Large Eddy Simulations of a supersonic jet exhausting a Rotating Detonation Combustion chamber

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Marie Skłodowska-Curie Actions

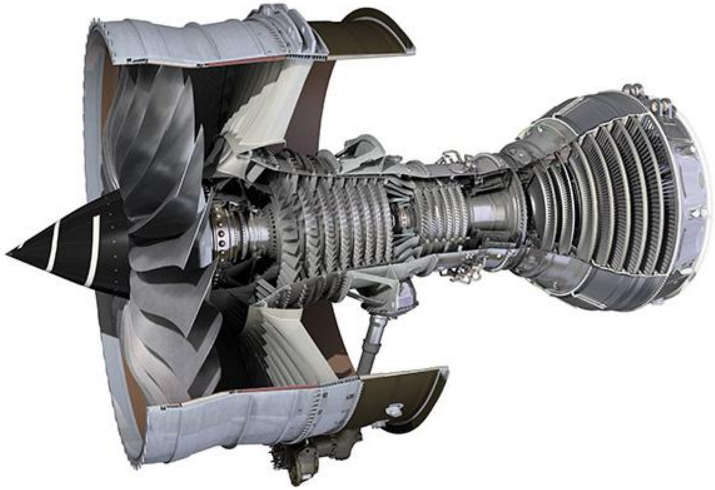
INSPIRE-ETN
INSPIRING PRESSURE GAIN COMBUSTION INTEGRATION RESEARCH, AND EDUCATION

Outline

I. Background
    1. Combustion concepts
    2. Rotating Detonation Engine
II. Simulation setup
III. Swirling effects
IV. Rotating Detonation Combustion
V. Outlook

Aircraft engines

- Tremendous improvements since the first aircraft engines
  - Increase in Bypass Ratio, Turbine Inlet Temperature
  - Improved design (numerical simulations)
  - **BUT: Same thermodynamic cycle**



Rolls Royce Trent XWB…

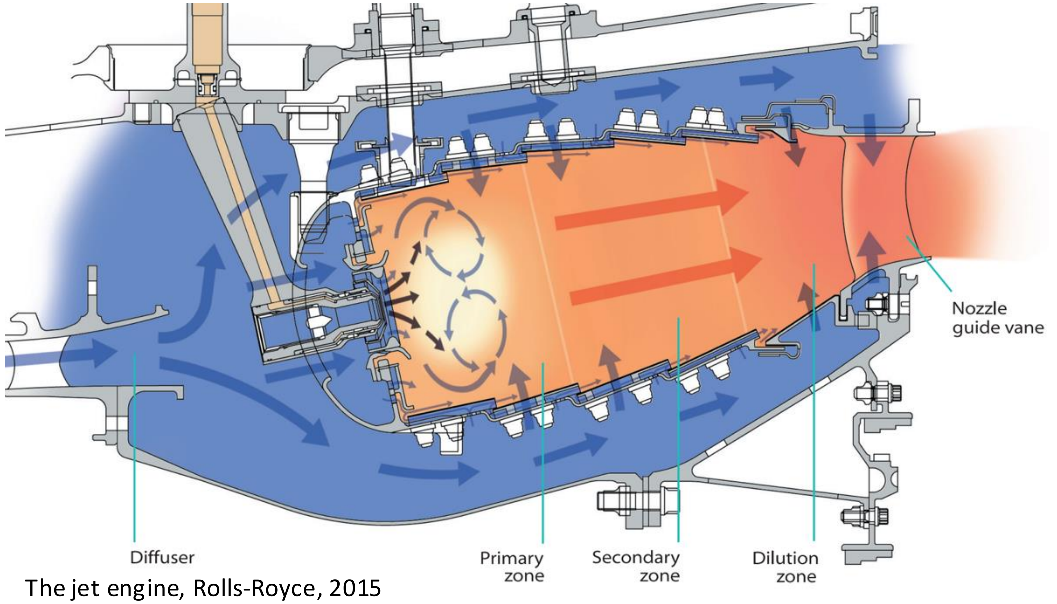
Pratt &Whitney JT3D (B707)
BPR = 1.42
Specific Fuel Consumption:
22 $g/kN.s$

Rolls-Royce Trent XWB (A350)
BPR = 9.6
Specific Fuel Consumption:
13.5 $g/kN.s$

… powering SAS's A350 (Max. thrust 375 kN)

Combustion concepts

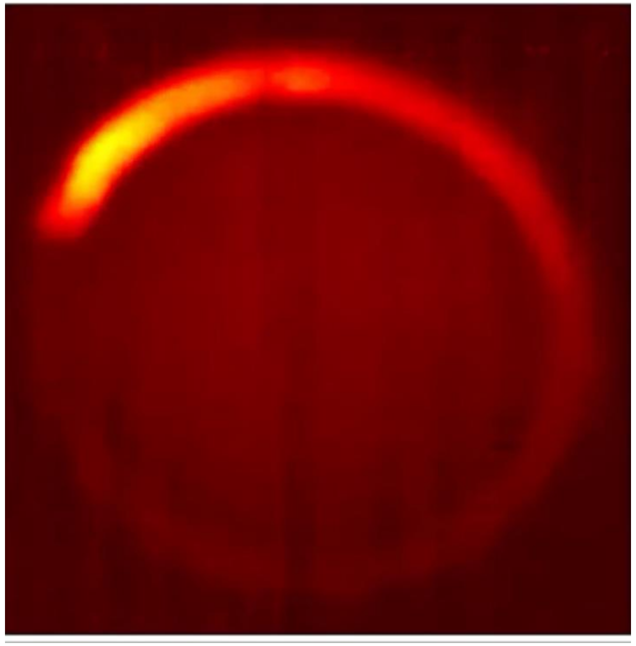
Deflagration

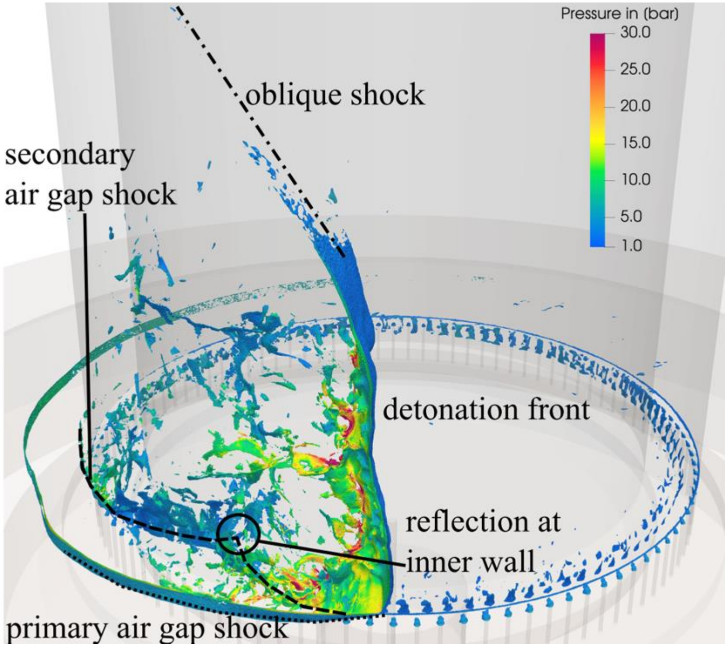


The jet engine, Rolls-Royce, 2015

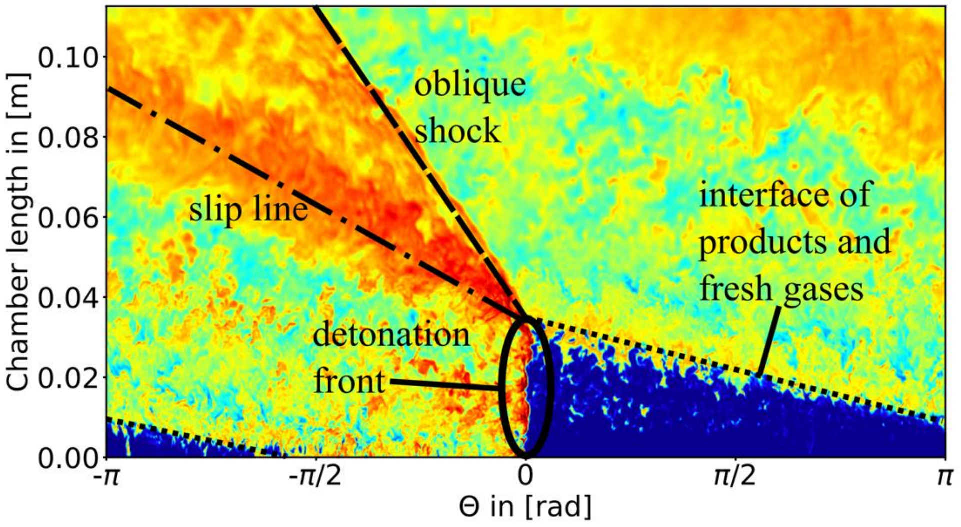
- 15% decrease in specific fuel consumption
- no moving parts
- compact
- Use of non-carbonated propellants

