise*
- Acoustic radiation is a powerful excitation in the near-field
  - *undesirable stresses on nearby components of the aircraft (take-off / lift-off conditions)*
  - *stressful stimulus for the crew, and those in the runway or carrier deck environment*
- Rectangular shaped nozzles
  - *Tight integration with airframe*
  - *Potential of reducing noise signature (minor-axis)*
  - *Thrust vector control potential*
  - *Ease of design and manufacture*

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

Rockets

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

Space tourism: Virgin Galactic spaceship www.cnn.com

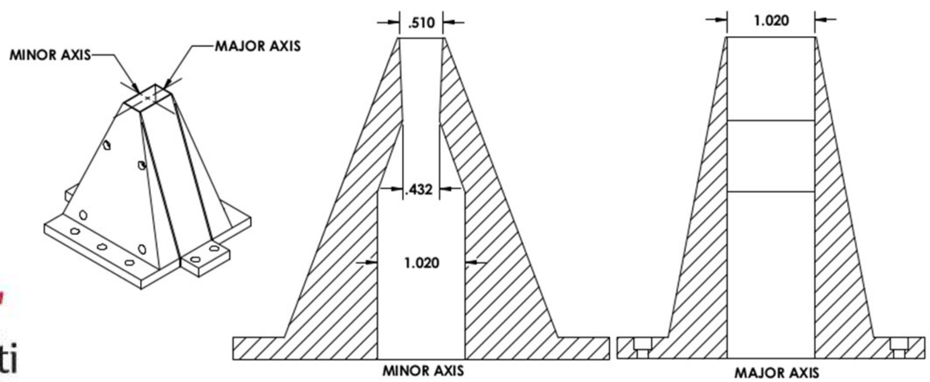
Motivation & Objective

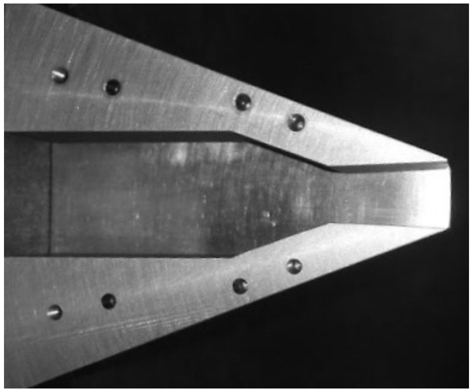
- Flow control for noise suppression technologies are required
- Current supersonic jet noise reduction techniques are mainly developed based on laboratory-scale and relatively low-temperature jet data
  - *Challenges with measuring flow inside the nozzle and the dynamics associated with supersonic & high-temperature flows*
  - *Jet & Shock-waves dynamics*
  - *Temperature limitations with the test rig*
- Practical high-performance jets are highly-heated ($T_t > 2000$ K)
  - *Limited understanding of noise generation process in highly-heated jets*
- **Objective**: to gain insights on the noise generation mechanism in highly-heated supersonic jets
  - *Focus on rectangular shaped nozzle (2:1 AR)*
  - *Use of Large Eddy Simulation approach and FW-H Acoustic Analogy*

Nozzle configuration & Design parameters

- 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*)

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





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).

UNIVERSITY OF Cincinnati

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

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

Operating conditions

- 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*

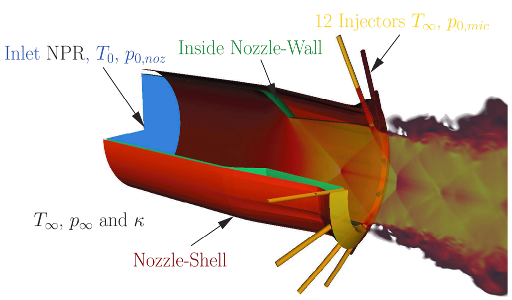
Case	NPR	TR	M_j	$u_j(m \cdot s^{-1})$	$T_j(K)$	Re
JetTR1	3.0	1.0	1.36	399	214	9.61×10^5
JetTR2	3.0	2.0	1.36	564	430	3.96×10^5
JetTR4	3.0	4.0	1.37	801	885	1.67×10^5
JetTR7	3.0	7.0	1.39	1070	1592	0.85×10^5

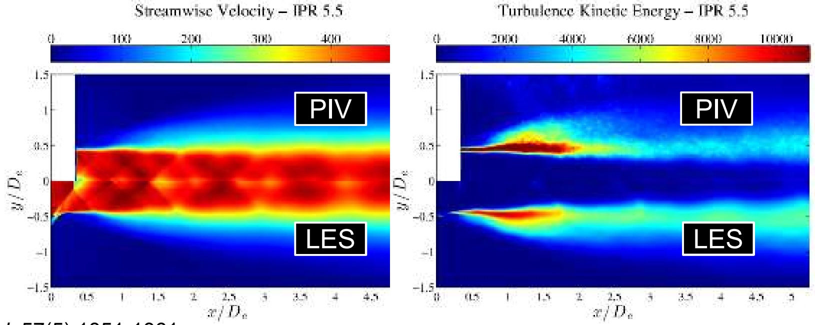
$$Re = \frac{\rho u_j D_{eq}}{\mu} = \frac{u_j D_{eq}}{\upsilon}$$

