Compressible flow solver: development and applications to subsonic/transonic flows

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Department of Aeronautics, Imperial College London

LFC-UK: Development of underpinning technology for laminar flow control

Nektar++ Workshop 2015, Imperial College London

Overview

Supersonic / Hypersonic

Supersonic military aircraft

Mach = u / c

Hypersonic re-entry vehicle

1 < Mach < 5

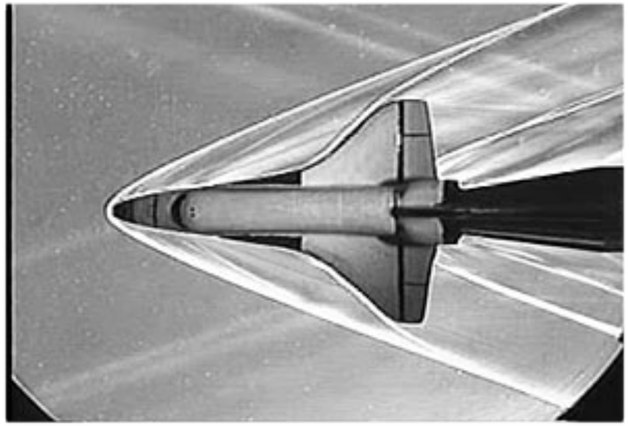
Mach > 5

Supersonic jet exhaust. Courtesy of Parviz Moin (CTR)

Overview

Supersonic / Hypersonic

Supersonic military aircraft



Hypersonic re-entry vehicle

1 < Mach < 5

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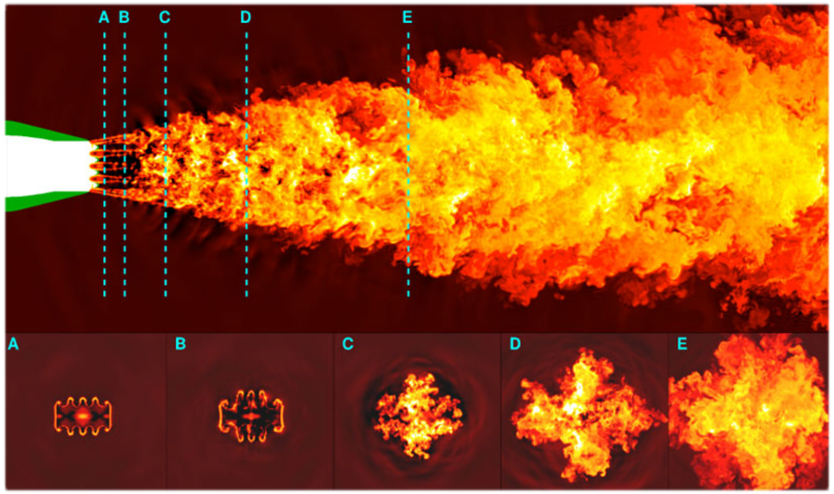


Supersonic jet exhaust. Courtesy of Parviz Moin (CTR)

Overview

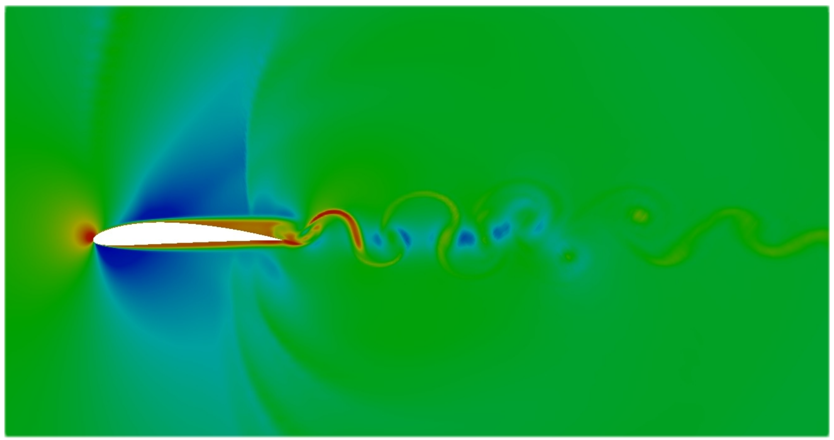
Subsonic / Transonic

Subsonic military transport aircraft

Transonic commercial airliner

Mach < 0.8

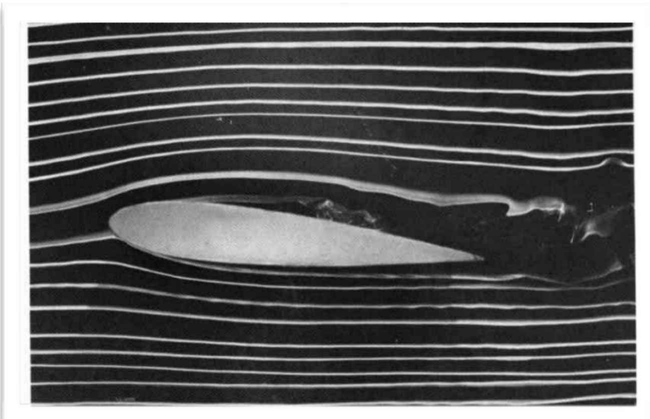
0.8 < Mach < 1.2



Transonic flow past an airfoil (Nektar++)

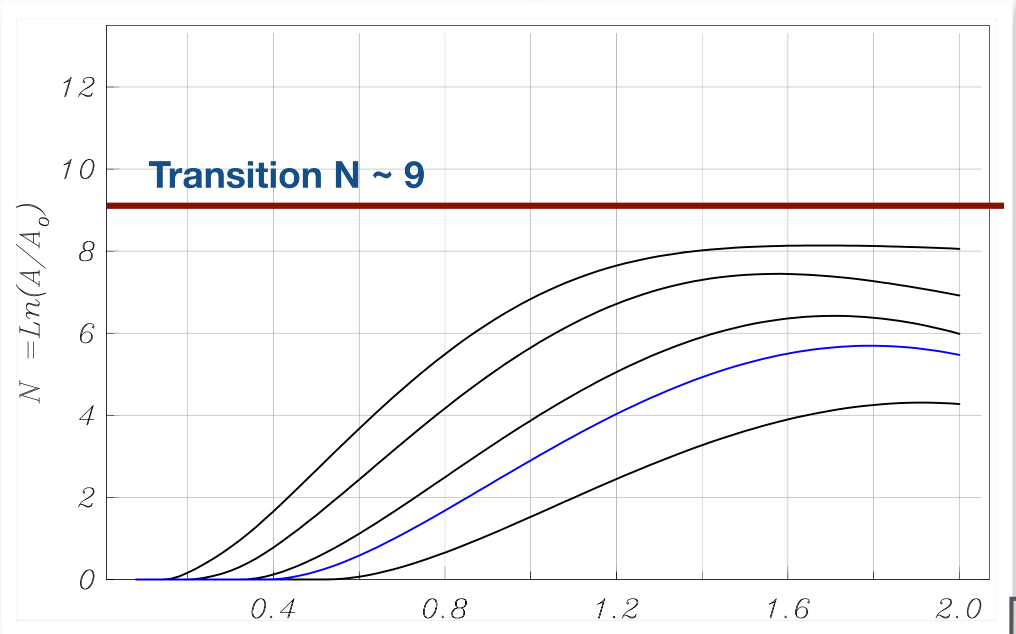
Overview

Subsonic / Transonic



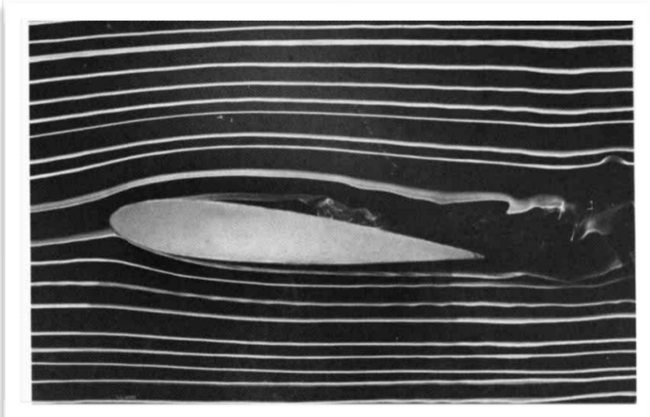
Overview

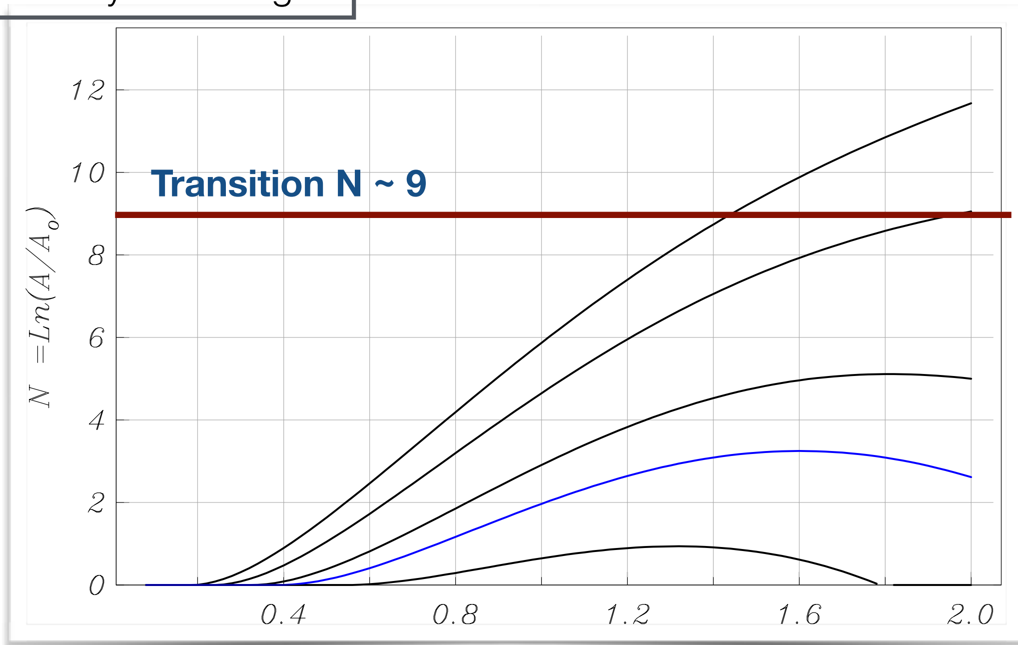
Subsonic / Transonic



Incompressible N-factors (e^N method)

Courtesy of S. Mughal





Compressible (transonic) N-factors (e^N method)

Overview

Compressible Flow Solver: Euler and Navier-Stokes equations

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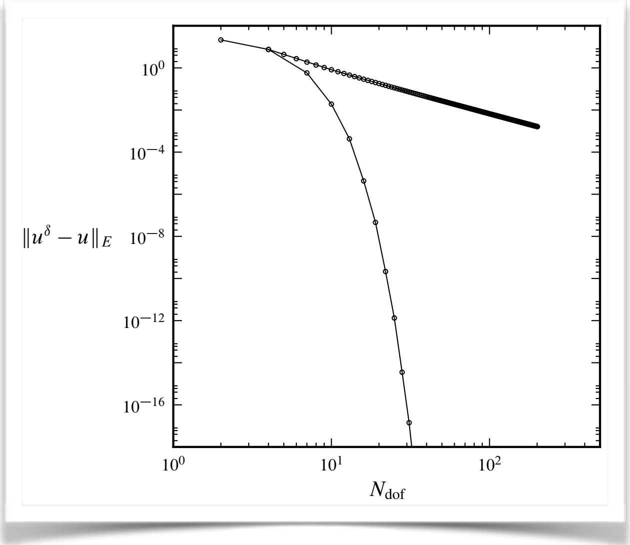