Detonation



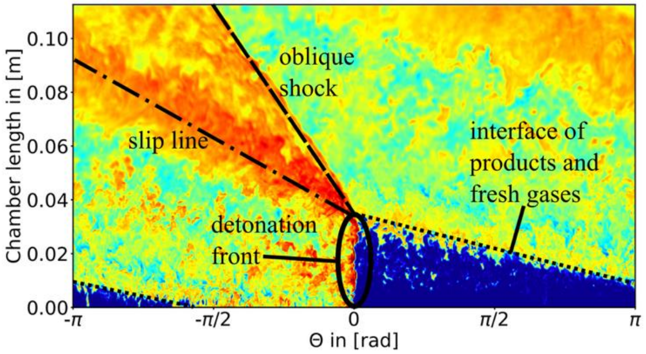


PGC @TU Berlin



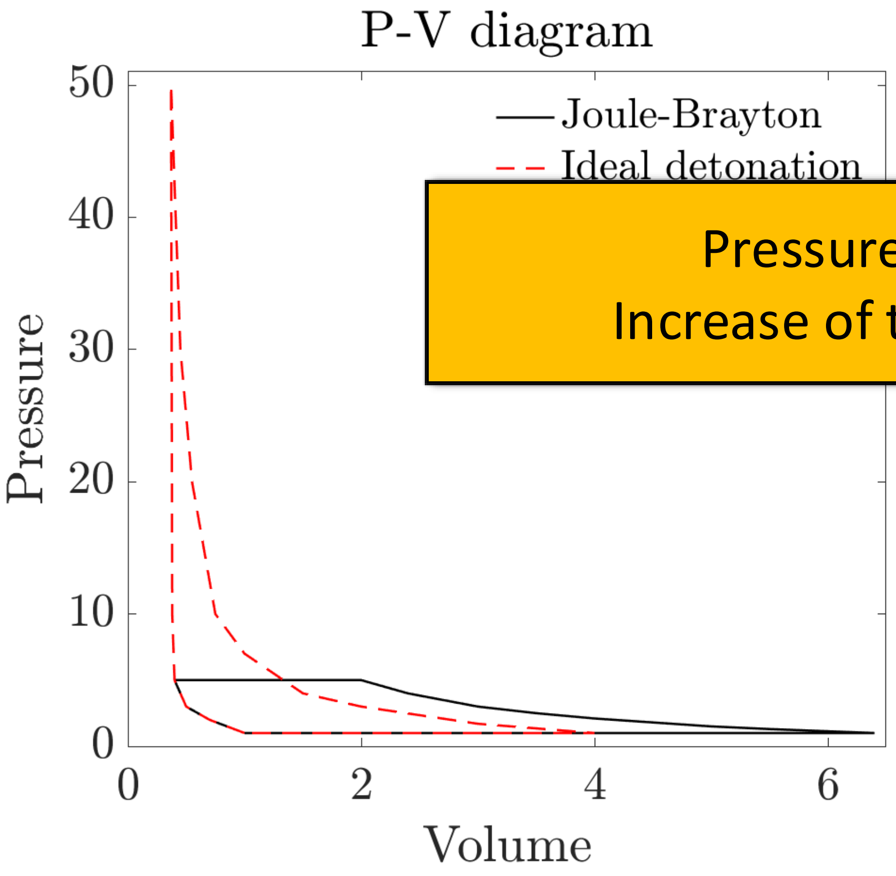
Adapted from: *LES of Rotating Detonation Engines : sensitivity and Physics*, Patrick Strempfl, PhD Thesis, 2024.

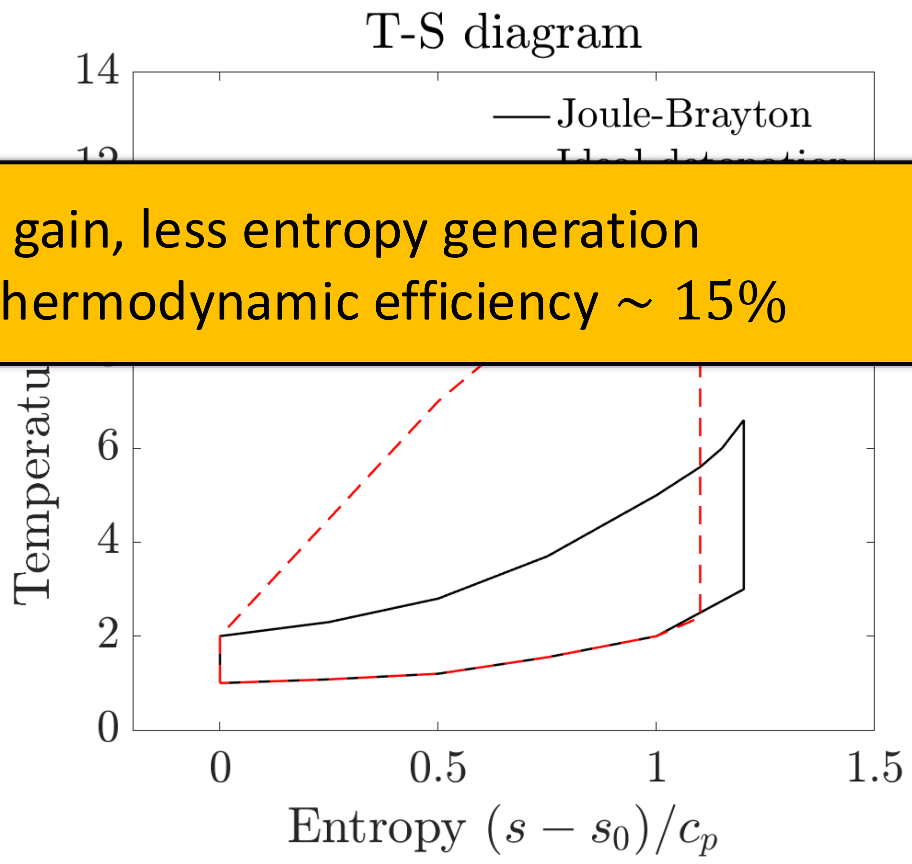
Thermodynamic cycle



Adapted from: *LES of Rotating Detonation Engines: sensitivity and Physics*, Patrick Strempfl, PhD Thesis, 2024.

Pressure gain, less entropy generation
Increase of thermodynamic efficiency ~ 15%

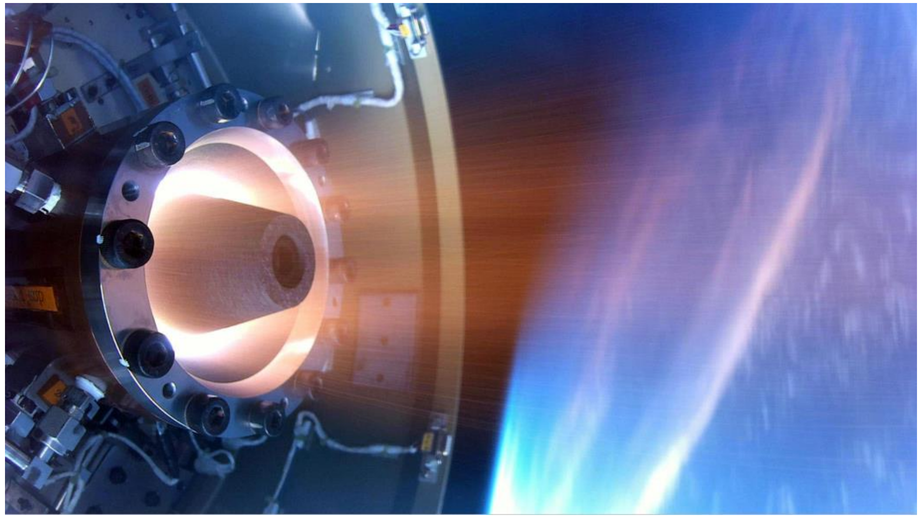




Adapted from: Comprehensive Thermodynamic Analysis of the Humphrey Cycle for Gas Turbines with Pressure Gain Combustion. Stathopulous P., Energies, Vol. 11 (12), 2018. DOI:10.3390/en11123521

A timeline of RDEs

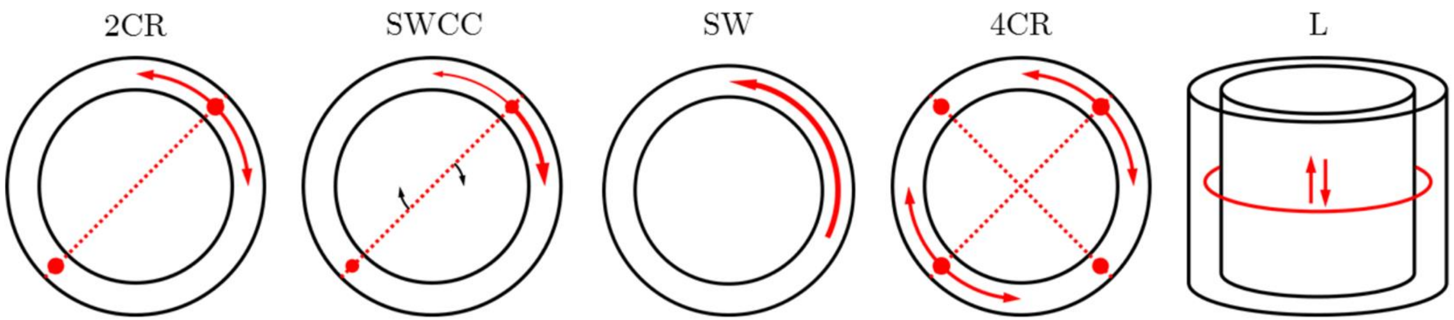
Period	
1950 – 1960	First investigations (Voitsekhovskii, Nicholls)
1960 – 2000	Period of limited development
2020	1st continuously sustained hydrogen/oxygen RDE prototype (U. Central Florida)
Jul. 2021	**1st ever flight by Japanese Aerospace Exploration Agency**
Sept. 2021	Flight test of liquid propellant RDC (Łukasiewicz, Poland)
2023	**Successful tests by NASA**
Mar. 2025	Successful test by Pratt & Whitney
Sep. 2025	Successful tests by GE Aerospace