Numerical Method

- Compressible "in-house" finite volume-based flow solver
  - Turbulence by means of implicit Large Eddy Simulation (LES) approach, with Jameson-type artificial dissipation mechanism; *Gojon, Gutmark, Mihaescu (2017), AIAA-2017-0002.*
  - Second-order central difference for space discretization
  - Four-stage Runge-Kutta for time integration
- Computational grid
  - Sponge zone + non-reflecting boundaries
  - 160 M cells → 960 CPUs
- Acoustic far-field: Ffowcs Williams-Hawkings (FW-H) acoustic analogy

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

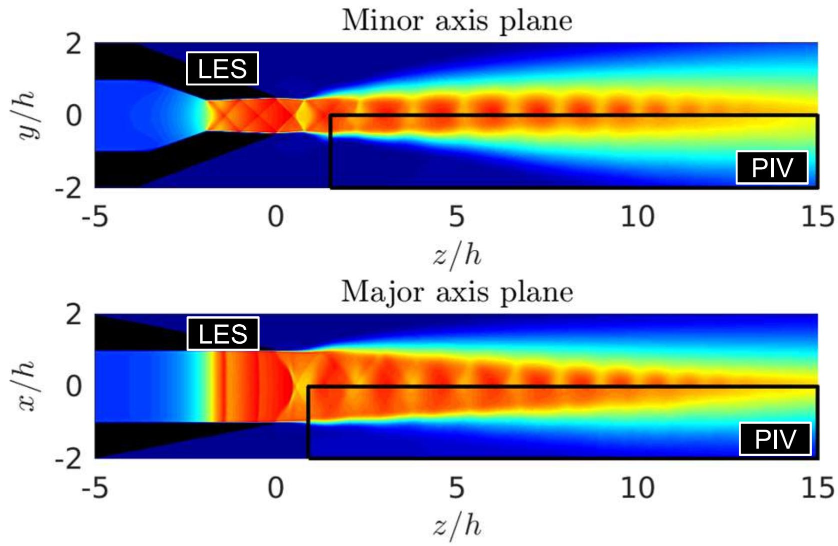


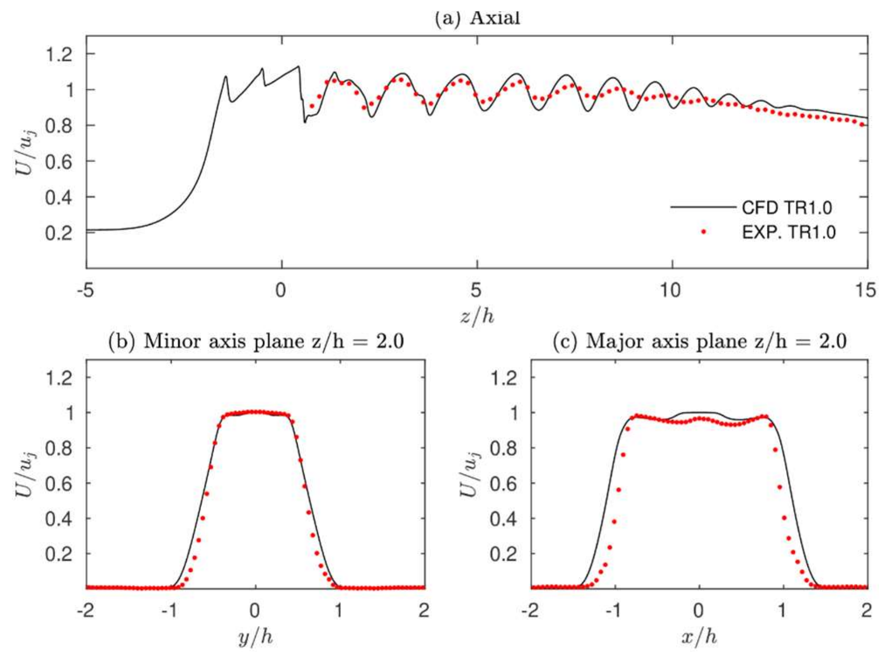


Semlitsch B., Cuppoletti D., Gutmark, E.J., & Mihaescu M., (2019), *AIAA Journal,* 57(5):1851-1861.