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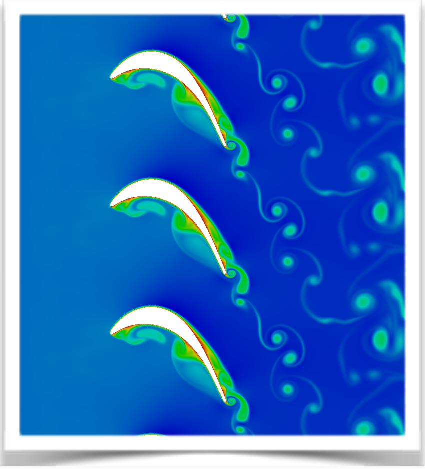
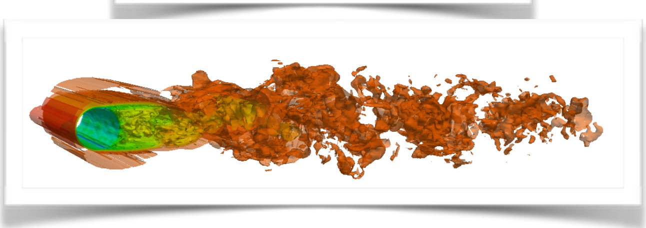
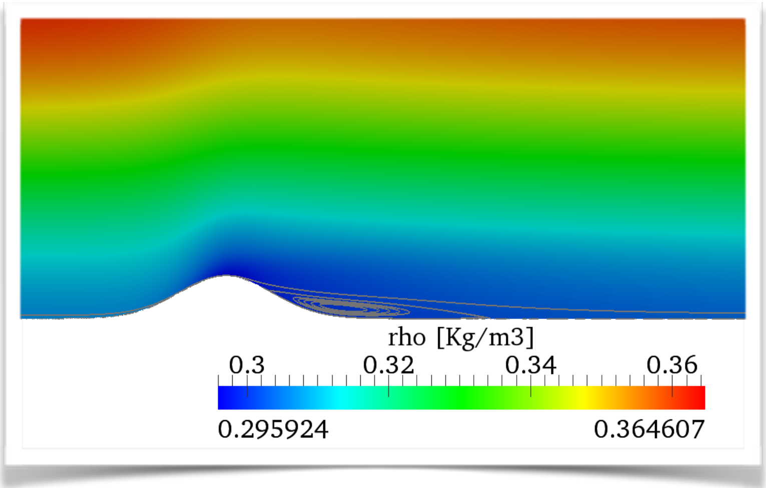




2. Stabilising techniques (dealiasing)



3. Subsonic/transonic flow applications

Outline

1. Underlying numerics (DG/FR)

2. Stabilising techniques (dealiasing)

3. Subsonic/transonic flow applications

4. Summary

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Underlying numerics

Account of History

Integral formulation

Discontinuous Galerkin (DG) method (Reed and Hill, 1973)

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$\Updownarrow$

Flux Reconstruction (FR) approach (Huynh, 2007)

Solution is discontinuous across elements

Underlying numerics

- Compressible (Euler and) Navier-Stokes equations

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot \mathcal{H}(\mathbf{u}, \nabla \mathbf{u}) = 0$$

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DG/FR

- Advective and diffusive flux tensors

$$\mathcal{H}(\mathbf{u}, \nabla \mathbf{u}) = \mathcal{H}^A(\mathbf{u}) + \mathcal{H}^D(\mathbf{u}, \nabla \mathbf{u})$$

Underlying numerics

- Compressible (Euler and) Navier-Stokes equations

$$\underbrace{\boxed{\frac{\partial \mathbf{u}}{\partial t}}}_{\text{Explicit}} + \underbrace{\boxed{\nabla \cdot \mathcal{H}(\mathbf{u}, \nabla \mathbf{u})}}_{\text{DG/FR}} = 0$$

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Explicit DG/FR

(Explicit —> RK, SSPRK, etc)

DG = Discontinuous Galerkin
FR = Flux Reconstruction

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- Geometrical flexibility ✔
- Parallelization ✔
- Stability (✔)

- Advective and diffusive flux tensors

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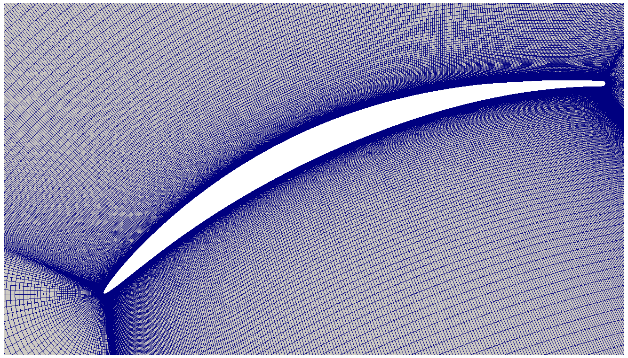
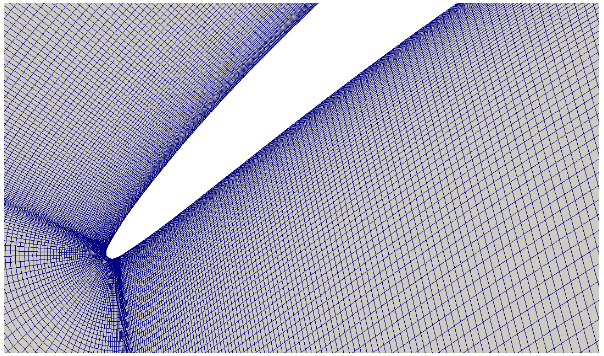
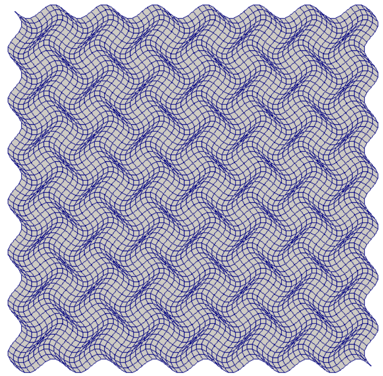
Unstructured (deformed/curved) elements

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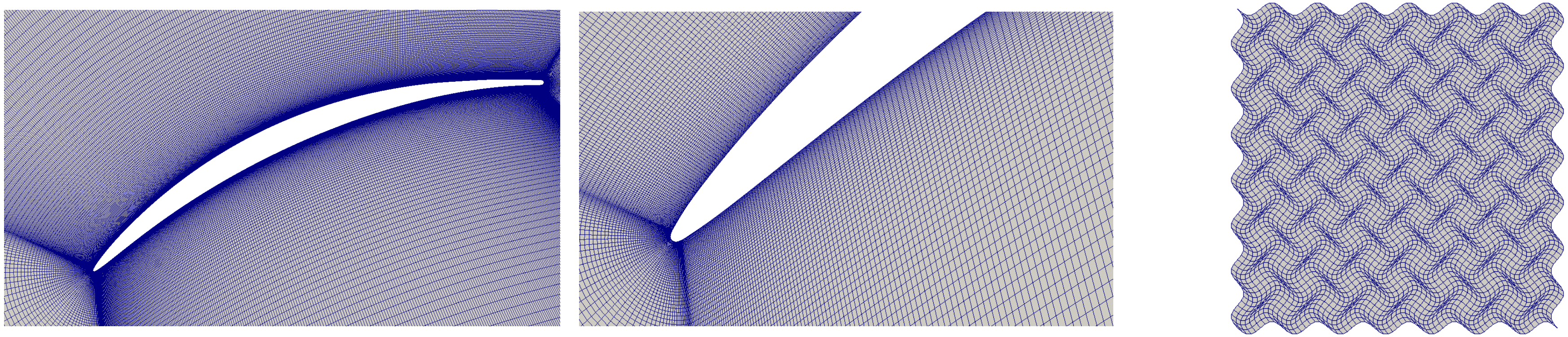

Map each element into a reference element

$$\boldsymbol{\xi} = \Theta(\boldsymbol{x})$$

Underlying numerics

DG = Discontinuous Galerkin

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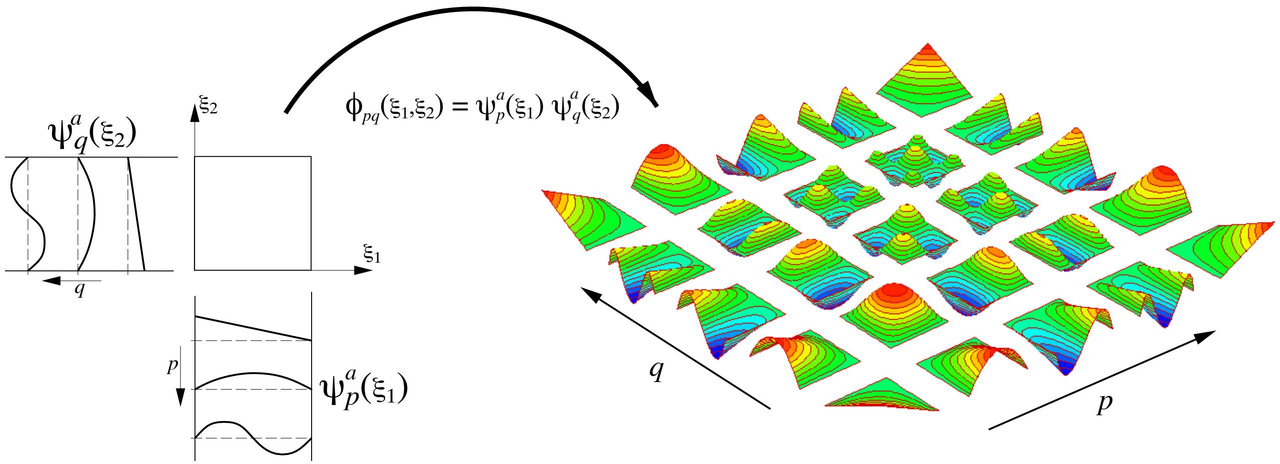
Define an expansion basis for each element



Up to now they are identical …

Underlying numerics

DG = Discontinuous Galerkin

Weak formulation

FR = Flux Reconstruction

Strong formulation

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Encapsulates DG among others[3]

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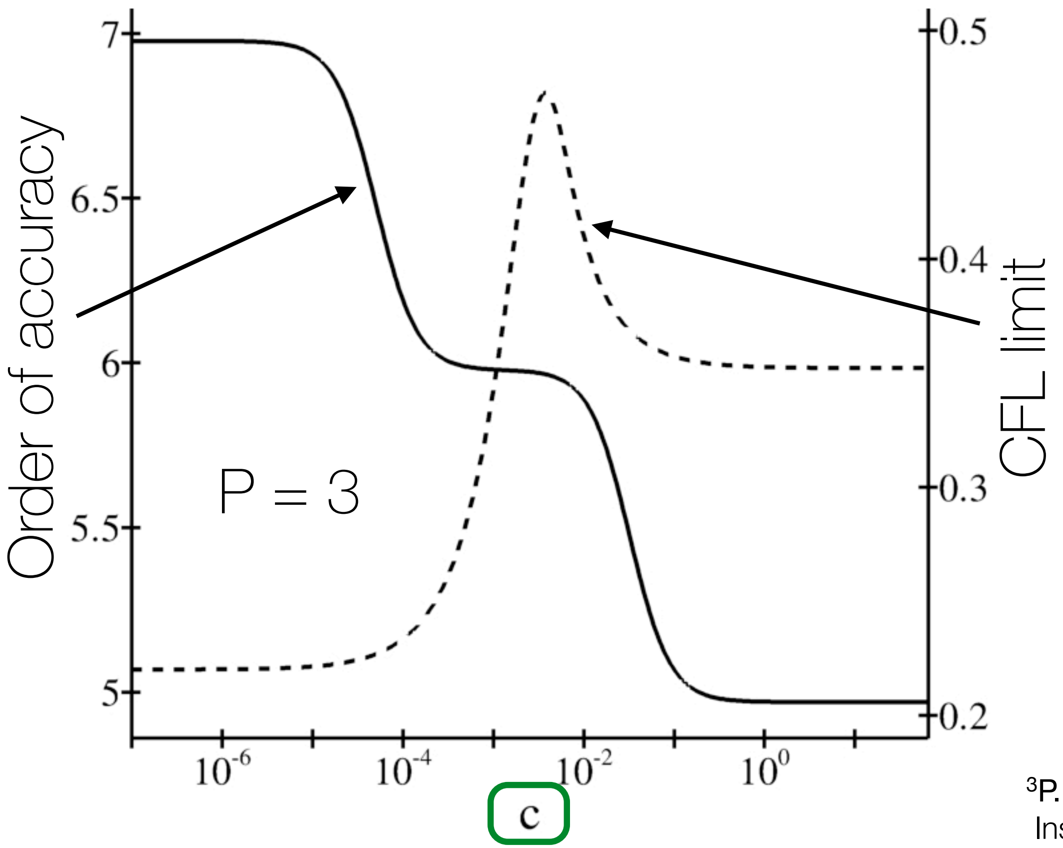

