The exploration of numerical methods and noise modelling techniques applied to the *Trailing Edge Noise* case with evaluation of their suitability for aero-acoustic design

Stanislav Proskurov, Sergey Karabasov and Vasily Semiletov

School of Engineering and Materials Science
Queen Mary University of London

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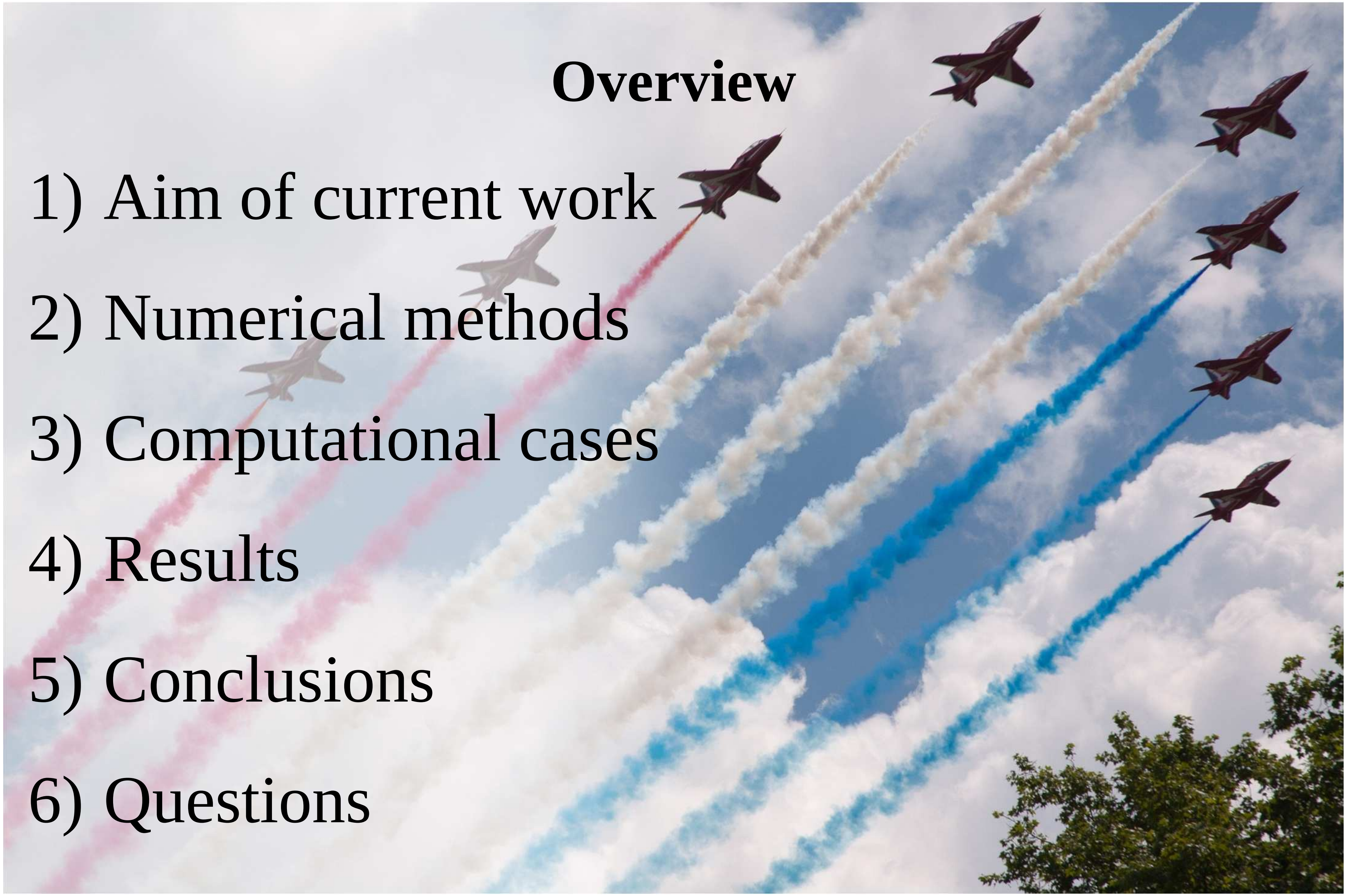