RDE Maiden flight, JAXA/Nagoya University, July 2021

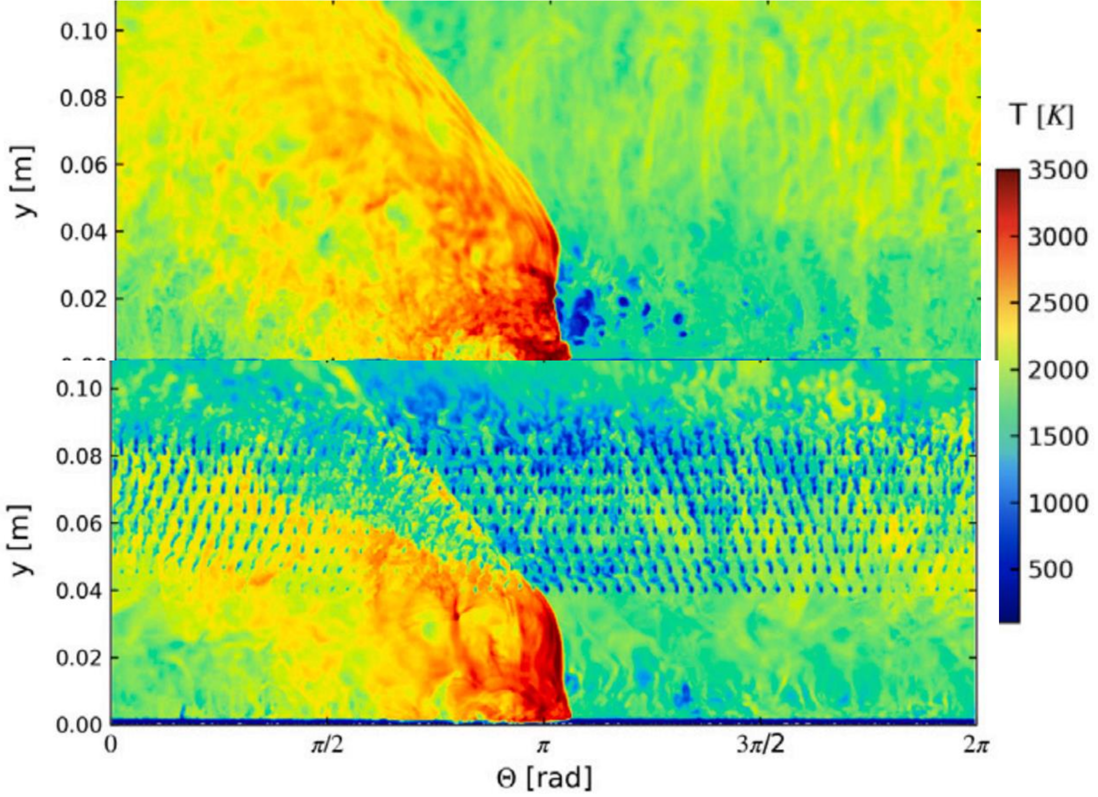

NASA Marshall Space Flight center, RDC test, December 2023

Research in RDEs

- Instabilities
- **Detonation modes**
- Residual deflagration
- Deflagration to detonation transition
- Injector design
- **Cooling**
- Component matching
- Integration within a full-scale engine
- …
- **Aeroacoustics**



Performance analysis of a rotating detonation combustor based on stagnation pressure measurements, Bach et al., *Combustion and Flame*, Vol. 217, pp. 21-36, 2020. DOI:10.1016/j.combustflame.2020.03.017

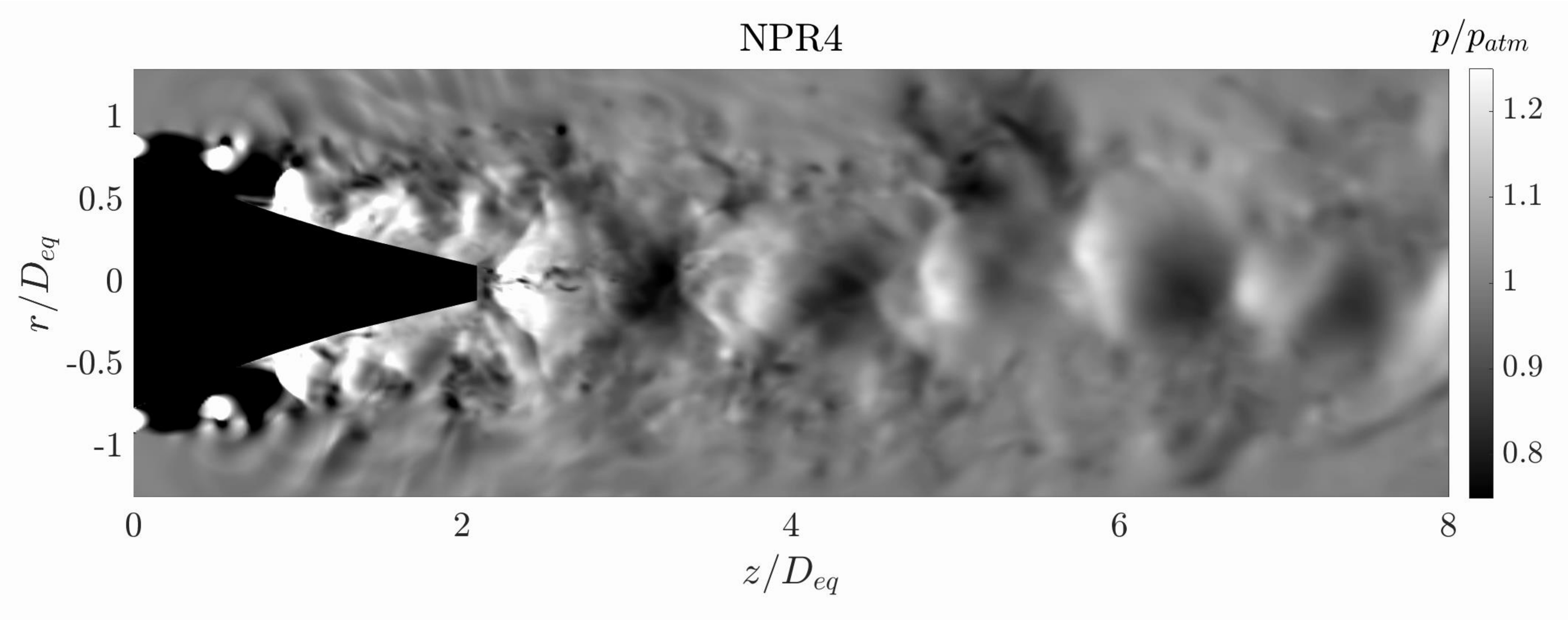


The impact of film cooling on the heat release within a rotating detonation combustor, Sridhara et al., Applications in Energy and Combustion Science, Vol. 20, 2024. DOI:10.1016/j.jaecs.2024.100300

Project motivation

How does a jet exhausting an aerospike nozzle behave?

How is the acoustic signature affected by the RDC conditions?

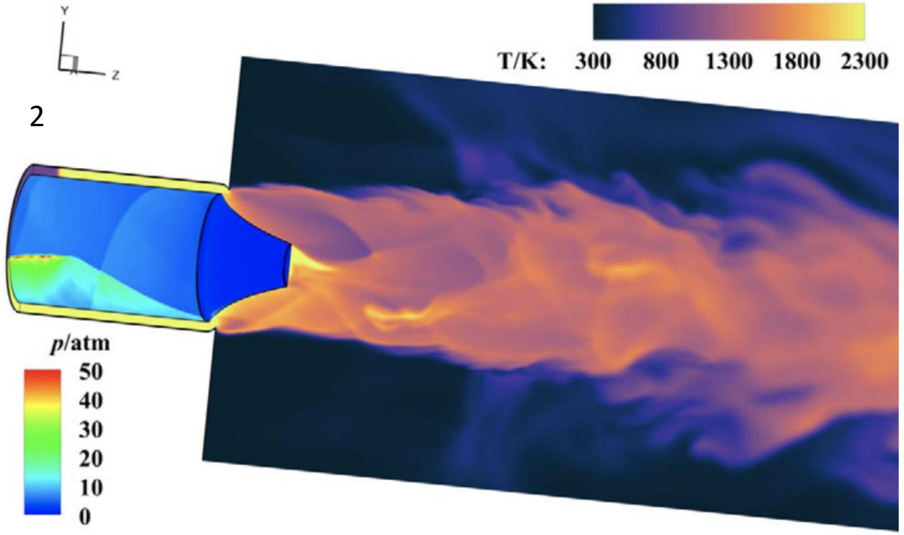


Why an aerospike nozzle?

- Very suitable for integration of RDC[1]
- Investigations on design and performance[2]
- No high-fidelity simulation and aeroacoustics
- Effect of various parameters: temperature, swirl number[3,4,5,6]

This presentation will focus on:
- **Swirling effects**
- **Rotating detonation condition**

NASA Marshall Space Flight center, RDC test, December 2023



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[1] *Experimental study of the performance of a rotating detonation engine with nozzle*, Fotia M. et al., Journal of Propulsion and Power, DOI: 10.2514/1.B35913.

[2] *Design and optimization of aerospike nozzle for rotating detonation engine*, X.-Y. Liu & al, Aerospace Science & Technology, Vol. 120, January 2022. DOI: 10.1016/j.ast.2021.107300.

[3] *Computational aeroacoustics for a cold, non-ideally expanded aerospike nozzle*, Golliard T. & Mihaescu M., *Journal of Turbomachinery,* Vol. 146(2), 2024. DOI:10.1115/1.4063877.

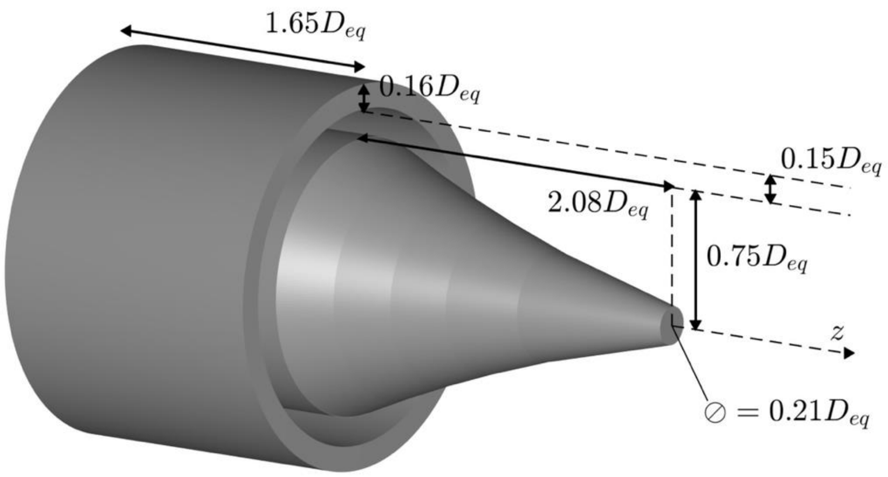
[4] *Swirling Flow Effect on the Aeroacoustic Signature of an Aerospike Nozzle*, Golliard T. & Mihaescu M., *Journal of Turbomachinery,* Vol. 147(1) 2024. DOI: 10.1115/1.4067383.