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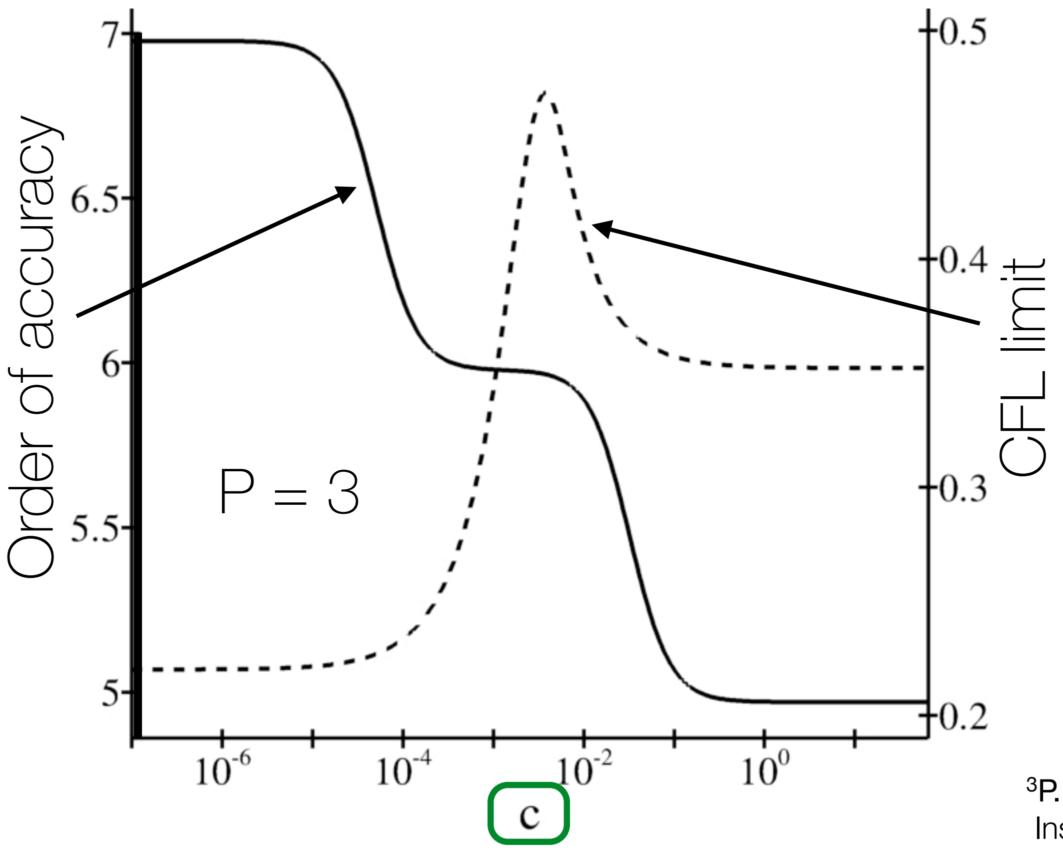

$c = 0$ FR$_{DG}$

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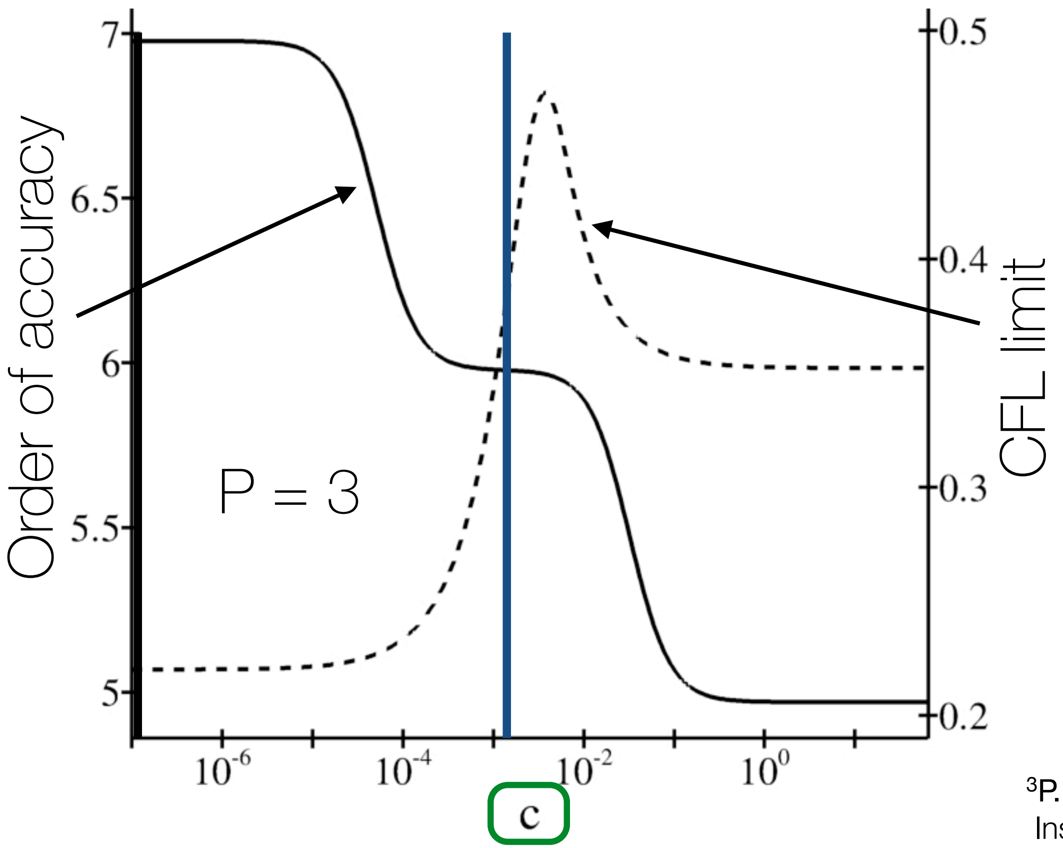

$c = 0$ $\quad FR_{DG}$

$$c = \frac{2(P+1)}{(2P+1)P(a_P P!)^2} \quad FR_{g2}$$

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We extended the proof to any nonlinear equation[1]

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Performance & Stability (✔)?

Inexact integration

Collocation-based

Exact integration

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2. Stabilising techniques (dealiasing)

3. Subsonic/transonic flow applications

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Stabilising techniques

Overview

Under- or marginal-resolution

High-Reynolds number flows

Inexact integration of the nonlinearities

Stabilising techniques

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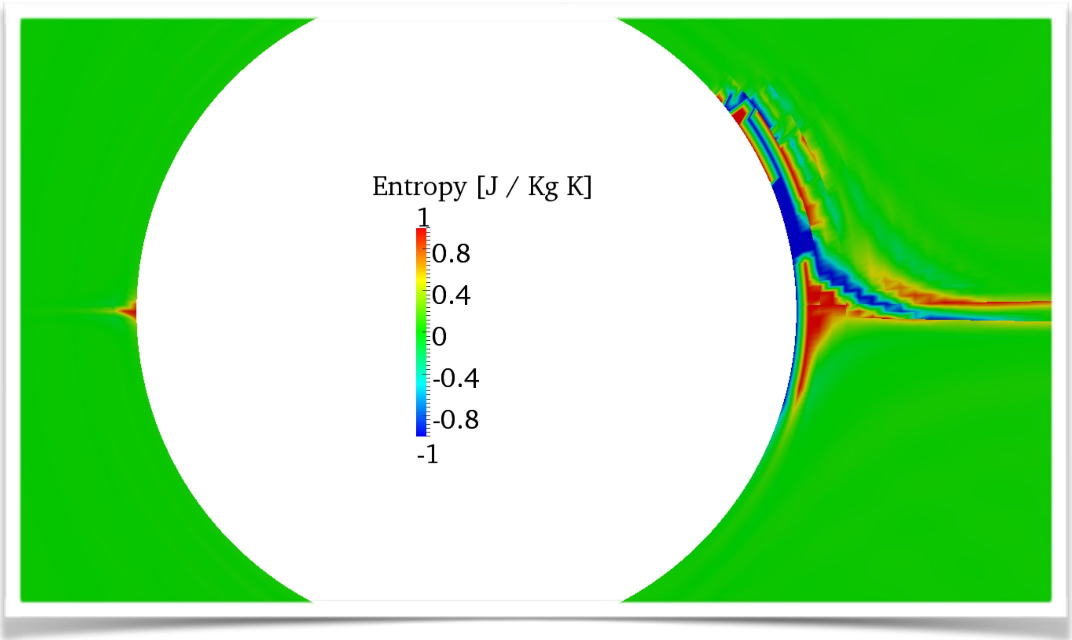

Unstable simulation due to under-resolution errors and inexact integration

Stabilising techniques

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- Consistent integration of the nonlinearities

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- Spectral Vanishing Viscosity (SVV) + others

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- More stable forms of the governing equations
  - Skew-symmetric form
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Overview

- Consistent integration of the nonlinearities
- Spectral Vanishing Viscosity (SVV) + others
- More stable forms of the governing equations
  - Skew-symmetric form
  - ...
- Optimal choice of the quadrature points

Stabilising techniques

Overview

- Consistent integration of the nonlinearities

$+^2$

- Spectral Vanishing Viscosity (SVV)

[2]J. Lombard et al. (Joint work between Imperial College and McLaren Racing)
Transient simulation of a wingtip vortex at $Re_c = 1.2\text{x}10^6$
Under Review, AIAA Journal, 2015,

Stabilising techniques

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- Consistent integration of the nonlinearities[3]

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Stabilising techniques

Aliasing sources

‘Nonlinearities’ in the equations —> PDE aliasing

‘Nonlinearities’ in the geometry —> Geometrical aliasing

Stabilising techniques

Aliasing sources

'Nonlinearities' in the equations —> PDE aliasing

$$\frac{\partial u}{\partial t} + \boxed{\nabla \cdot \boldsymbol{f}} = 0$$

nonlinear/quasi-linear fluxes

$$\frac{\partial u}{\partial t} + \boxed{a \frac{\partial u}{\partial x}} = 0$$

$$\boxed{a = a(u)}$$

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'Nonlinearities' in the geometry —> Geometrical aliasing