Overview

1) Aim of current work
2) Numerical methods
3) Computational cases
4) Results
5) Conclusions
6) Questions

Aim of current work

Test the capability of CAA stochastic Fast Random Particle Mesh (FRPM) method to predict broadband noise on a benchmark test case – *trailing edge noise*

- *Assess the potential of the FRPM method*
- *Develop the method to overcome current shortcomings…*
- *Provide design trends in days rather than months*

Use high-fidelity ‘state of the art’ LES CFD-CAA to understand the specific noise mechanisms

- *How the stochastic FRPM method may be improved?*

Numerical methods

FE Discontinuous Galerkin *solver*

Stochastic source generation

⇩

Filtering of a convecting white noise field approach

Requires a steady state RANS simulation

CABARET-FD *based on* ***MILES+FWH***

MILES scheme with improved dispersion and dissipation properties

High-fidelity LES simulation

Numerical methods
Pros & Cons

FE Discontinuous Galerkin *solver*

Much less expensive!

Requires RANS solution to provide 1 point statistics

Less sensitive to mesh type / refinement / solver numerics

RANS uses physics assumptions (correlations / turbulent energy spectra)

RANS modelling has poor accuracy for predicting flow separation

No tonal noise components

CABARET-FD *based on* ***MILES+FWH***

Large scale turbulence resolved rather than modelled

Has the greatest potential to provide accurate, physically realistic solution

Best for understanding the nature of acoustic sources for a specific problem

Computationally expensive

Sensitive to mesh type and refinement

FE DG solver

Quadrature Free Discontinuous Galerkin solver (time domain)

Parallel, unstructured

Acoustic Perturbation Equations – 4 (**APE−4** variant)[1]

Low dissipation/dispersion **ADER**[2] explicit time stepping

Acoustic sources obtained via FRPM method

2D and 3D parallelised FRPM

1. Ewert, R. and Schroder, W., "Acoustic perturbation equations based on flow decomposition via source filtering," Journal of Computational Physics, Vol. 188, No. 2, 2003, pp. 365–398.

2. Toro, E. F., Millington, R. C., and Nejad, L. A. M., "Towards Very High-Order Godunov Schemes," Godunov Methods: Theory and Applications. Edited review, E. F. Toro (Editor), Vol. 3352, 2001, pp. 905–937.

FE DG solver

System of equations of the form:

$$\frac{\partial U(x,t)}{\partial t} + \frac{\partial F_j(x,t)}{\partial x_j} = S(x,t)$$

Expand the *solution*, *flux functions* and *sources* in terms of nodal basis functions, $\phi_k(x_i)$

$$U(x,t) = \phi_k(x) U_k(t)$$
$$F_j(x,t) = \phi_k(x) F_{j_k}(t)$$
$$S(x,t) = \phi_k(x) S_k(t)$$

Multiplying by the test function, integrating over the volume, applying integration by parts and the divergence theorem yields:

$$\int_V \phi_i \phi_k \frac{\partial U}{\partial t} dV + \int_\Gamma \phi_i \phi_k F_{j_k} n_i dS - \int_V F_{j_k} \frac{\partial \varphi_i}{\partial x_j} \phi_k dV = \int_V \phi_i \phi_k S_k dV$$

Mass matrix: $M_k = \int_V \phi_i \phi_k dV$

Further, assuming F_j is linear (computing Jacobian matrix separately to realise QF concept)