Some flow validation results: low-temperature jets

- Normalized time-averaged velocity data comparisons (TR1): LES vs. PIV



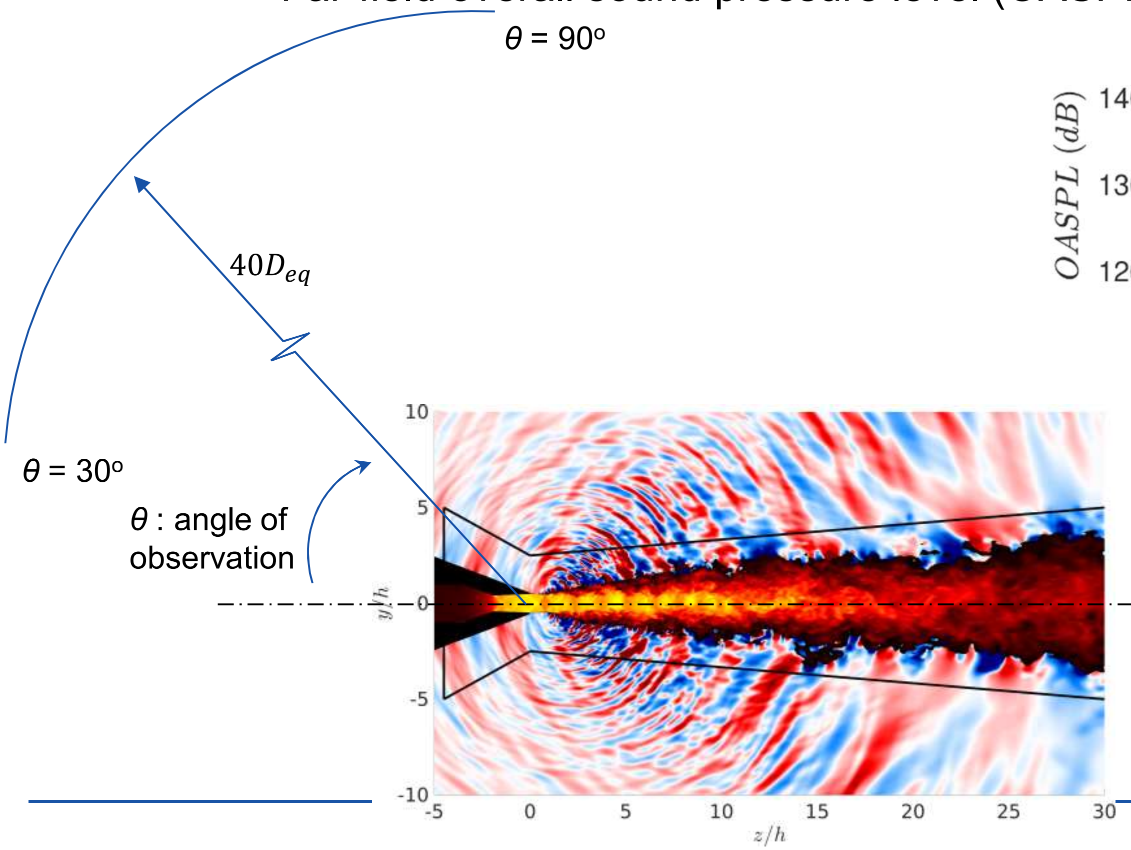


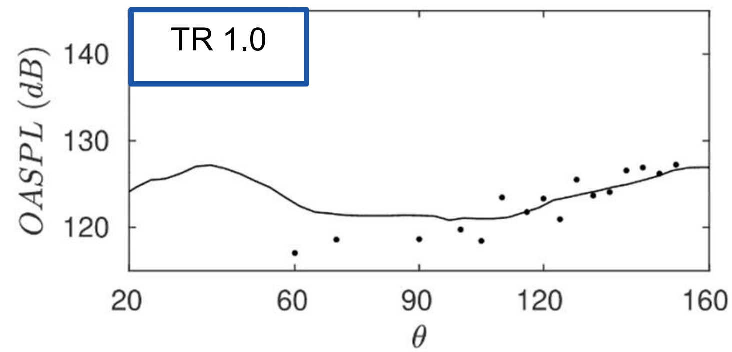
Experimental data courtesy of Prof. Ephraim Gutmark, the Gas Dynamic and Propulsion Lab, University of Cincinnati

Gojon R., Gutmark, E.J., & Mihaescu M. (2019) Antisymmetric Oscillation Modes in Rectangular Screeching Jets*, AIAA Journal,* 57(8):3422-3441.