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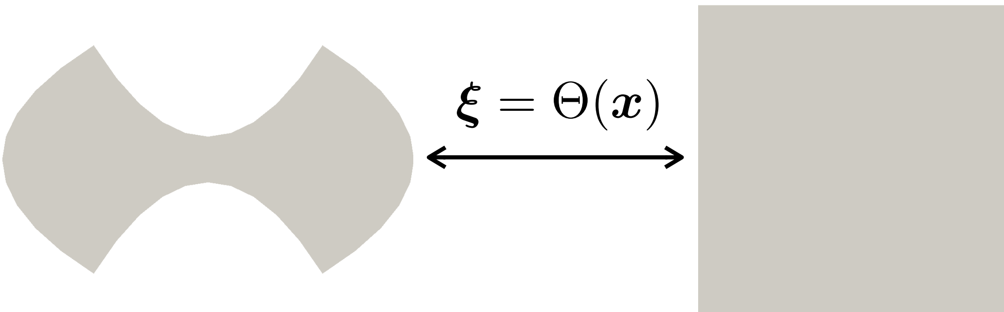

Spatially varying geometric factors

Stabilising techniques

Dealiasing strategies

- Consistent integration of the nonlinearities

Local

DG $$\frac{\mathrm{d}u}{\mathrm{d}t} = \mathbf{M}^{-1}\Big|_{Q_P}\left(\mathcal{L}_V\Big|_{Q_P} + \mathcal{L}_I\Big|_{Q_P} + \mathcal{N}_V\Big|_{Q_V} + \mathcal{N}_I\Big|_{Q_I}\right)$$

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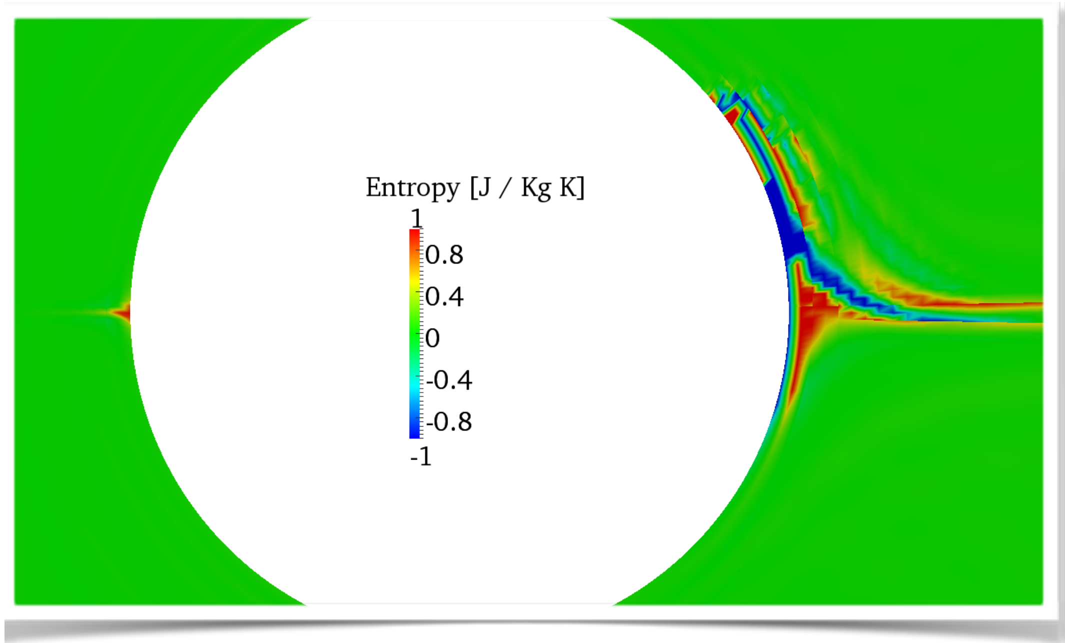
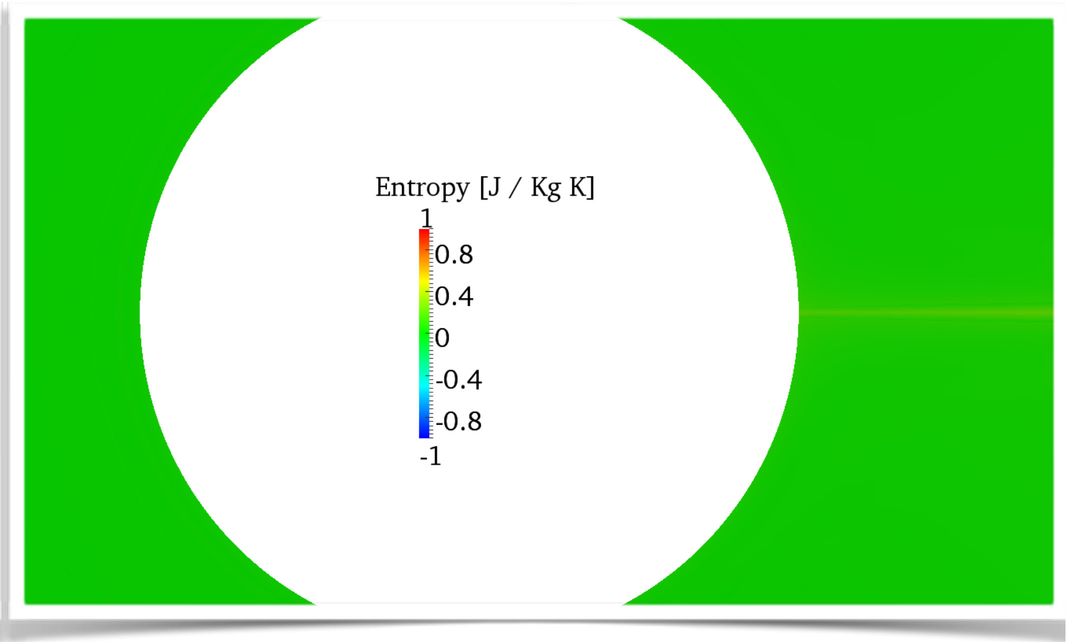
Stabilising techniques

Flow applications

Compressible Euler equations



Unstable simulation due to under-resolution and under-integration errors

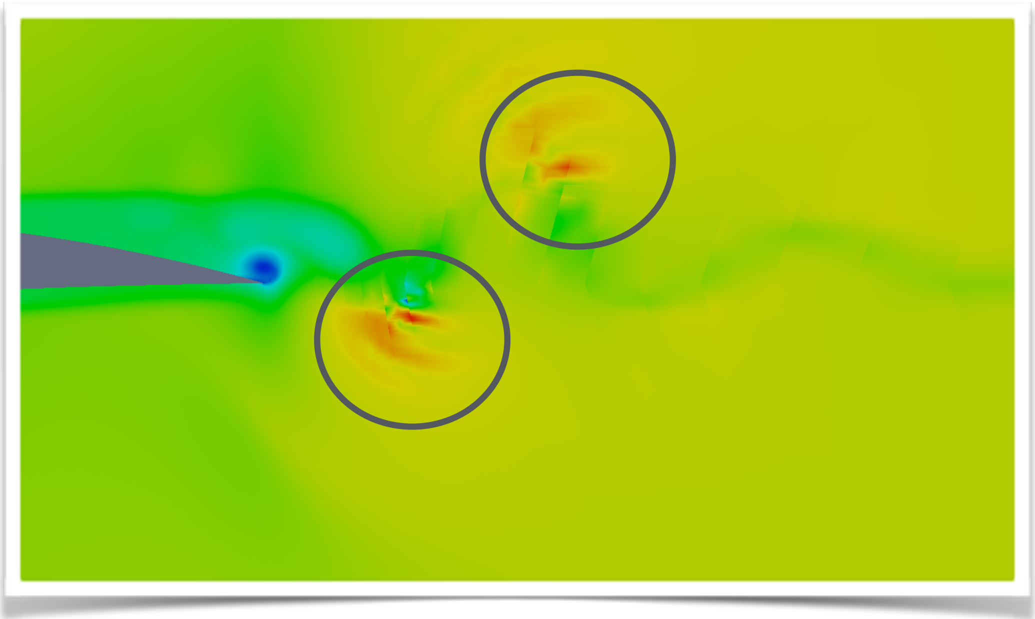


Stable simulation with Local dealiasing technique

Stabilising techniques

Flow applications

Compressible Navier-Stokes equations - NACA 4412



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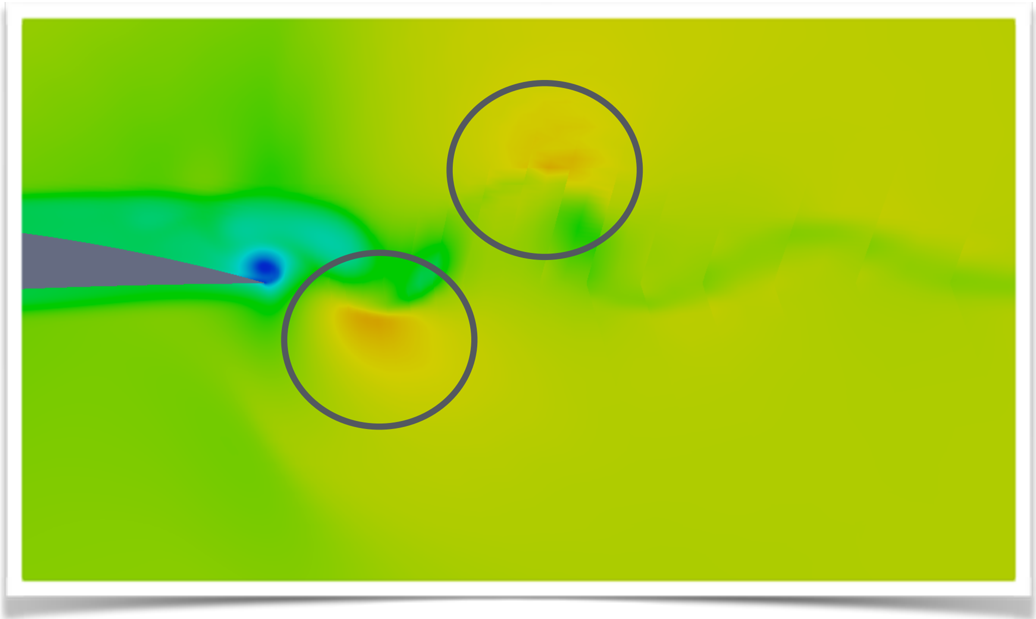