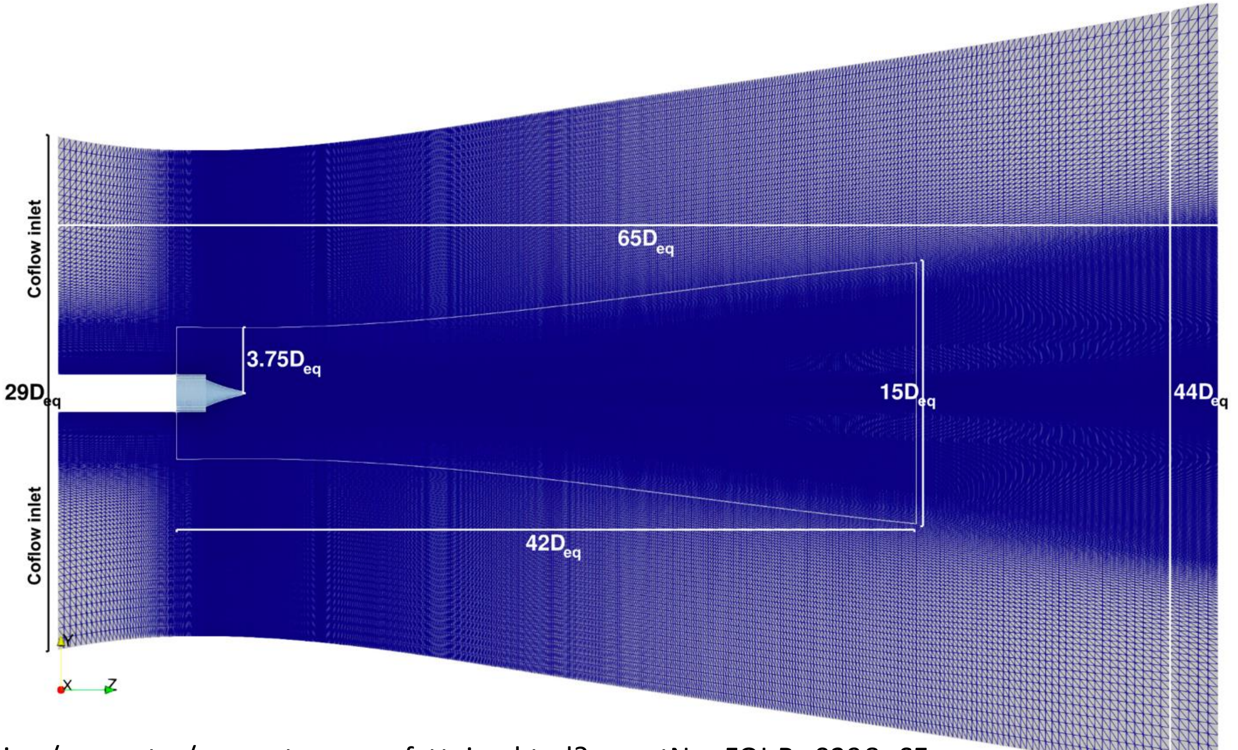
[5] *Swirling Flow Effects on Highly-Heated Aerospike Nozzle*, Golliard T. & Mihaescu M., AIAA/CEAS Aeroacoustics 2024, DOI:10.2514/6.2024-3032.

[6] *Computational Aeroacoustics of a Heated Supersonic Jet exhausting an Aerospike Nozzle*, Golliard T. and Mihaescu M., submitted to Physics of Fluids

High-fidelity simulations

- Aerospike nozzle (U. Cincinnati)
- Finite-volume solver M-Edge – Implicit LES[1]
  - Explicit 4-stage Runge-Kutta time integration
  - 2nd order CD scheme in space
  - 4th order CD for viscosity flux term
  - Artificial dissipation to avoid grid-to-grid and Gibbs oscillations
  - Characteristic B.C. + mesh stretching
  - Ffowcs Williams-Hawkings equation for far-field aeroacoustics[2]
- Validated for several configurations[3,4]



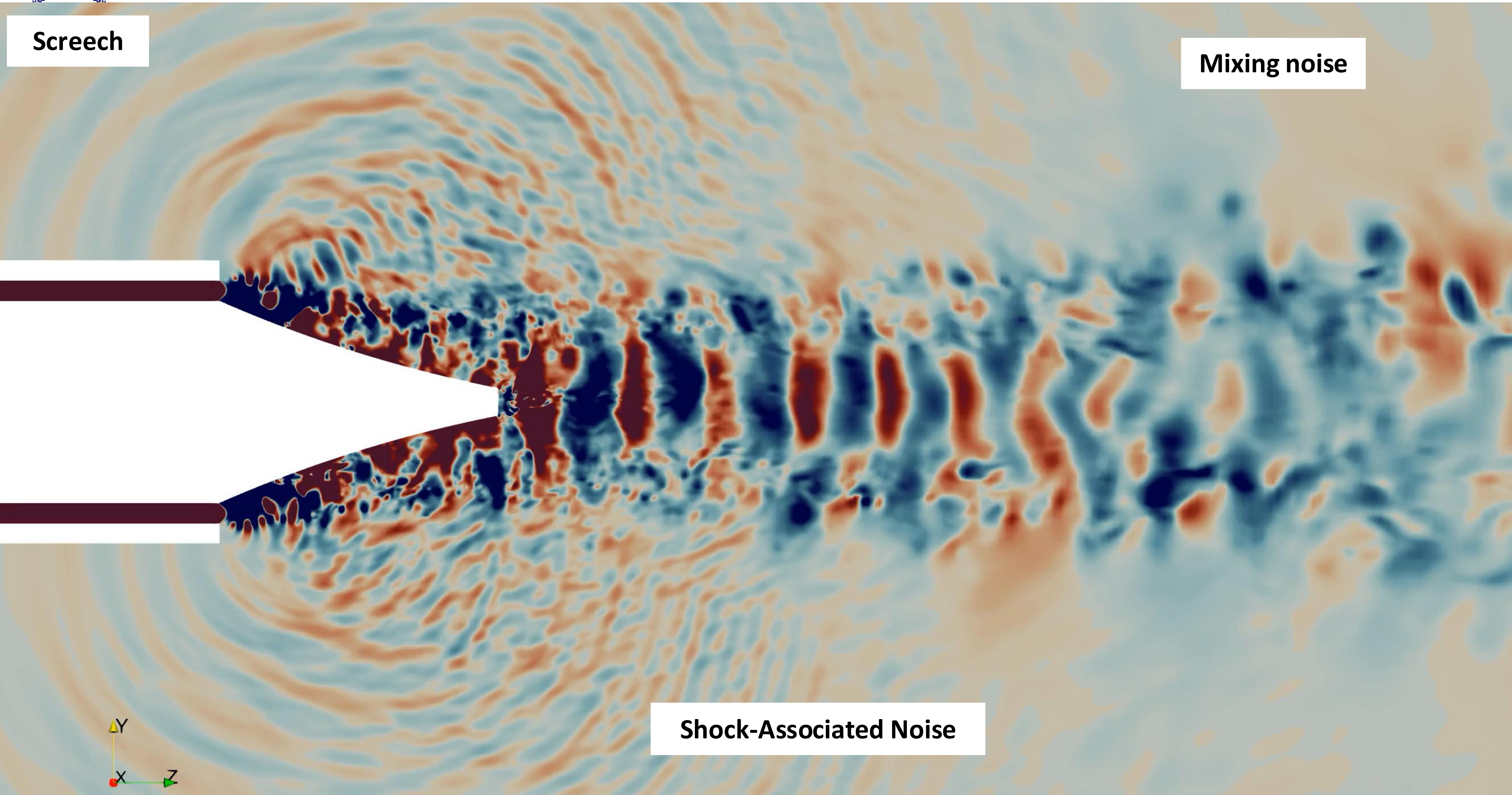


[1] Edge, a navier-stokes solver for unstructured grids, P. Eliasson, 2001. Preprint at https://foi.se/rapporter/rapportsammanfattning.html?reportNo=FOI-R--0298--SE.

[2] *Sound Generation by Turbulence and Surfaces in Arbitrary Motion*, Williams, J.E. Ffowcs & Hawkings, D.L., *Philosophical transactions of the Royal Society of London*, Vol. 264 No. 1151 (1972): pp. 321–342. DOI: 10.1098/rsta.1969.0031.

[3] *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.

[4] *Large-eddy simulations of flow and aeroacoustics of twin square jets including turbulence tripping*, Ahn M. & Mihaescu M., Physics of Fluids 35, 2023. DOI: 10.1063/5.0147295