Aeroacoustic validation results: low-temperature jets

- Far-field overall sound pressure level (OASPL) comparisons

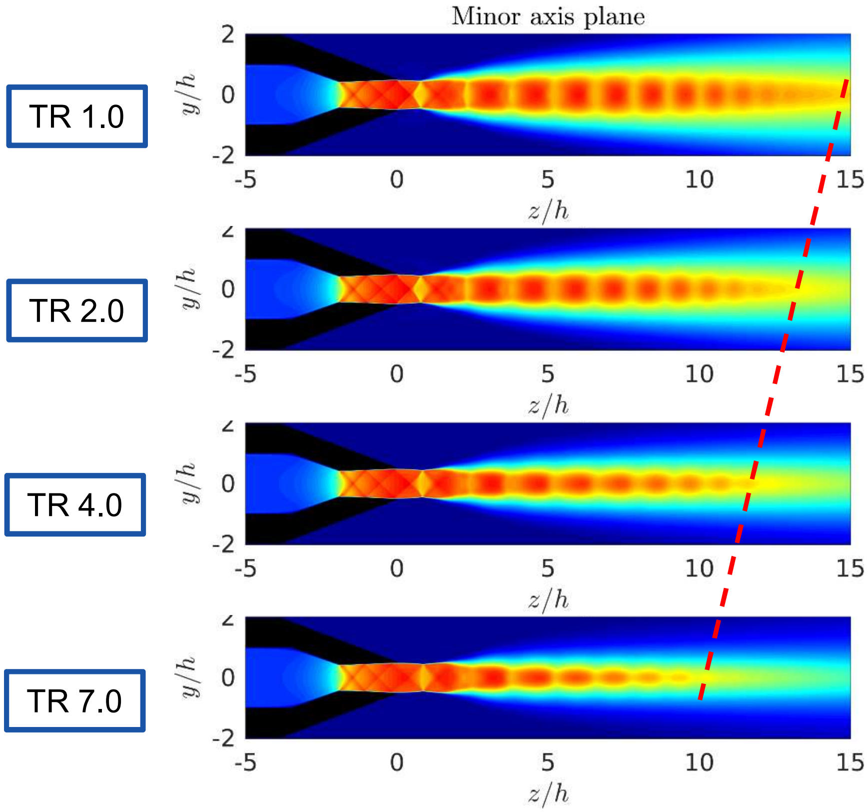




- Far-field acoustics by Ffowcs Williams-Hawkings (FWH) acoustic analogy
- FWH porous open surface for acoustic sources

Gojon R., Gutmark, E.J. Mihaescu M. (2019) Antisymmetric Oscillation Modes in Rectangular Screeching Jets, *AIAA Journal,* 57(8):3422-3441.

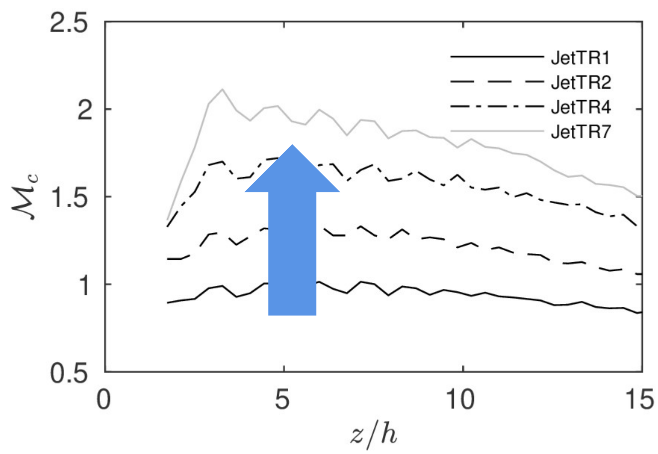
Time-averaged normalized axial velocity



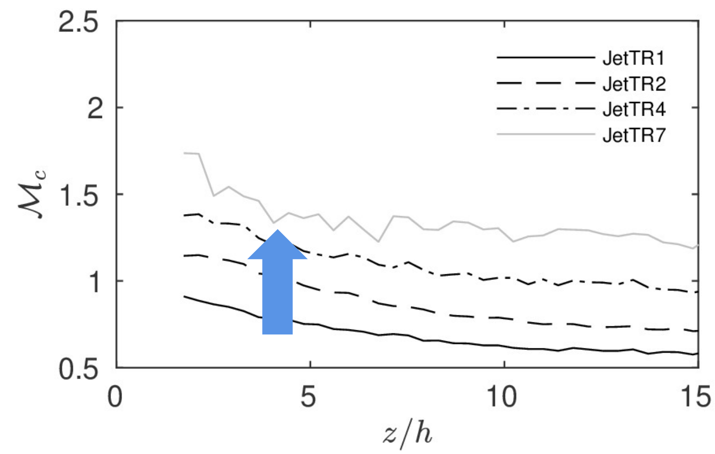
Chen S., Gojon R. *and* Mihaescu M. (2018) High-Temperature Effects on Aerodynamic and Acoustics Characteristics of a Rectangular Supersonic Jet, *AIAA paper, AIAA 2018-3303*.