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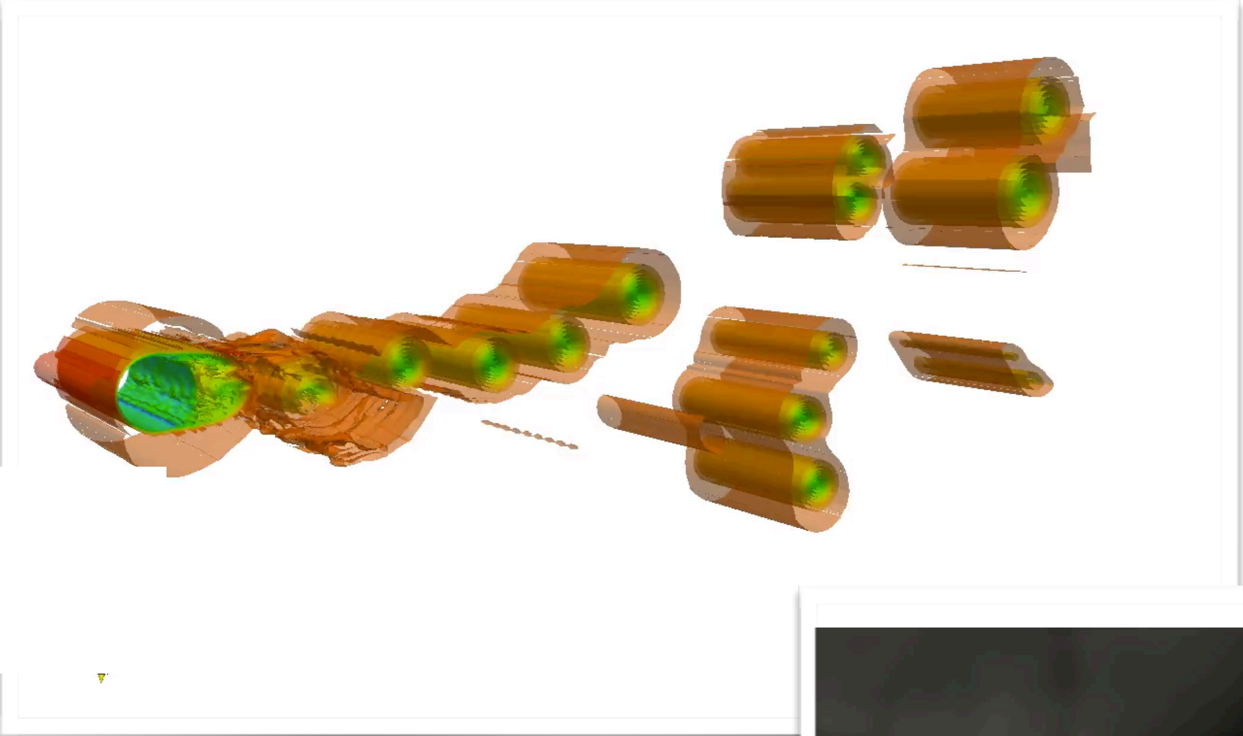

Cylinder - Density
Mach = 0.2, Re = 3900
Local dealiasing

T106C blade - Temperature
Mach = 0.2, Re = 200
Local dealiasing

Stabilising techniques

Summary

- Consistent integration improves robustness
- Local/global dealiasing techniques can be equally applied to DG and FR
- Local approach enhance efficiency
- Additional details[3]

[3] G. Mengaldo D. De Grazia, D. Moxey, P.E. Vincent and S.J. Sherwin
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1. Underlying numerics (DG/FR)

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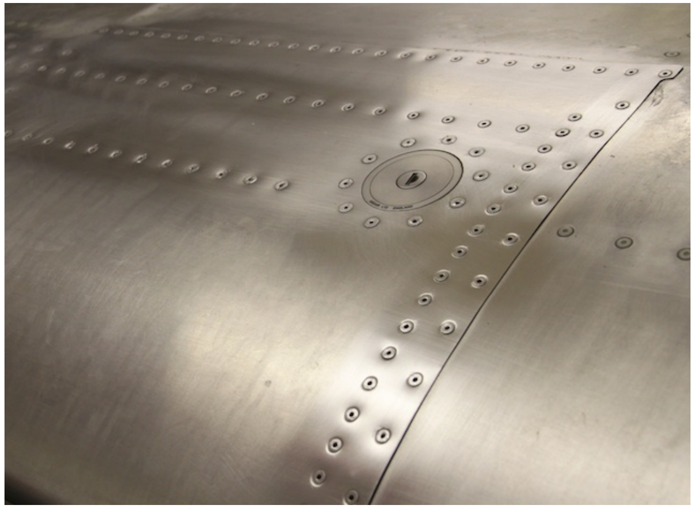
3. Subsonic/transonic flow applications

4. Summary

Subsonic/transonic applications

Motivation

Roughness elements / steps / gaps / imperfections are a common feature on wings



Boundary-layer instabilities and separation

Subsonic/transonic applications

Motivation

Boundary-layer instabilities and separation

Reduced models (triple-deck theory)

Numerical solution of the governing equations (DNS/LES)

Wind tunnel experiments

LFC-UK

Flight experiments

Subsonic/transonic applications

Motivation

Boundary-layer instabilities and separation

Focus of this work

Reduced models (triple-deck theory)

Numerical solution of the governing equations (DNS/LES)

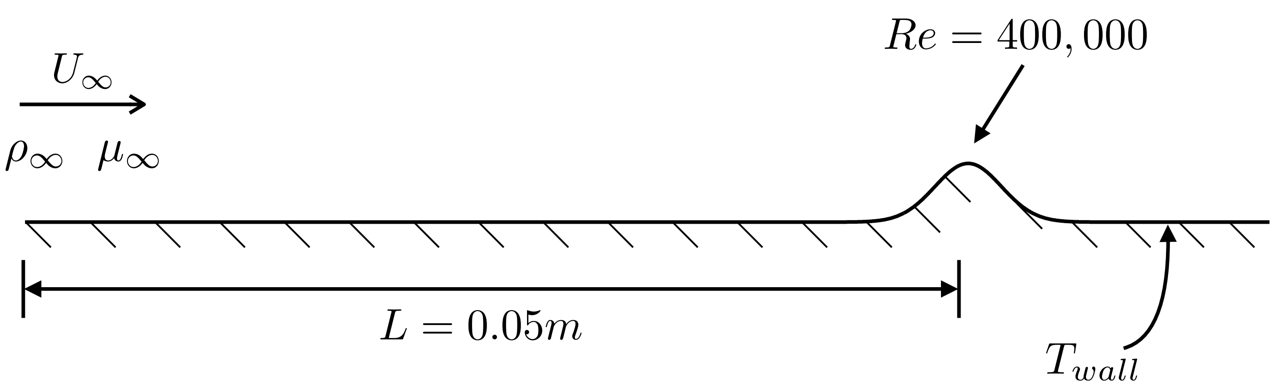
Wind tunnel experiments

LFC-UK

Flight experiments

Subsonic/transonic applications

Model problem



Idealised small imperfections at leading-edge

	$M = \frac{U_\infty}{c_\infty}$	T_{wall}	h_r	$Re = \frac{\rho U_\infty L}{\mu}$	$Pr = \frac{C_p \mu}{\kappa}$
Case 1	0.50	216.29 K	[0.05, 0.10, 0.15] δ_{99}	4x10^5	0.72
Case 2	0.87	258.0 K	[0.05, 0.10, 0.15] δ_{99}	4x10^5	0.72