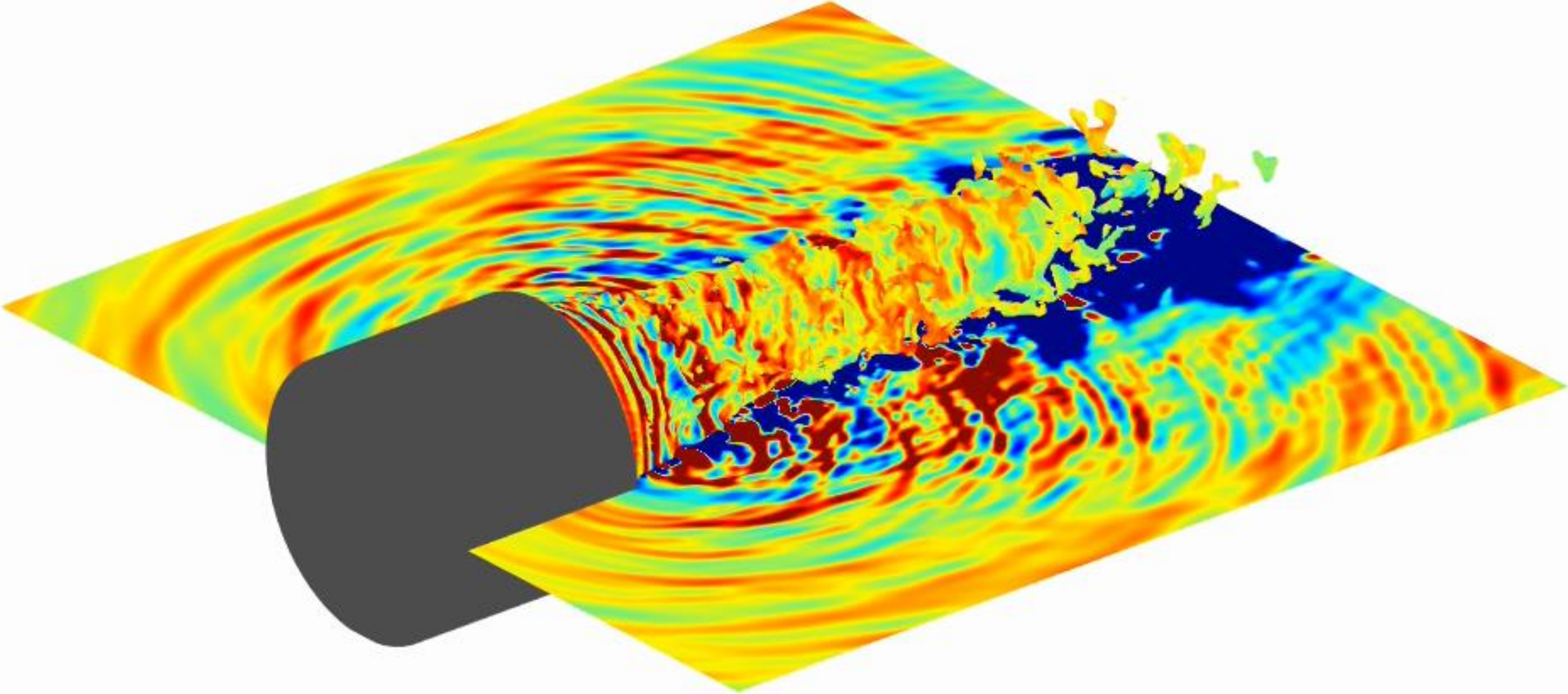


Screech

Mixing noise

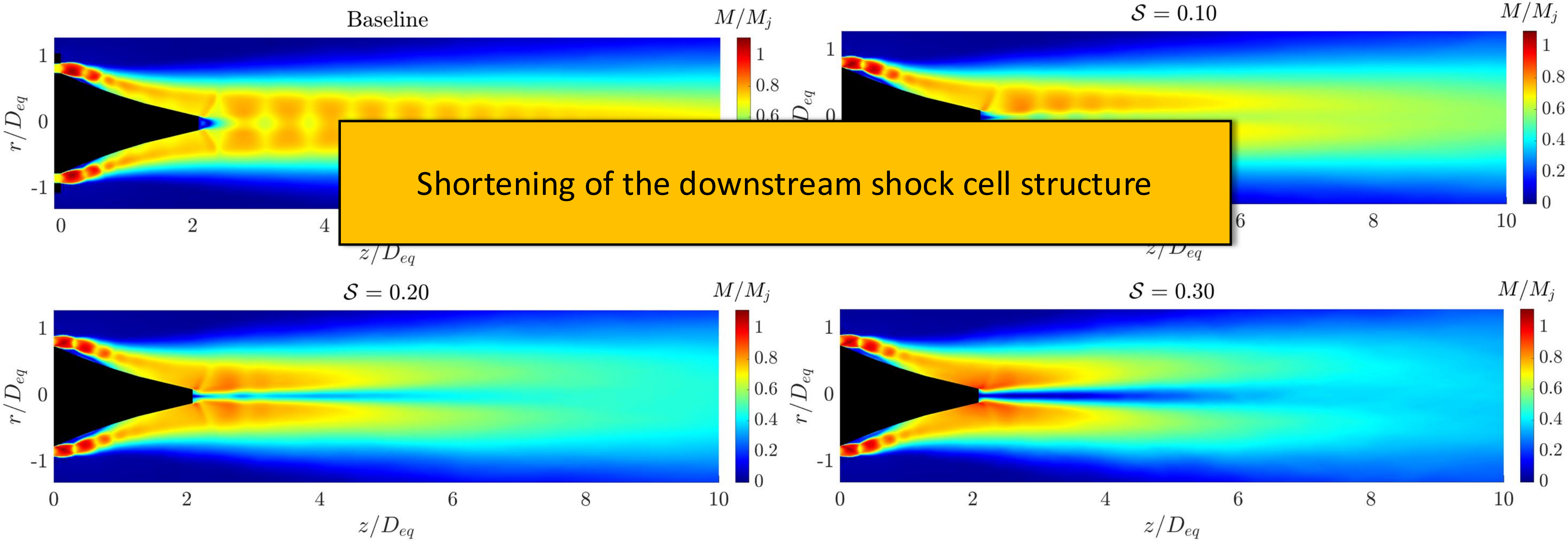
Shock-Associated Noise

Swirling effects



Isosurfaces of the Mach number ($M = 1.2$) colored by the density; acoustic pressure on the 2D plane (Inlet swirl number $S = 0.30$)

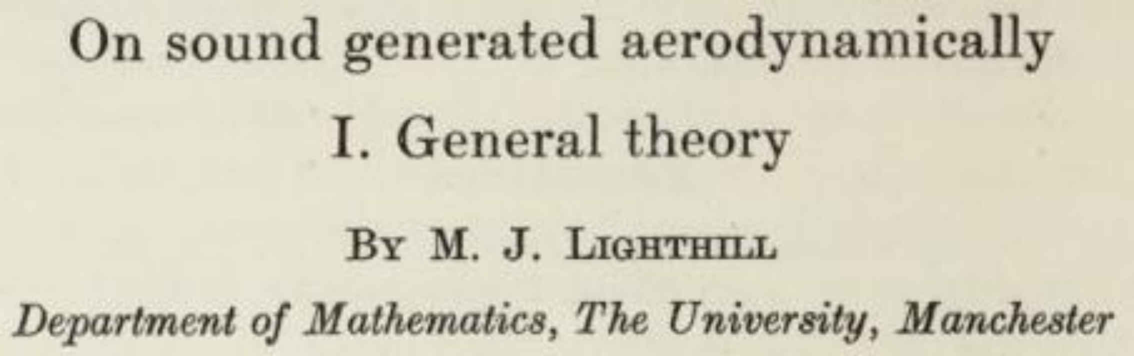
Time-averaged Mach number



Shortening of the downstream shock cell structure

Swirling Flow Effect on the Aeroacoustic Signature of an Aerospike Nozzle, Golliard T. & Mihaescu M., *Journal of Turbomachinery,* Vol. 147(1) 2025. DOI: 10.1115/1.4067383.

Far-field acoustics[1]

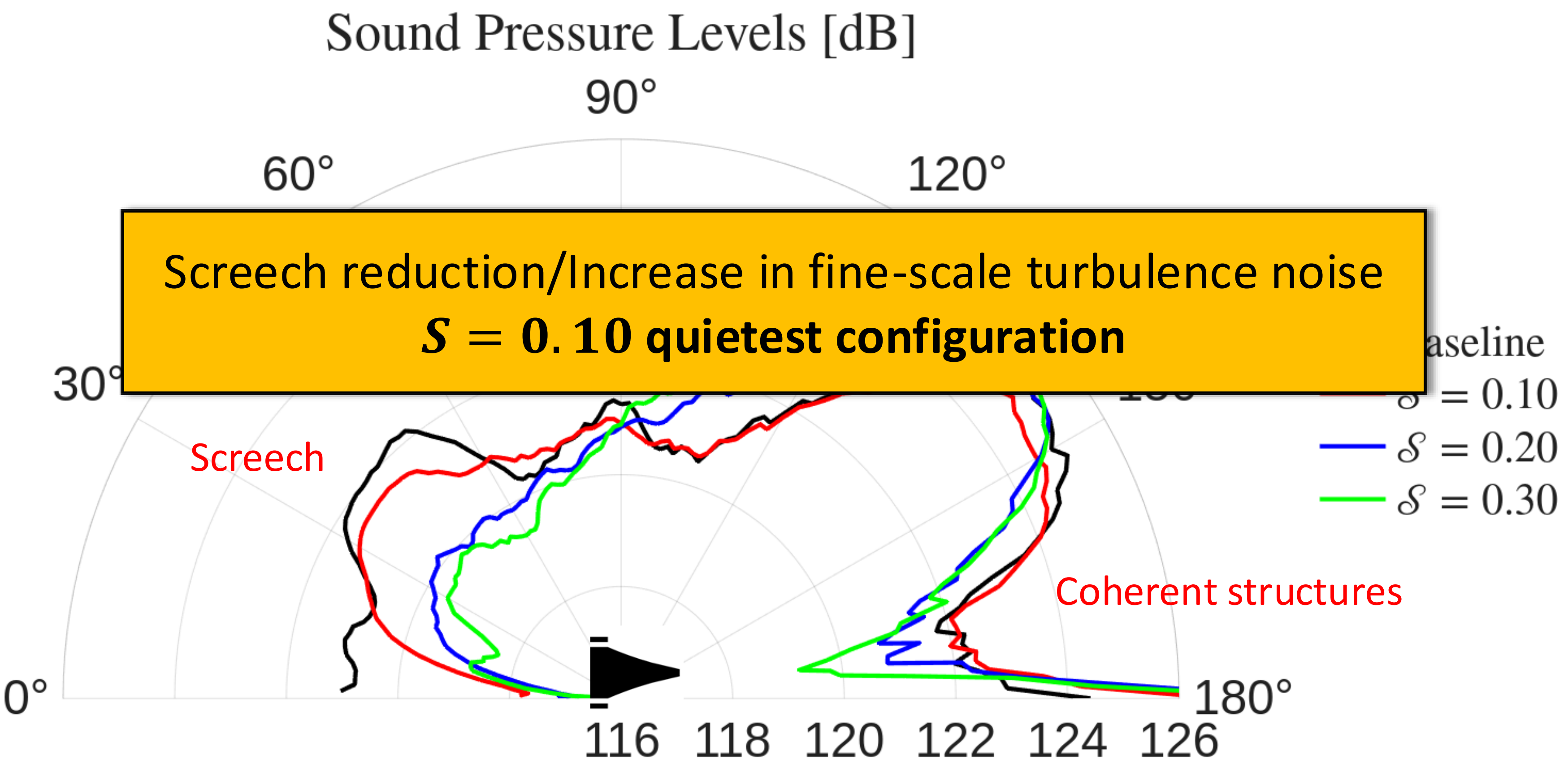


On sound generated aerodynamically

I. General theory

By M. J. Lighthill

Department of Mathematics, The University, Manchester



Screech

Coherent structures

Screech reduction/Increase in fine-scale turbulence noise

$S = 0.10$ quietest configuration

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[1] *Sound Generation by Turbulence and Surfaces in Arbitrary Motion*, Williams, J.E. Ffowcs and Hawkings, D.L., *Philosophical transactions of the Royal Society of London. Series A: Mathematical and physical sciences* Vol. 264 No. 1151 (1972): pp. 321–342. DOI: 10.1098/rsta.1969.0031.