Jet shear layer: convection Mach number

Minor axis plane



Major axis plane

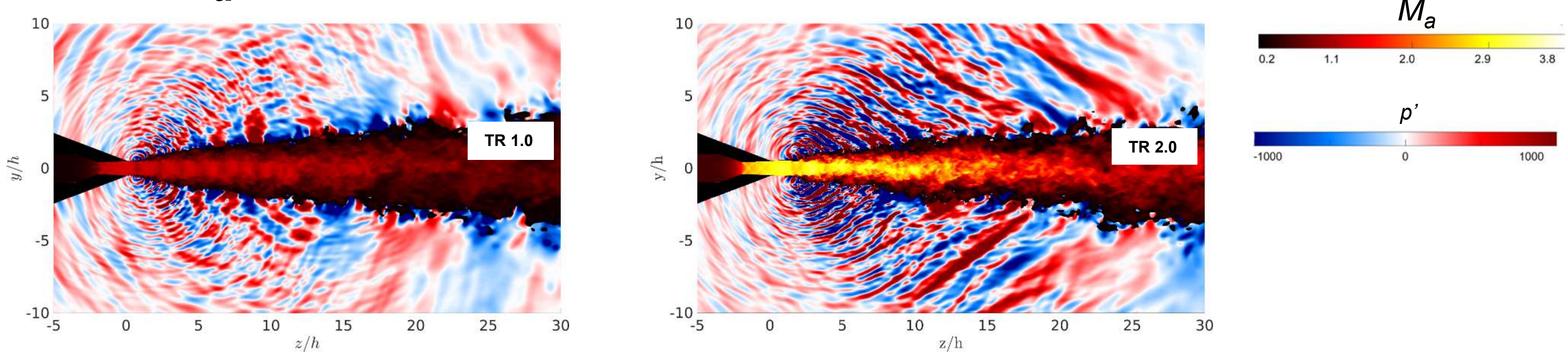


Averaged convection Mach number

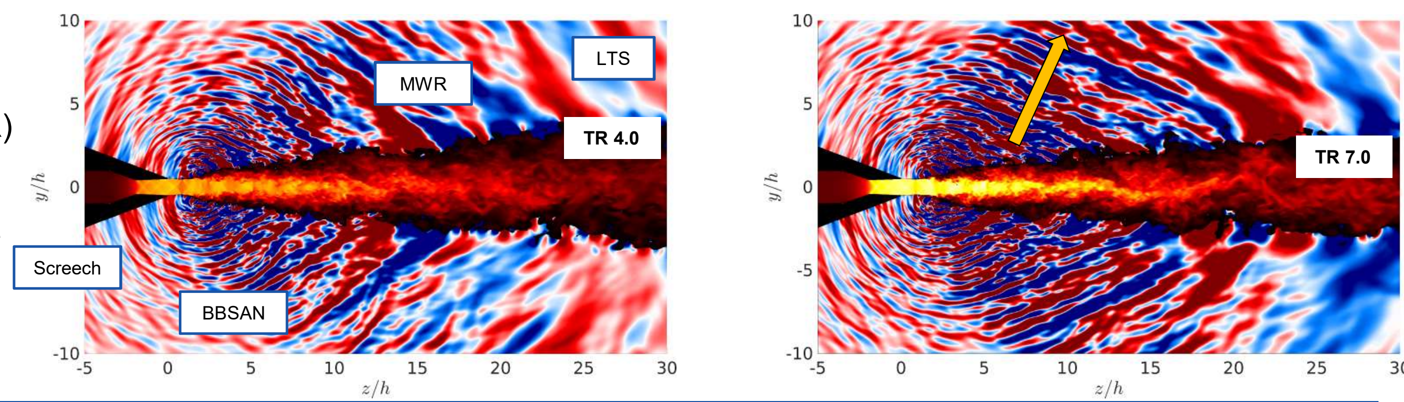
Subsonic → supersonic

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

Instantaneous near field acoustics: M_a & pressure fluctuation



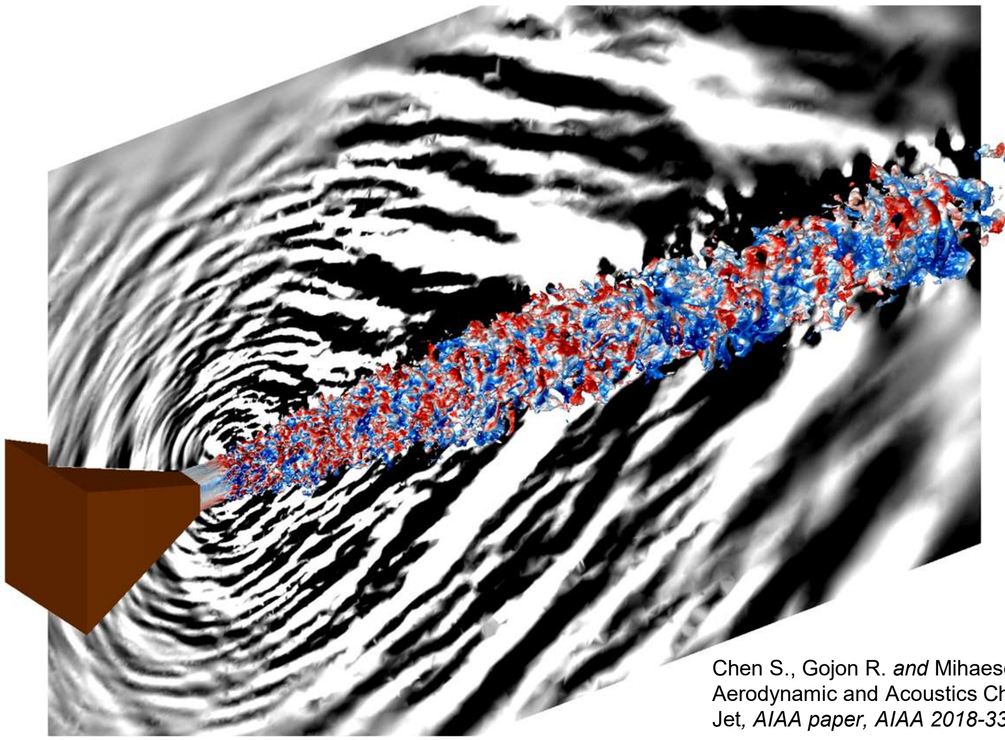
- Large turbulent structure (LTS) noise (mixing noise)
- Mach wave radiation (MWR)
- Screech tones
- Broadband shock associate noise (BBSAN)



Chen S., Gojon R. *and* Mihaescu M. (2018) High-Temperature Effects on Aerodynamic and Acoustics Characteristics of a Rectangular Supersonic Jet*, AIAA paper, AIAA 2018-3303*.