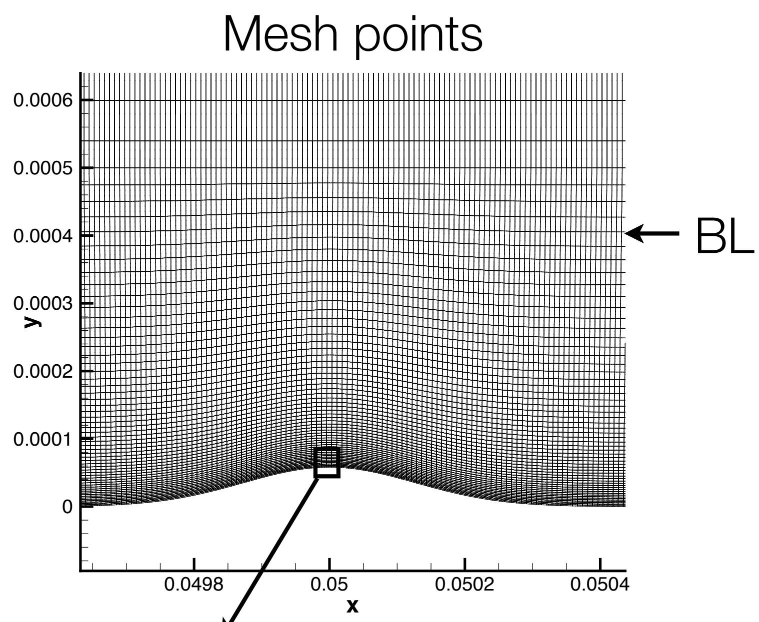
Subsonic/transonic applications

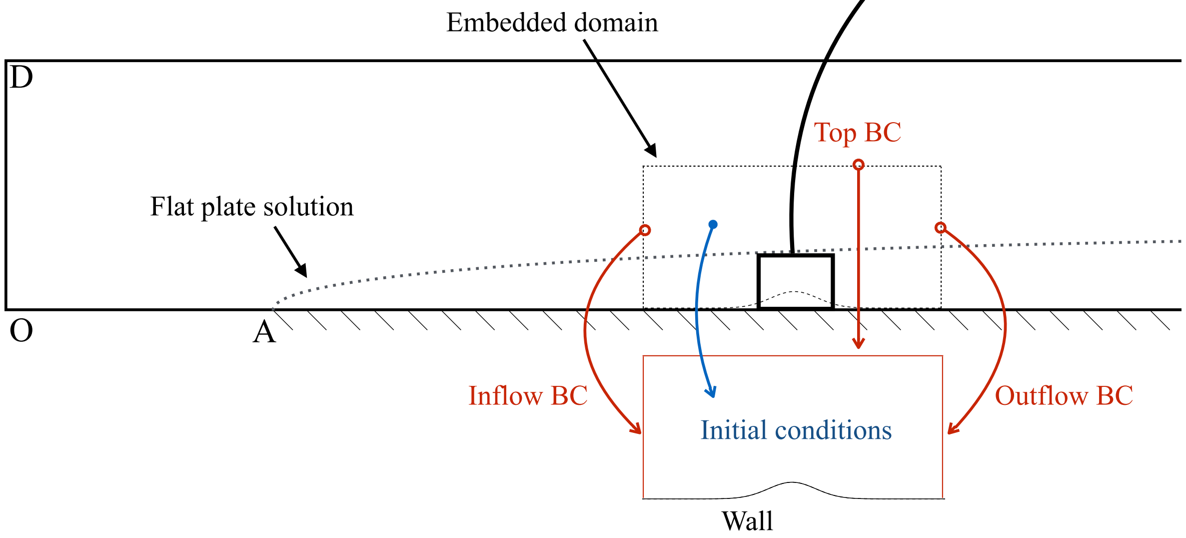
DNS process

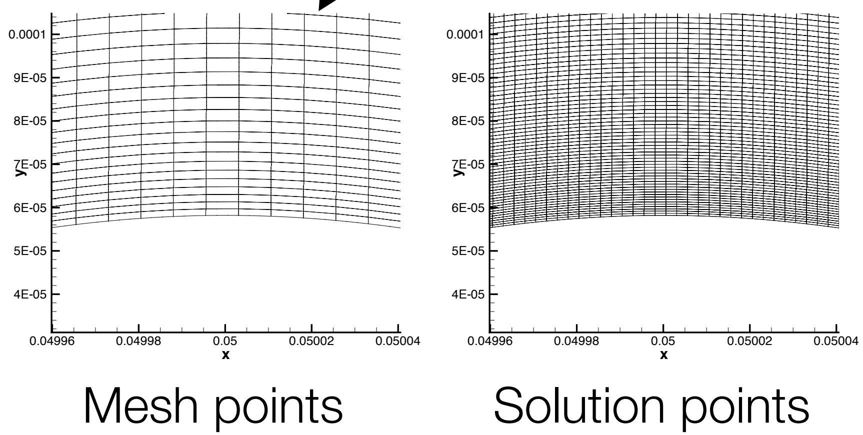
Embedded domain resolution

$$N_{el,x} = 500, N_{el,y} = 66 \text{ (55 within BL)}$$

$$\Delta x_{min} < 50^{-6}m, \ \Delta y_{min} < 10^{-6}m$$







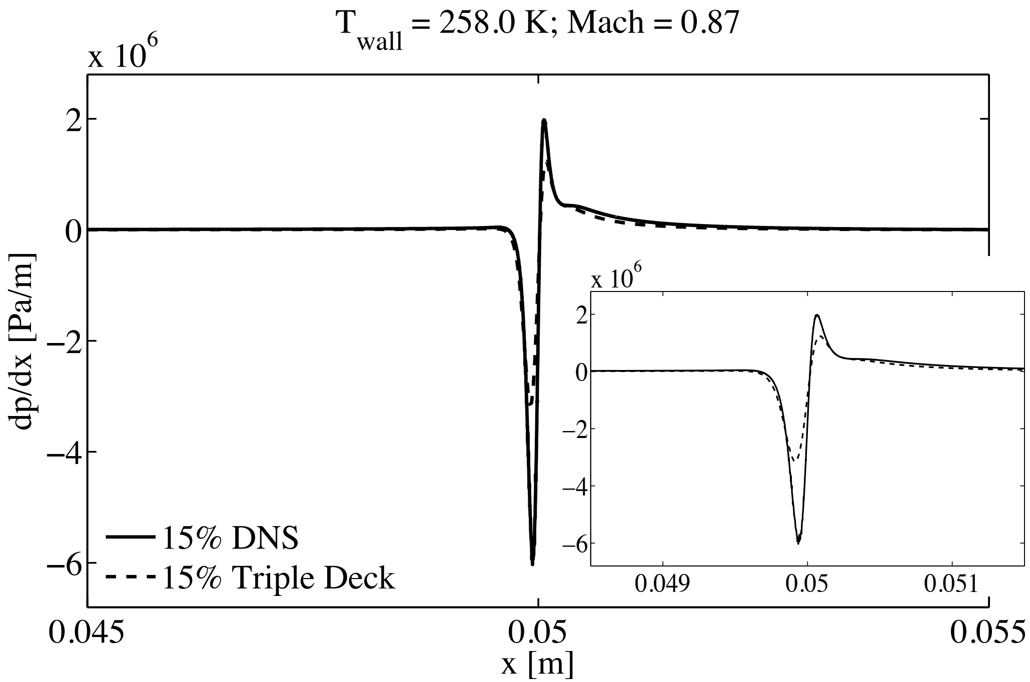
Subsonic/transonic applications

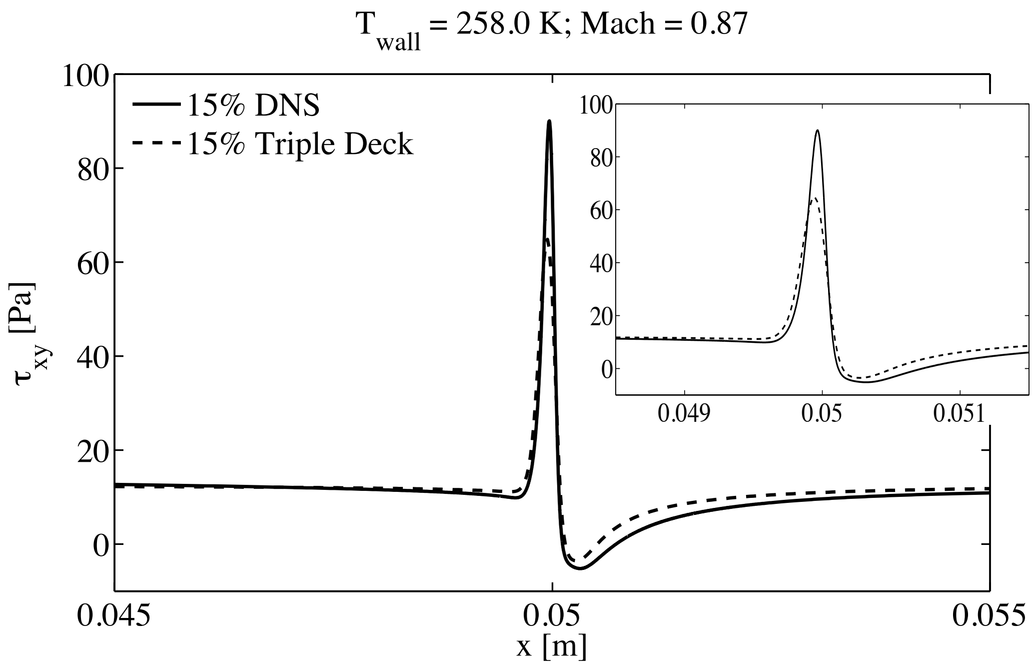
Triple-deck[4]

[4] G. Mengaldo, M. Kravtsova, A.I. Ruban, and S.J. Sherwin
Triple-deck and direct numerical simulation analyses of high-speed subsonic flows past a roughness element
Journal of Fluid Mechanics, 2015, Volume 774

Subsonic/transonic applications

Triple-deck[4]





$\longrightarrow h_r = 0.15\, \boldsymbol{\delta}_{99}$

- Differences increase with hump height

[4]G. Mengaldo, M. Kravtsova, A.I. Ruban, and S.J. Sherwin
Triple-deck and direct numerical simulation analyses of high-speed subsonic flows past a roughness element
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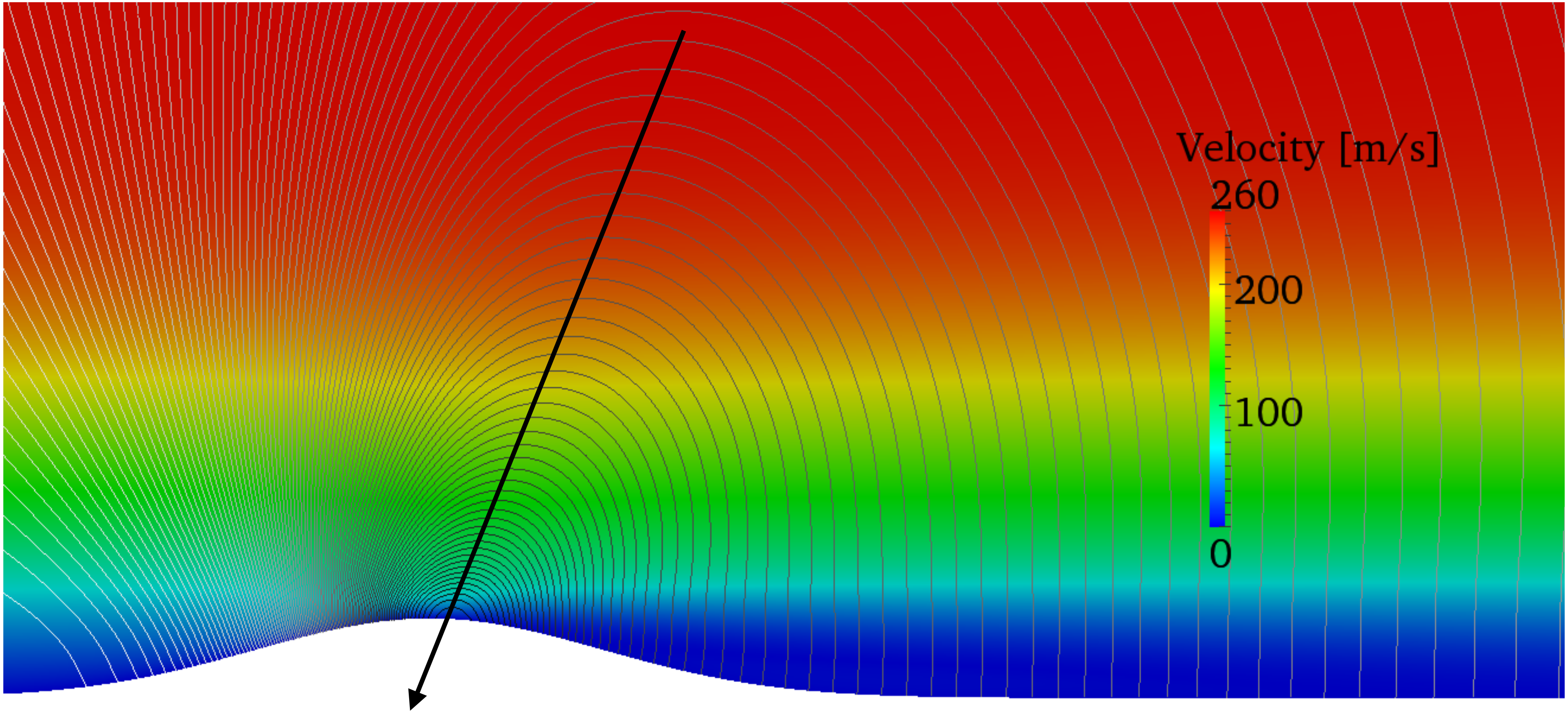
Subsonic/transonic applications

Triple-deck

Grey lines = iso-contours of pressure

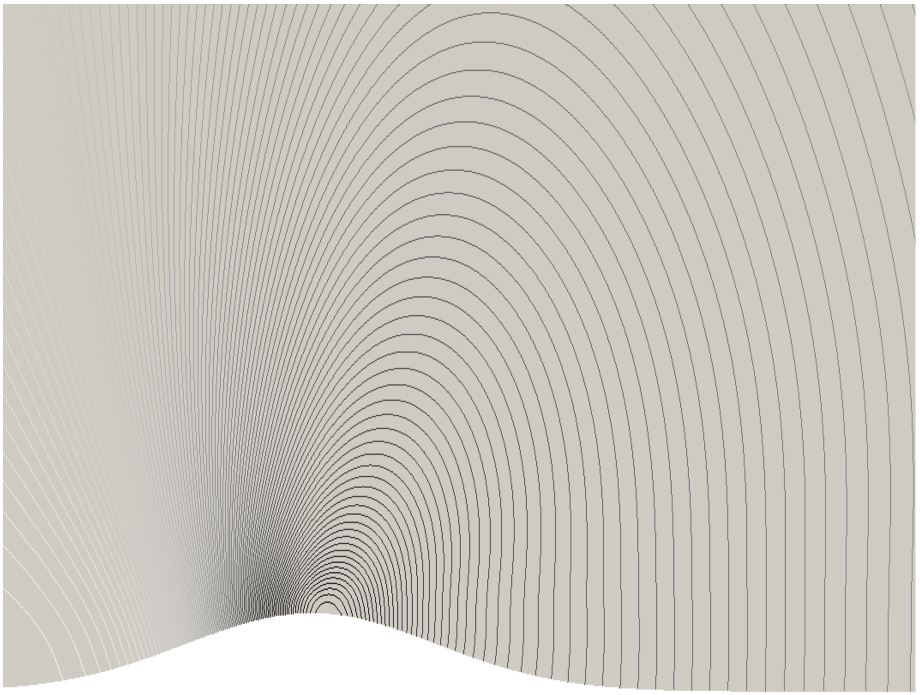


Wall-normal pressure gradient

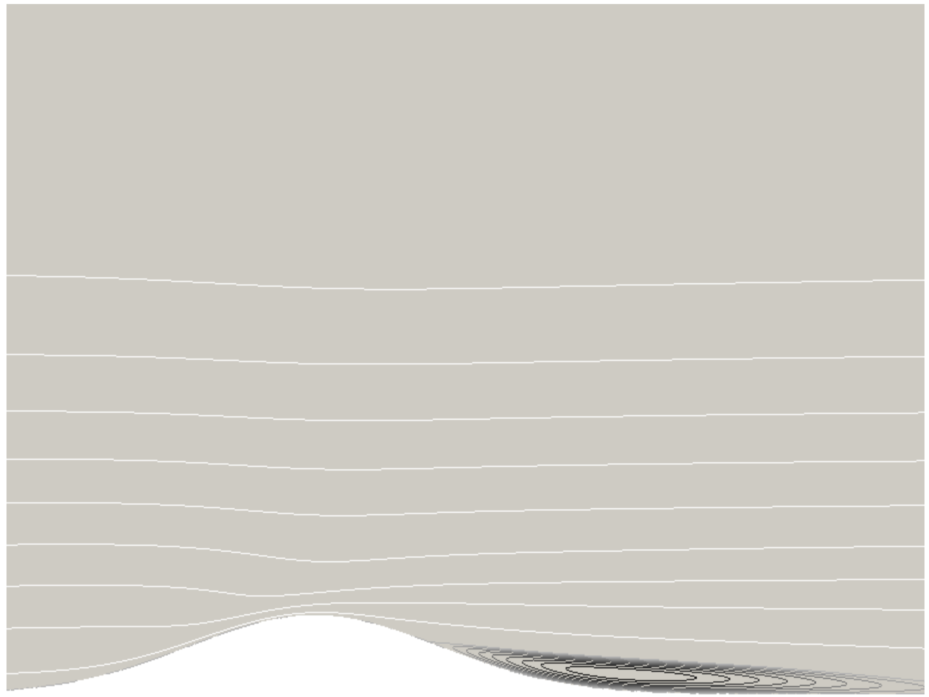
Subsonic/transonic applications

Triple-deck

Iso-contours of pressure



Iso-contours of velocity



Wall-normal pressure gradient

- sharper and higher peaks in DNS
- different flow acceleration/deceleration
- noticeable difference in the reattachment point