Swirling effect

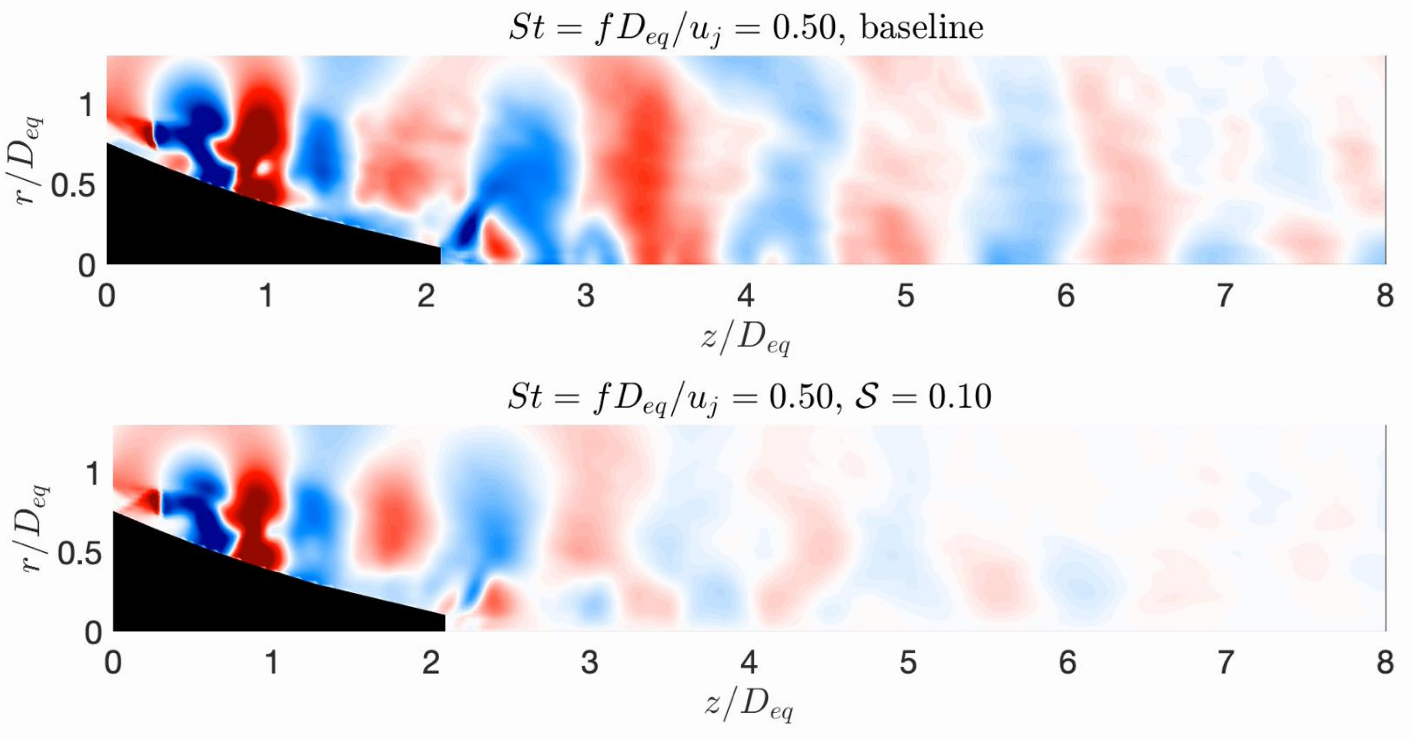
- Shock-associated noise/screech reduction
- **Faster decay of coherent structures**
- Higher order jet azimuthal modes

$$p(r,z,\theta,t) = \sum p_m(r,z,t)\, e^{im\theta}$$

$m = 0$ and $m = 1$ wavepackets[1]

- Vortex breakdown at higher swirl numbers

S	0.05	0.10	0.20	0.30
T/T_{ref}	0.99	0.99	0.97	0.75



Jet mode decomposition (SPOD)

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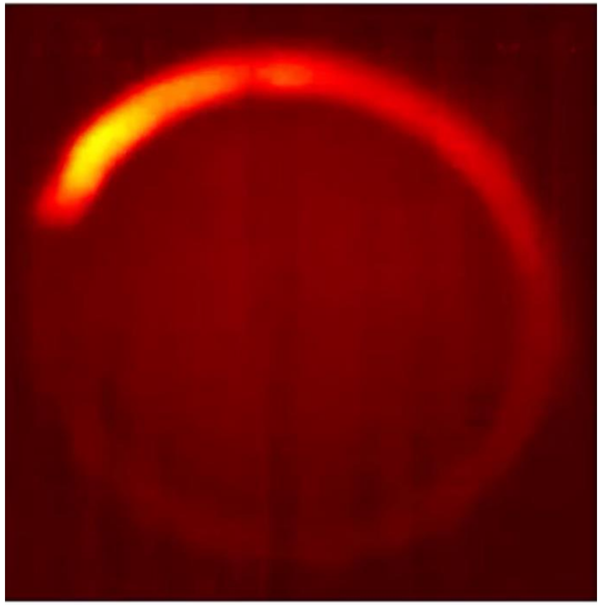
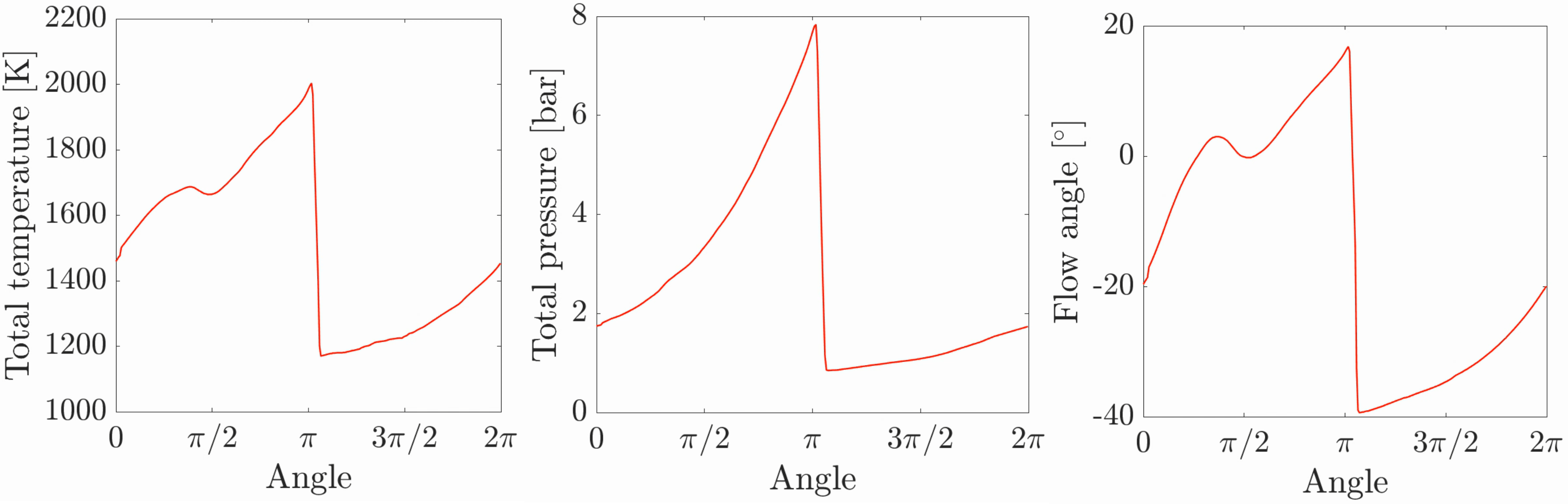
[1] *Noise sources in a low-Reynolds-number turbulent jet at Mach 0.9,* Freund, J.B., *Journal of Fluid Mechanics,* Vol. 438, 2001, pp. 277-305. DOI: 10.1017/S0022112001004414

Rotating Detonation Conditions

Boundary conditions

- Similar geometry to rigs at TU Berlin and U. Cincinnati ($v \sim 2800\ m/s$)
- Boundary conditions inspired by validated reactive Euler simulations[1]
- **Very complex flow physics**





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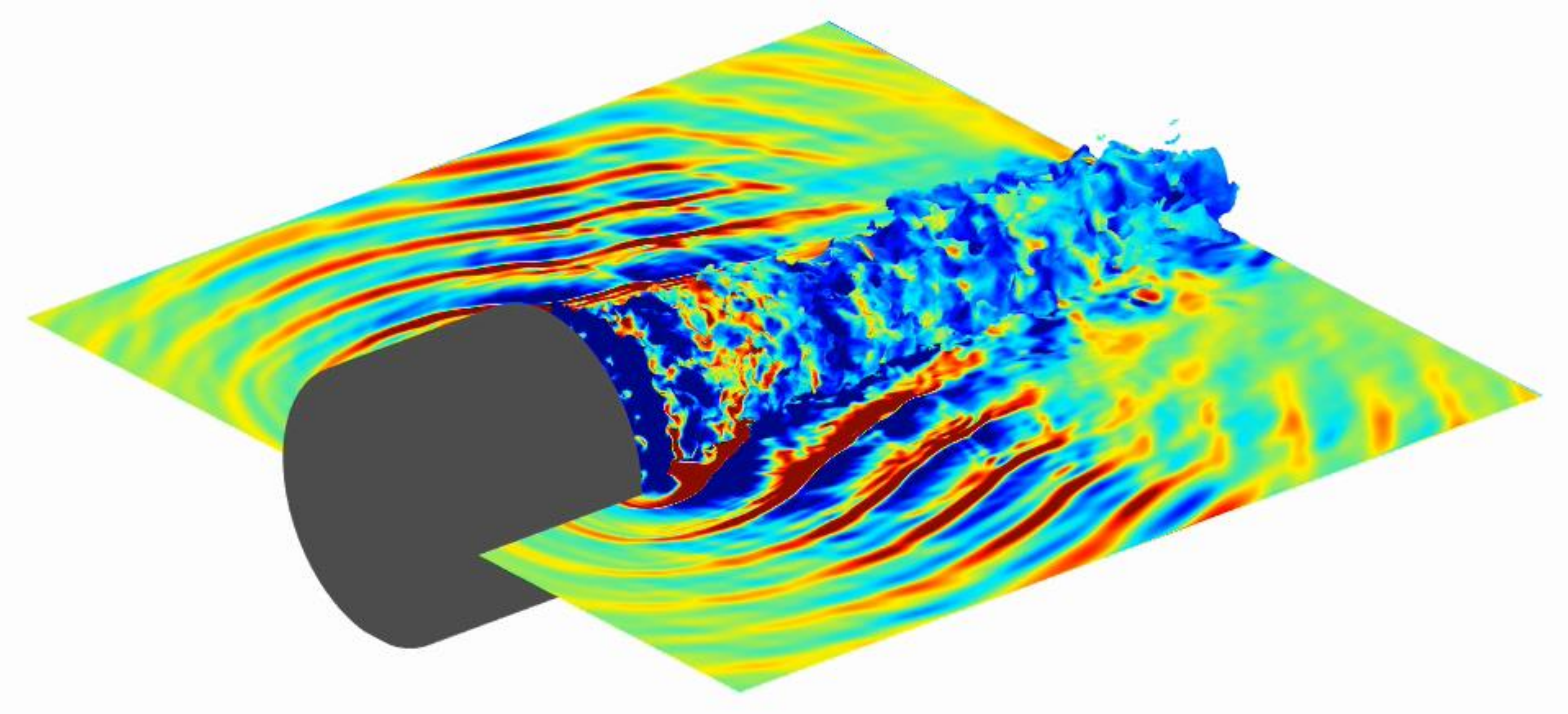
[1] *Parametric Influence on Rotating Detonation Combustion: Insights from Fast Reactive Euler Simulations*, Klopsch et al., *AIAA Journal*, Vol. 62 (1), 2024. DOI: 10.2514/1.J063193