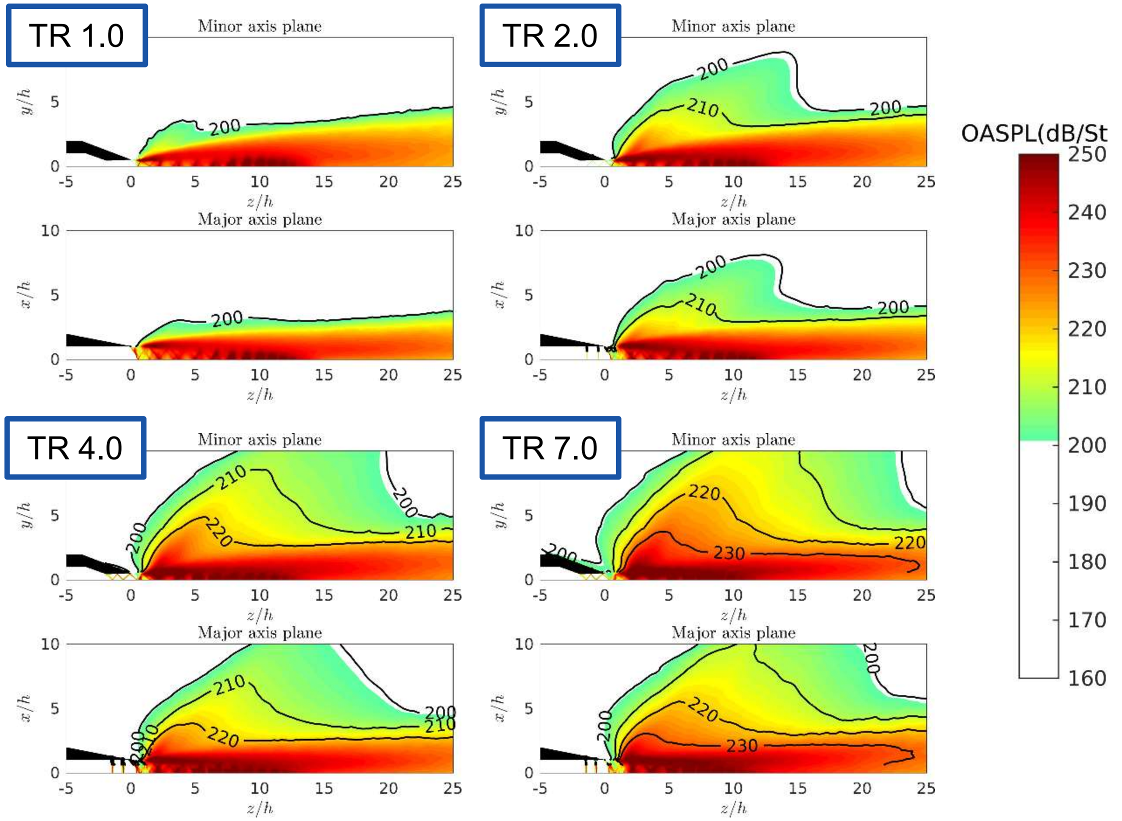
Dynamics of the highly-heated jet: TR 7.0

3-D: isosurfaces of density + acoustic



Chen S., Gojon R. *and* Mihaescu M. (2018) High-Temperature Effects on Aerodynamic and Acoustics Characteristics of a Rectangular Supersonic Jet*, AIAA paper, AIAA 2018-3303*.