Subsonic/transonic applications

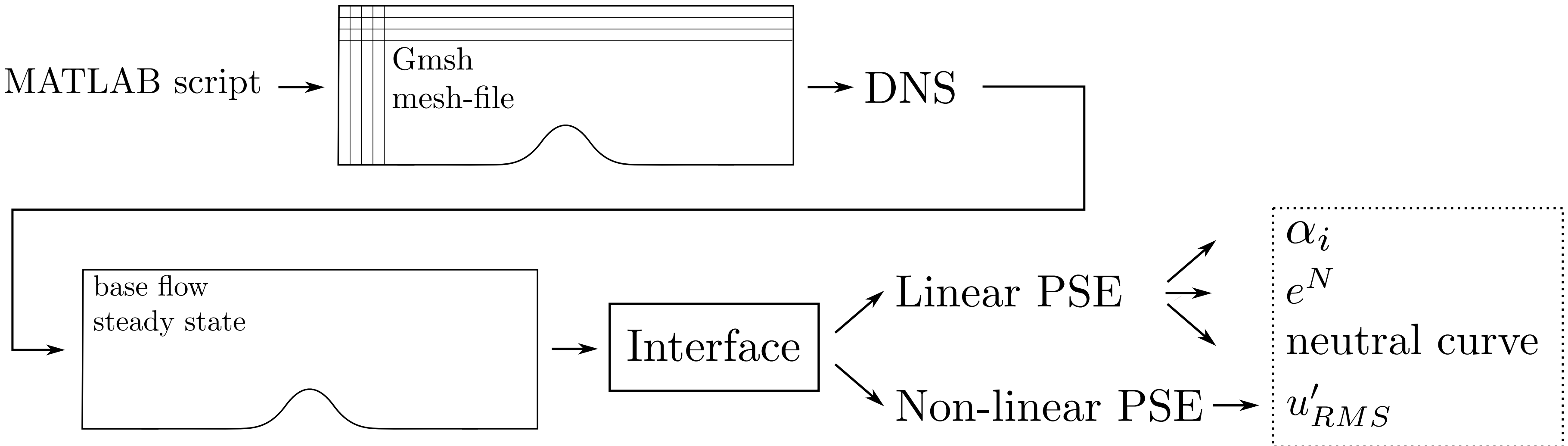
PSE + LST

Framework for linear/nonlinear PSE & LST on complex geometries

Subsonic/transonic applications

PSE + LST

Framework for linear/nonlinear PSE & LST on complex geometries



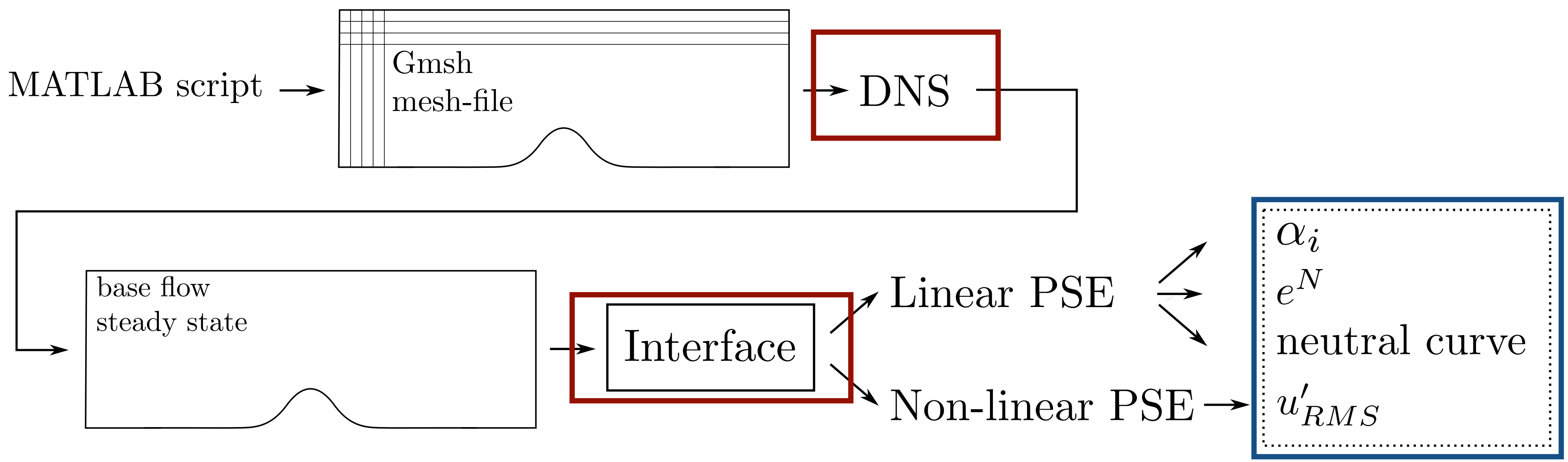
Subsonic/transonic applications

PSE + LST

Framework for linear/nonlinear PSE & LST on complex geometries

Nektar++ to obtain high-fidelity DNS data

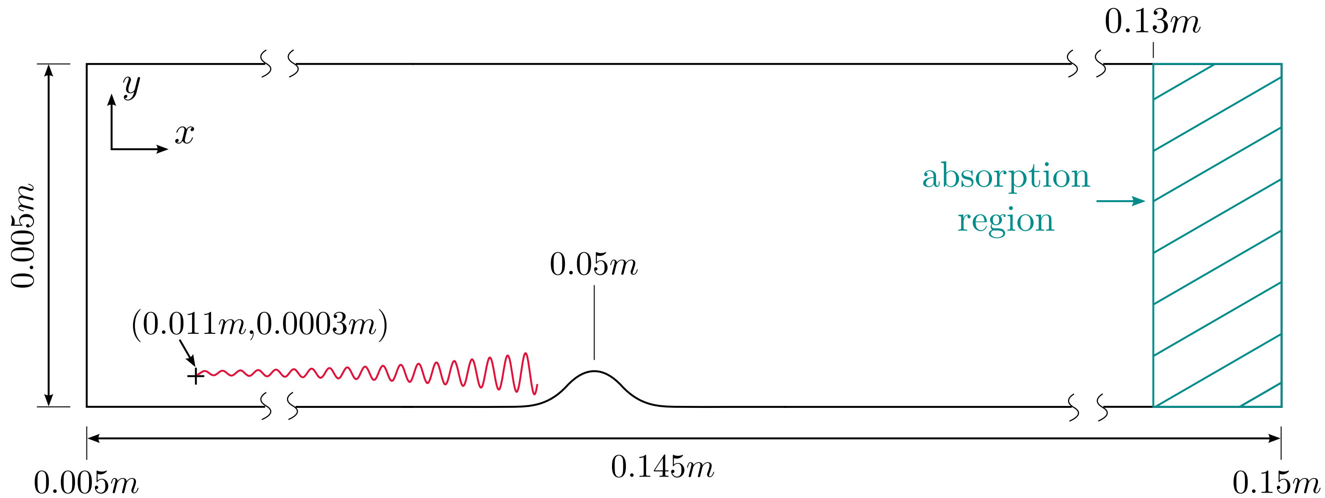
Interface tool for existing linear/nonlinear PSE & LST codes