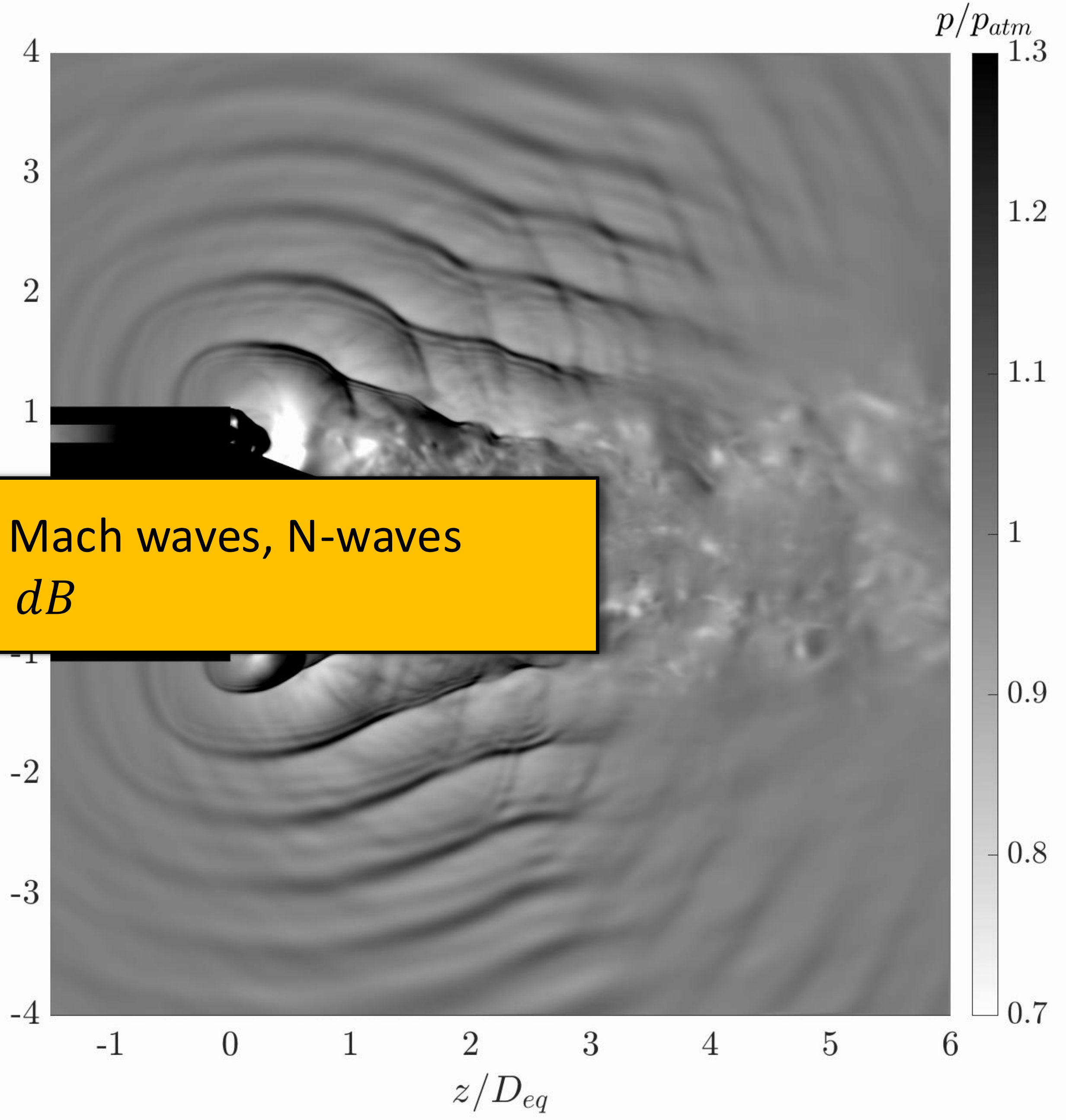


Isosurfaces of the Mach number ($M = 1.2$) colored by the density; acoustic pressure on the 2D plane

Rotating Detonation Effect

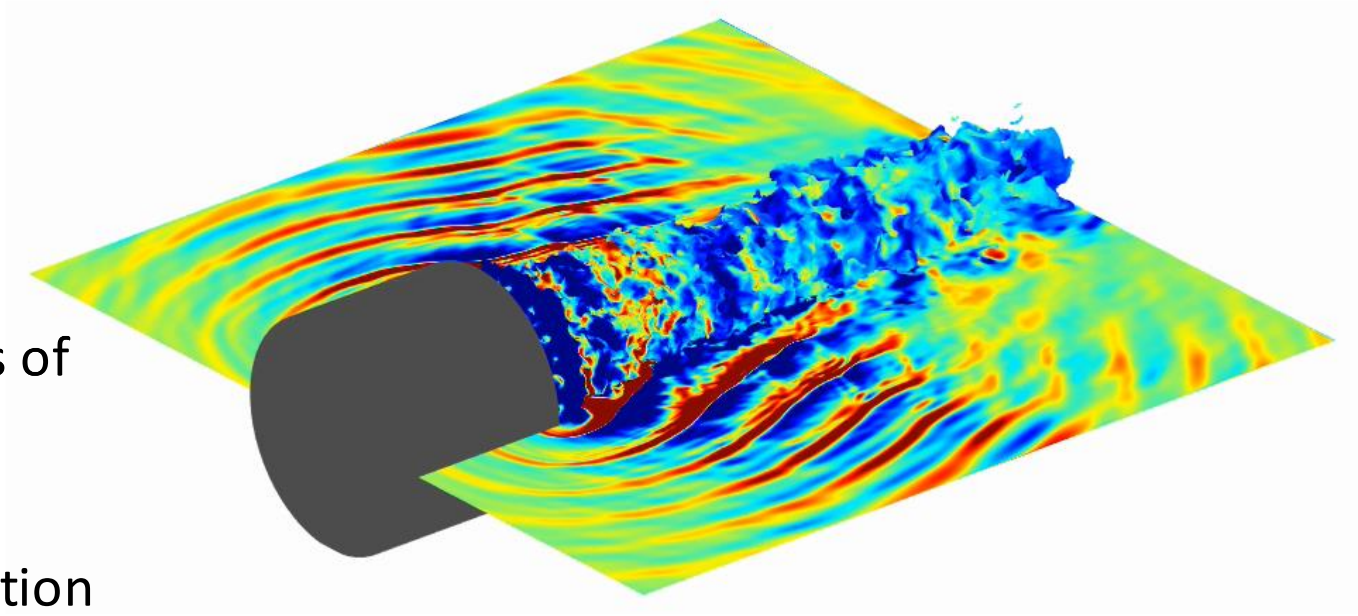
- **Strong effect of the residual oblique shock on the near-field acoustic**
- Non-linear wave propagation (N-waves)
- Streamwise de
  varying Mach w
- Acoustic scatte
  aerospike bluff body
- RDC acts like a forcing term for first jet azimuthal modes

$$p(r,z,\theta,t) \sim p_1(r,z,t)e^{i\theta}$$



Strong non-linear effects: Mach waves, N-waves
$\sim +15\ dB$

Outlook



- High-fidelity simulations and aeroacoustics of aerospike nozzles for RDC
- **RDC = Multifaceted engineering problem**
  - 15% decrease in specific fuel consumption
  - Combustion control
  - Acoustic emission
  - Thermal management
  - Embedment in a full-scale gas turbine
  - …
- Requires **experimentally validated, accurate predictive models** for further development and flow control
- Next milestones: **noise reducing technologies** (**chevrons**, fluid injection, coflow…)

Source: NASA

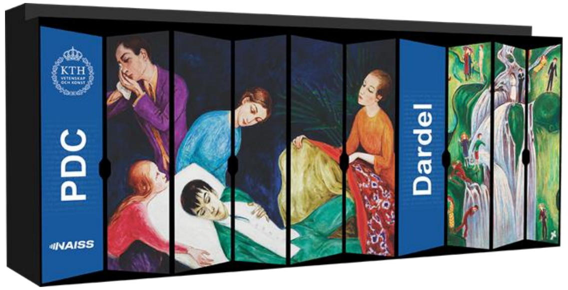
KTH VETENSKAP OCH KONST FLOW

Acknowledgments

INSPIRE-ETN
INSPIRING PRESSURE GAIN COMBUSTION INTEGRATION
RESEARCH, AND EDUCATION

NAISS

European Commission
Marie
Skłodowska-Curie
Actions



https://inspire.cerfacs.fr/en/

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PhD defense ~ March 2026

The aerospike geometry was provided by Prof. Gutmark (Univ. of Cincinnati)

This project has received funding from the "INSPIRE" EU Project H2020-MSCA-ITN-2020, Marie Skłodowska-Curie Innovative Training Networks, Project No. 956803.

Numerical Methods

Enhanced aeroacoustic capabilities with the finite volume-based flow solver

- Optimised artificial dissipation (Jameson-type) which separate turbulent structures and shocks, *Gojon, Gutmark, Mihaescu (2019), AIAA* Journal 57 (8): 3422-41.