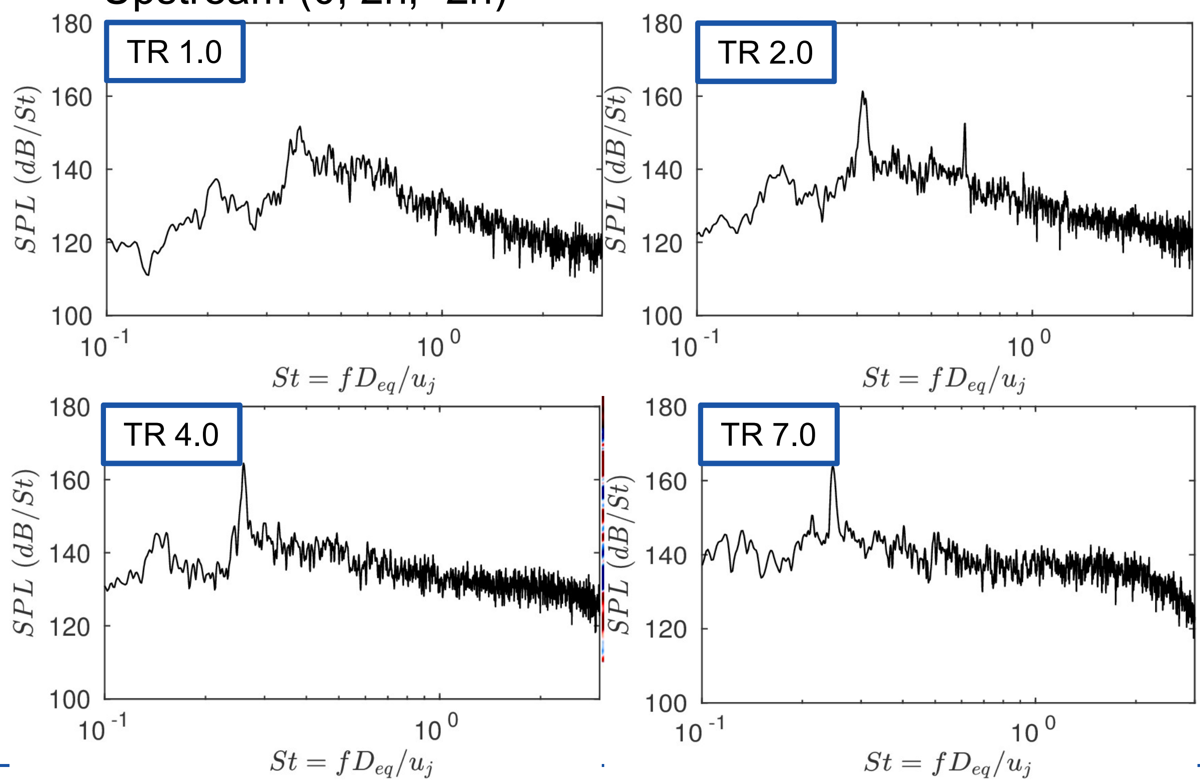
Near field sound pressure level



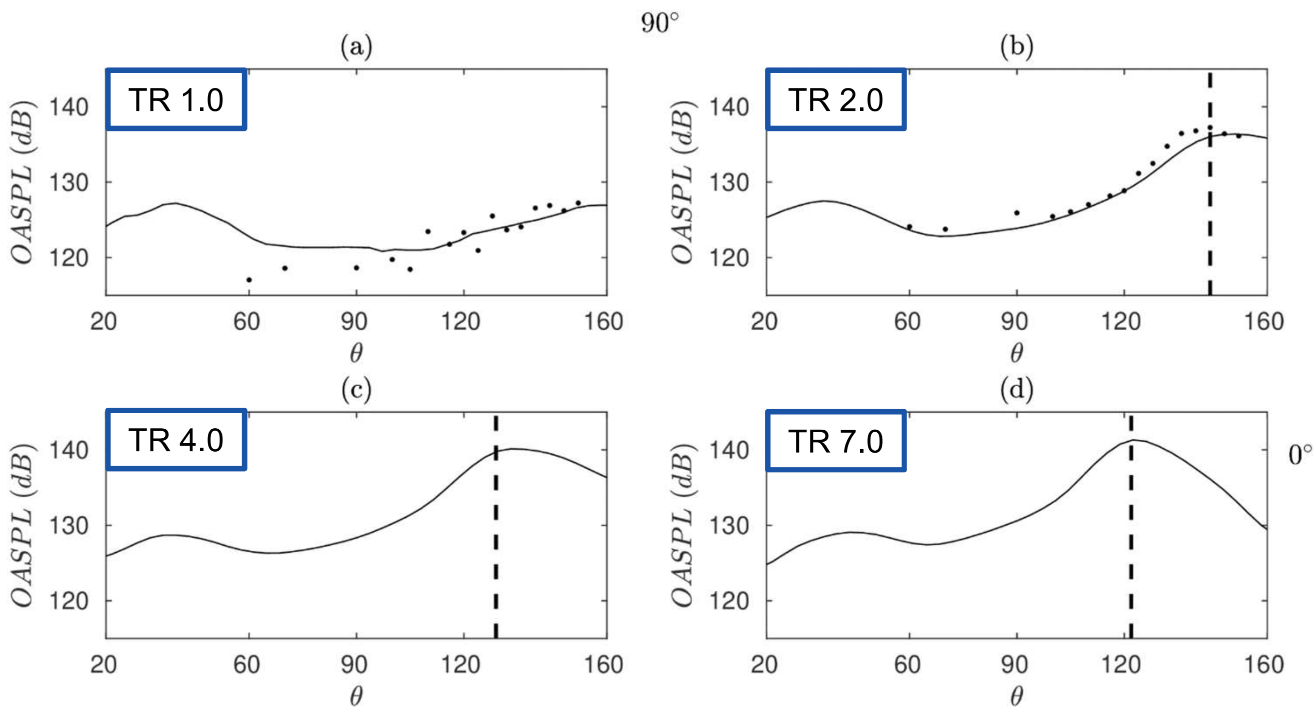
Chen S., Gojon R. *and* Mihaescu M. (2018) High-Temperature Effects on Aerodynamic and Acoustics Characteristics of a Rectangular Supersonic Jet, *AIAA paper, AIAA 2018-3303*.

Pressure spectra analysis - screech

- Upstream (0, 2h, -2h)



Far field OASPL: FW-H approach



Chen S., Gojon R. *and* Mihaescu M. (2018) High-Temperature Effects on Aerodynamic and Acoustics Characteristics of a Rectangular Supersonic Jet*, AIAA paper, AIAA 2018-3303*.