Subsonic/transonic applications

PSE + LST

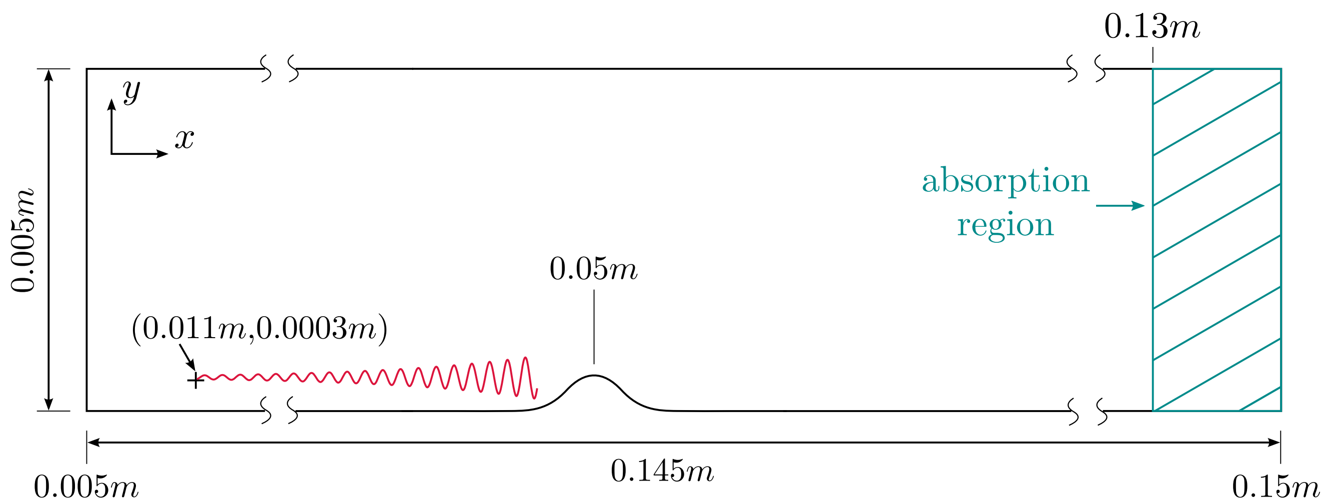
Flow configuration

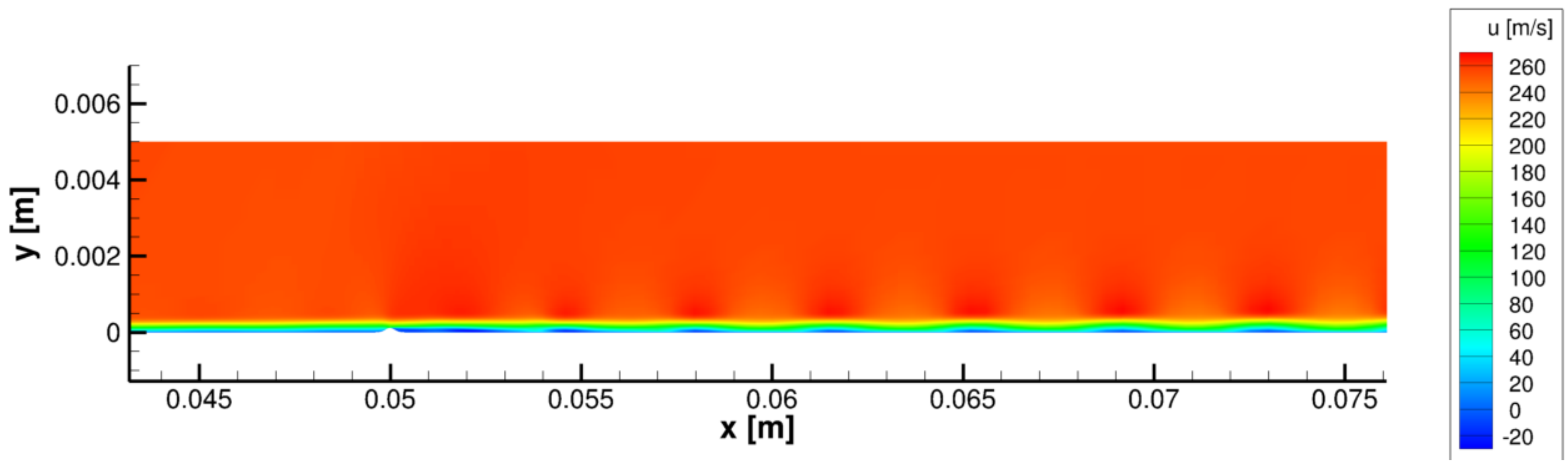


Subsonic/transonic applications

PSE + LST

Flow configuration

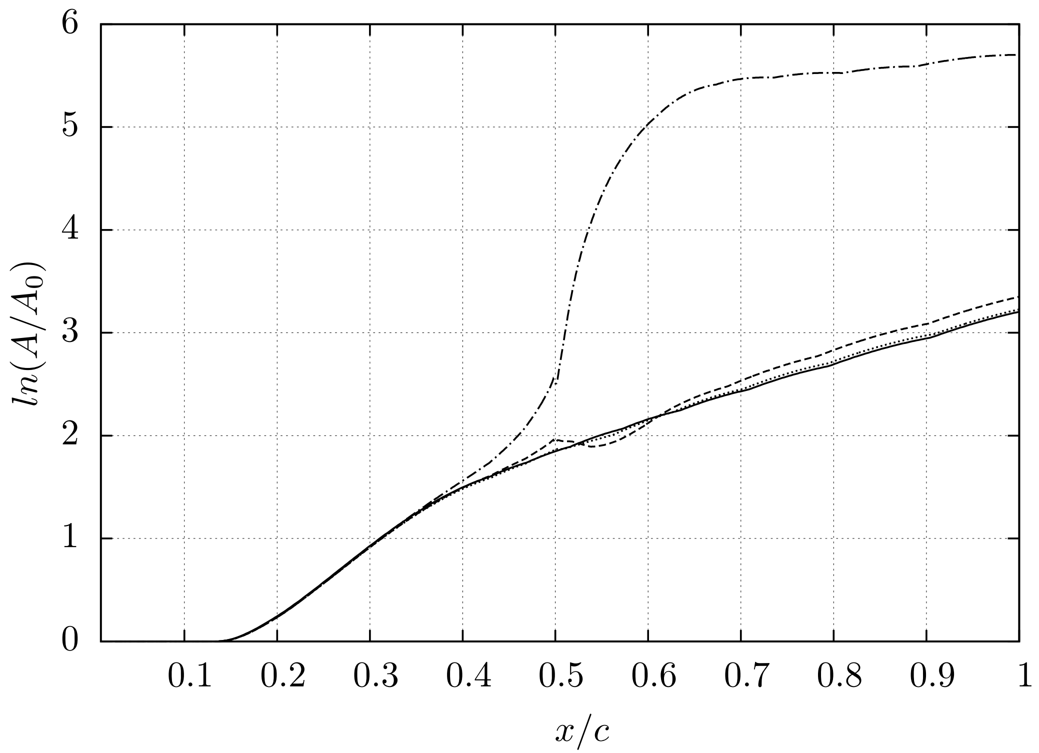




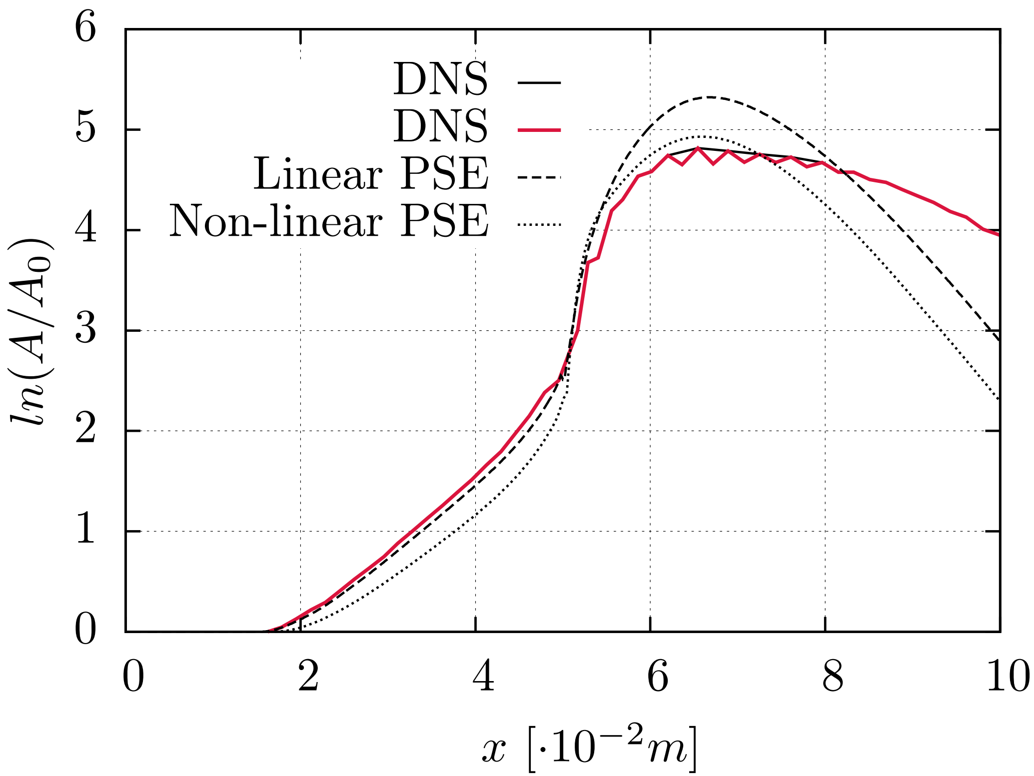
Subsonic/transonic applications

PSE + LST

Some preliminary results



N-factors - linear PSE



Comparison PSE-DNS

Outline

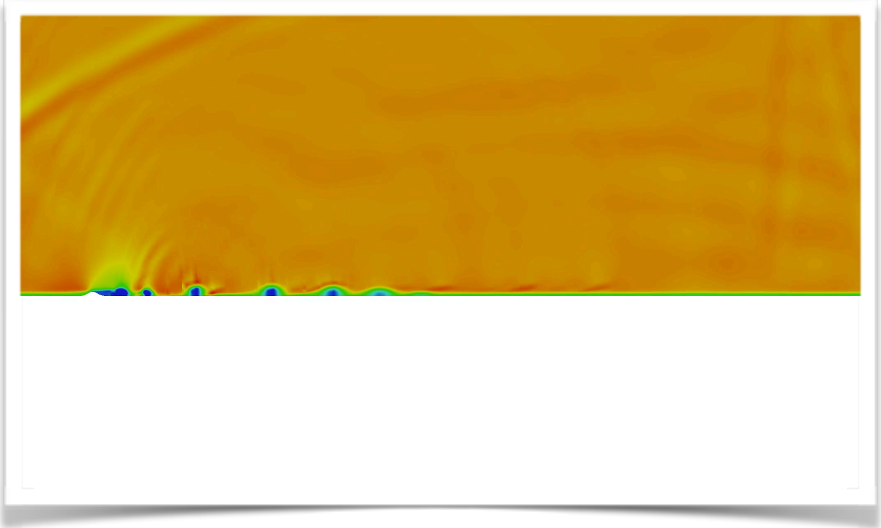
1. Underlying numerics (DG/FR)
2. Stabilising techniques (dealiasing)
3. Subsonic/transonic flow applications
4. Summary

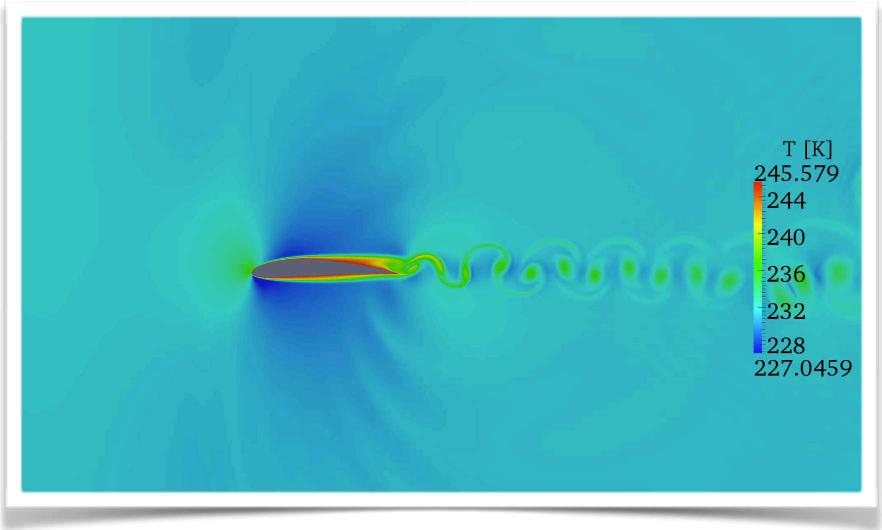
Summary

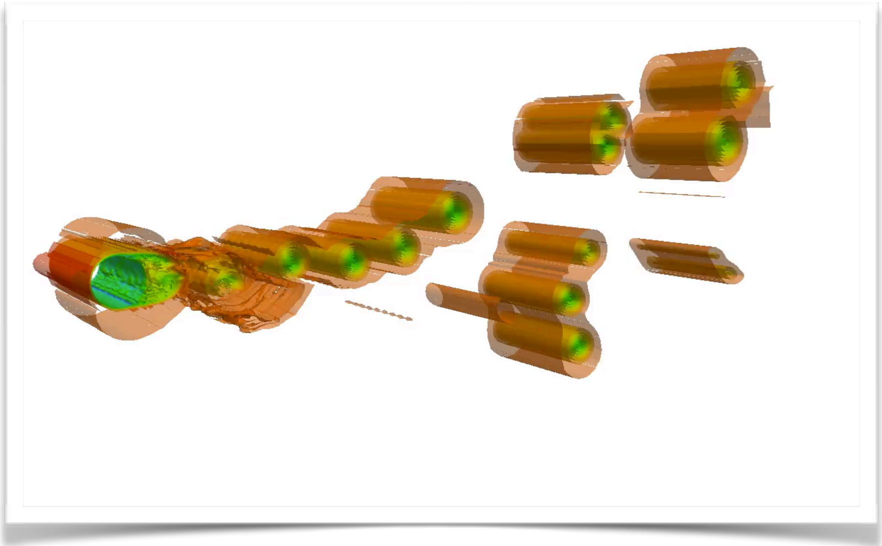
- Robust (and efficient) numerical framework for compressible flows
  - Euler equations
  - Navier-Stokes
- Implementation of both DG and FR (FR for 1D and 2D quad only)
- Implementation of both local and global dealiasing techniques
- Successfully applied to high-Reynolds number aeronautical problems
- Boundary conditions? —>

G. Mengaldo et al.
A Guide to the Implementation of Boundary Conditions in Compact High-Order Methods for Compressible Aerodynamics, 2014, AIAA Aviation

Thank you!







Shock-capturing / P-adaption / adjoint formulation are also included!
—> Next presentation by Dirk Ekelschot!