Artificial dissipation [Ducros et al. JCP, 1999] at the end of each time step to the inviscid flow (Jameson type)

❑ $D_{01} = \left[\epsilon_{01}^{(2)}(U_1 - U_0) - \epsilon_{01}^{(4)}(\Delta U_1 - \Delta U_0)\right]\phi_{01} r_{01}$

Dissipation functions which separate turbulent structures and shocks

❑ $\epsilon_{01}^{(2)} = \max(\epsilon_0^{(2)}, \epsilon_1^{(2)})$ **with** $\epsilon_0^{(2)} = C_2 \phi_0 \left(\frac{|\sum p_k - p_0|}{\sum p_k + p_0}\right) s_2$

❑ $\epsilon_{01}^{(4)} = (\frac{1}{2} + \frac{1}{2}\min(\max(\phi_0, \phi_1), \max(\theta_0, \theta_1)))\ \max\left(0, C_4 - \epsilon_{01}^{(2)}\right) s_4$

Constants set to $(C2;\ C4) = (1.5, ; 0.04)$

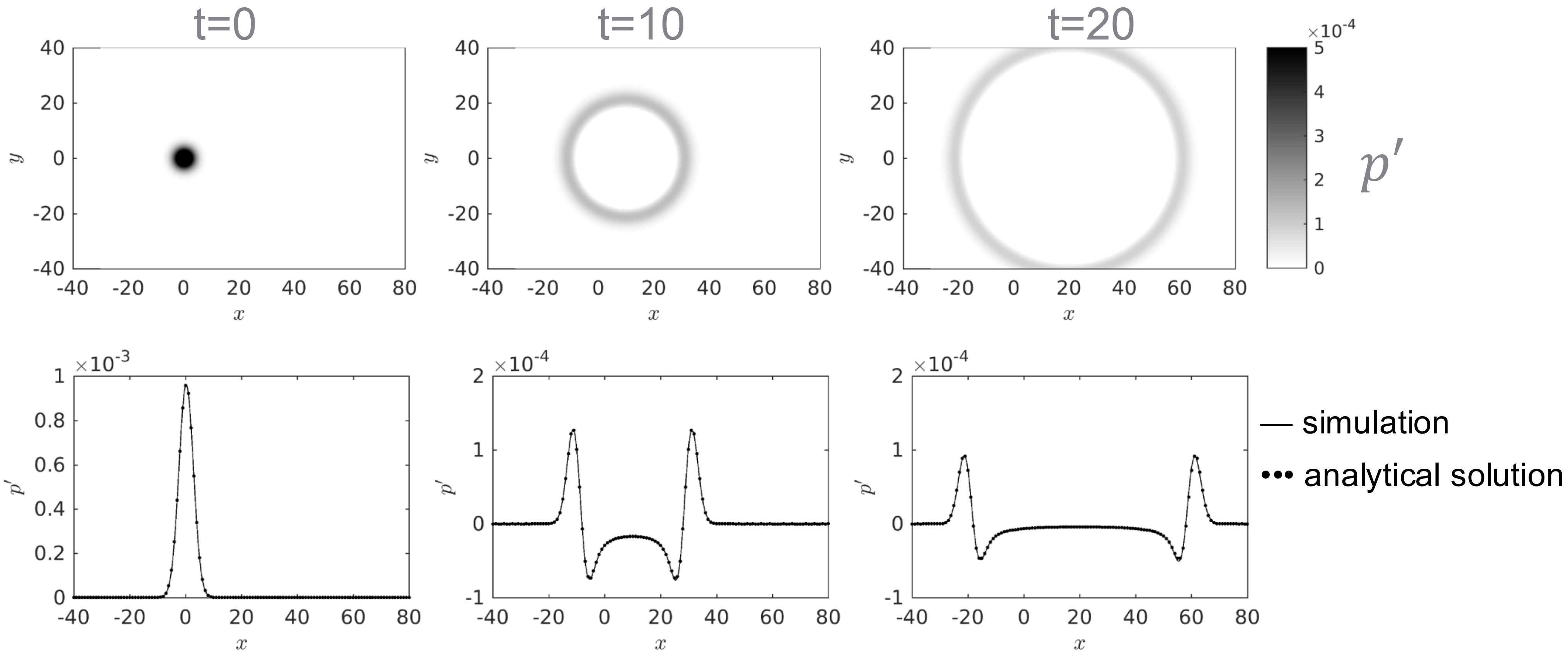
with

$\phi_0 = \frac{(\nabla . u_0)^2}{(\nabla . u_0)^2 + \omega^2}$ → ~ 1 **near shocks,** ~ 0 **elsewhere**

$\theta_0 = \frac{\omega^2}{(\nabla . u_0)^2 + \omega^2}$ → ~ 1 **near turbulent structures,** ~ 0 **elsewhere**

2-D test cases

❑ Acoustic pulse in a uniform flow (M = 0.5)

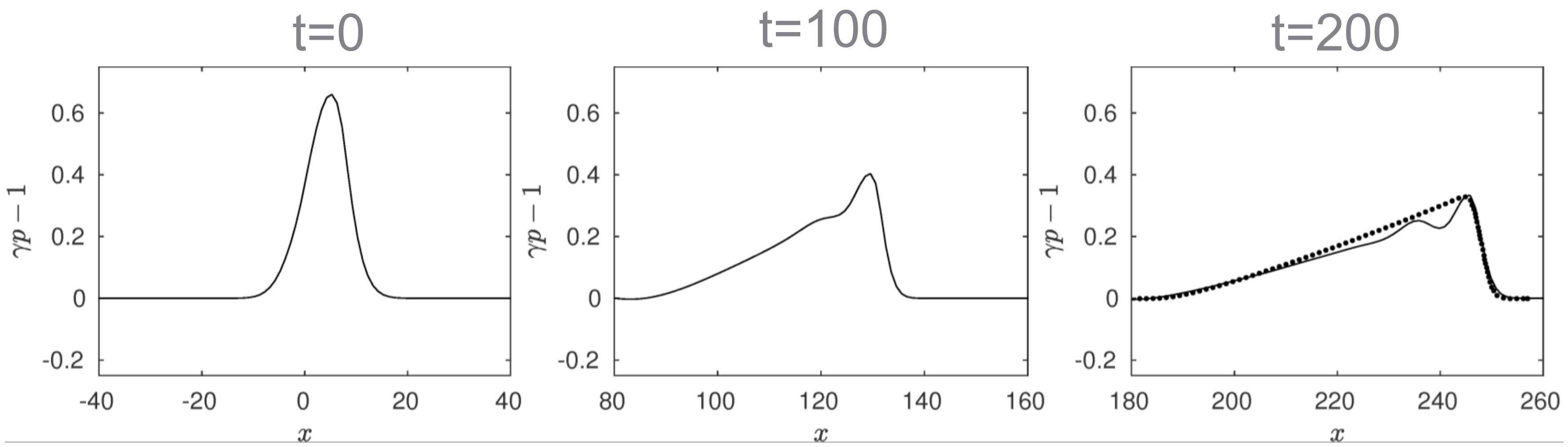


Ref: Tam and Webb (JCP,1993)

Gojon R., Gutmark, E.J., & Mihaescu M., (2017), *AIAA 2017- 0002.*

2-D test cases

❑ Shock propagation



— simulation

••• 1-D results from Bogey et al. (JCP,2009)

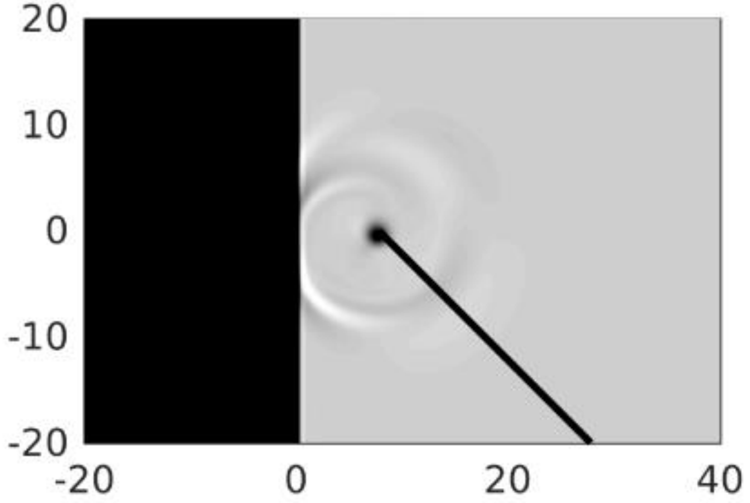
Good agreement with the 1-D results

Ref: Bogey et al. (JCP, 2009)

2-D test cases

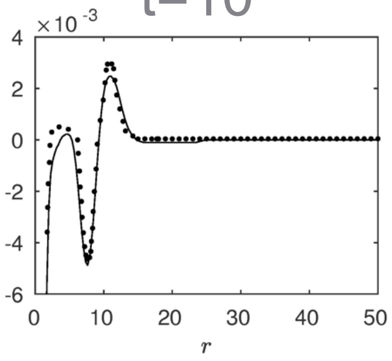
❑ Shock-vortex interaction

t=10

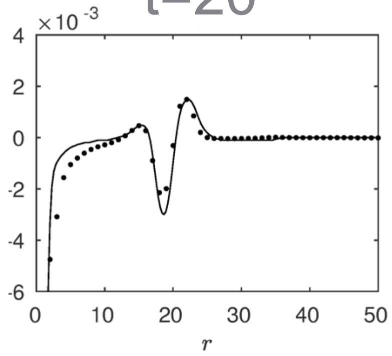


Comparisons, cut at $\theta = -45$
degrees from the vortex center

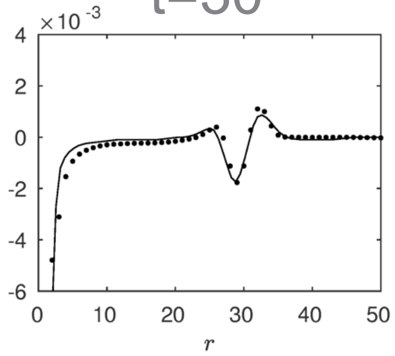
t=10



t=20



t=30



— simulation

• • DNS results of
Inoue (JFM, 1999)

Good agreement with the DNS results

Gojon R., Gutmark, E.J., & Mihaescu M., (2017), *AIAA 2017- 0002*.