Far field pressure spectra

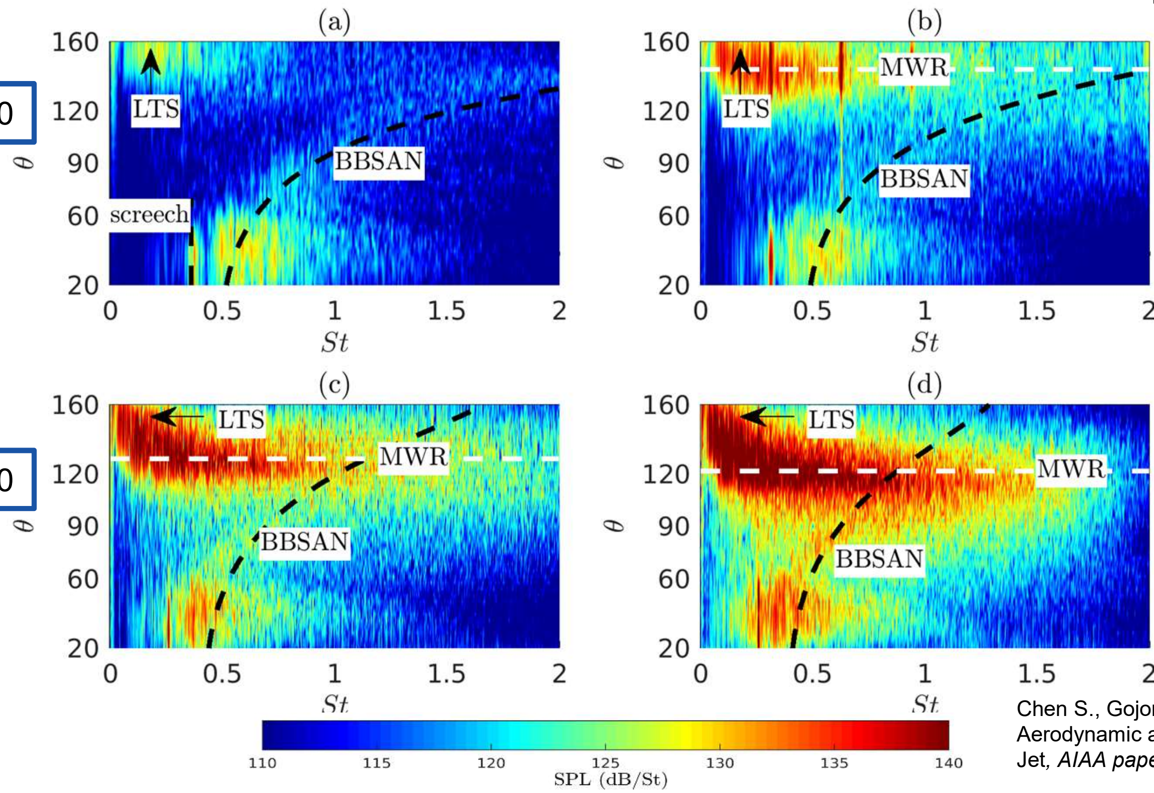
Dashed line: BBSAN Model (Harper-Bourne and Fisher model AGARD 1974

TR 1.0

TR 2.0

TR 4.0

TR 7.0



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Conclusions – temperature ratio effects

- LES study of temperature effects on a rectangular supersonic jet
  - NPR 3.0, over-expanded jet
  - TR 1.0, 2.0, 4.0, and 7.0 (2100 K)
  - Temperature dependent air properties (gamma 1.4 → 1.25)
- Flow field characteristics
  - Increased jet velocity but reduced jet potential core length
  - Increased shear layer convection Mach number (subsonic → supersonic)
  - Slightly modified shock structures
- Acoustic field characteristics
  - Increased sound pressure levels in all directions and frequencies
  - Significantly strong Mach wave radiation
  - Screech tone exists (St decreases)

Challenges & Outlook

- **Efficientely addressing** the challenges related with high-fidelity CFD when it comes to supersonic jets
  - High-temperature effects in supersonic jets
  - Near-wall treatment inside the nozzle
  - Complex physics interplay (e.g. compressibility effects, shocks and vortex-shock interaction, non-linearities, noise generation & acoustic radiation)
  - Non-reflective boundary conditions for acoustic waves
  - Real geometry effects, co-flow effects and NPRs effects
  - Developing flow control technologies

Acknowledgements

Asuka Gabriele Pietroniro, Lukas Schickhofer, Shyang Maw Lim, Roberto Mosca, Song Chen, Emelie Trigell, (Ghulam Majal missing).

SNIC

PDC @ KTH
Cray XC40 system 53632 cores
(1676 nodes with 32 cores/node)

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Some recent publications on the topic

- https://arc.aiaa.org/doi/abs/10.2514/1.J056936?journalCode=aiaaj
- https://arc.aiaa.org/doi/abs/10.2514/1.J057514
- https://arc.aiaa.org/doi/abs/10.2514/1.J057629
- https://arc.aiaa.org/doi/abs/10.2514/6.2019-2753
- https://arc.aiaa.org/doi/abs/10.2514/1.J057537
- https://arc.aiaa.org/doi/abs/10.2514/6.2018-3303
- https://arc.aiaa.org/doi/abs/10.2514/6.2017-3018
- https://arc.aiaa.org/doi/abs/10.2514/6.2017-0002