FRPM method in a nutshell

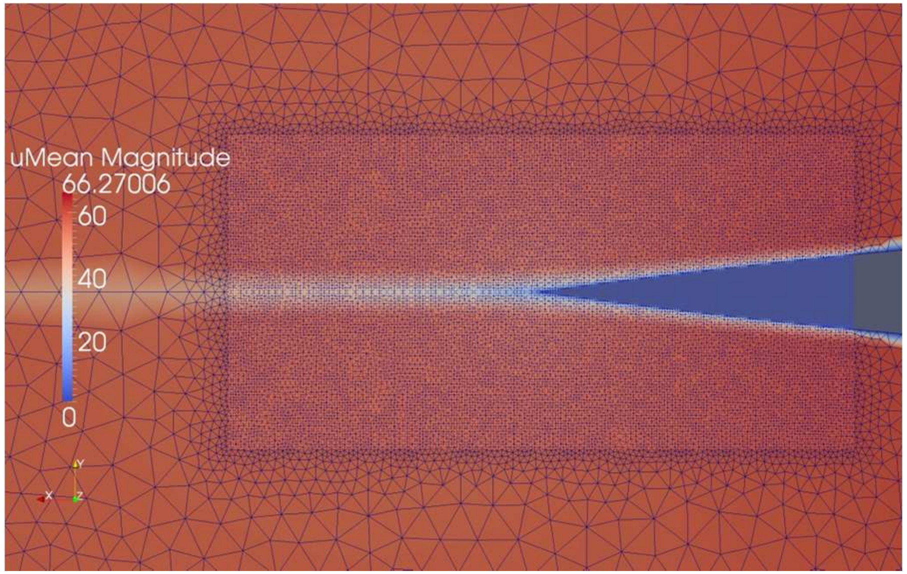
RANS $k - \omega$ SST

Provide…

Integral length scale
Turbulent kinetic energy $\bar{k}$
ω *or* ϵ*, sound speed,*
density, $\overline{u}\ \overline{v}\ \overline{w}$ *velocities*

Map the mean flow to:

Auxiliary cartesian FRPM grid & CAA prism O-grid



1) Seed random particles and convect them with a mean flow
2) Interpolate the random numbers onto the neighbouring auxiliary mesh nodes
3) Perform the integral $\psi(x,t) = \int_V A\, G(x - x')\mathcal{U}(x', t)$ at every node

$\hat{A} = \sqrt{\frac{2}{3\pi}}\bar{k}^{\frac{1}{2}} \approx 0.46\bar{k}^{\frac{1}{2}}$ $\quad G(x) = \exp\left(-\frac{\pi}{4}\frac{x^2}{l^2}\right)$ $\quad \mathcal{U}$ – unity white noise field

FRPM method in a nutshell

Different source models are possible,

'Source A'[3] used here:

$$u' = \nabla \times \psi$$

$$\omega' = \nabla \times u'$$

$$\boldsymbol{\Omega}' \propto \left(1 - \frac{\pi x^2}{2l^2}\right) \exp\left(-\frac{\pi}{2}\frac{x^2}{l^2}\right)$$

$$\boldsymbol{q} = \underline{-\{\boldsymbol{\Omega_0} \times \boldsymbol{u}'\} - \{\boldsymbol{\Omega}' \times \boldsymbol{u_0}\}} - \cancel{\{(\boldsymbol{\Omega}' \times \boldsymbol{u}')'\}}$$

APE-4 equations could be written out as following,

$$\frac{\partial p'}{\partial t} + \frac{\partial}{\partial x_j}\left(c_0^2 \rho_0 u_j' + p' u_{0_j}\right) = 0$$

$$\frac{\partial u_i'}{\partial t} + \frac{\partial}{\partial x_i}\left(u_{0_j} u_j' + \frac{p'}{\rho_0}\right) = \boldsymbol{q}$$

RHS source term

3. Ewert, R., Dierke, J., Siebert, et al., "CAA broadband noise prediction for aeroacoustic design", Journal of Sound and vibration, Vol. 330, 2011, pp. 4139-4160.

Compact Accurately Boundary Adjusting high-Resolution Technique

Properties

Explicit, second order in space & time

Non-dissipative & low dispersive

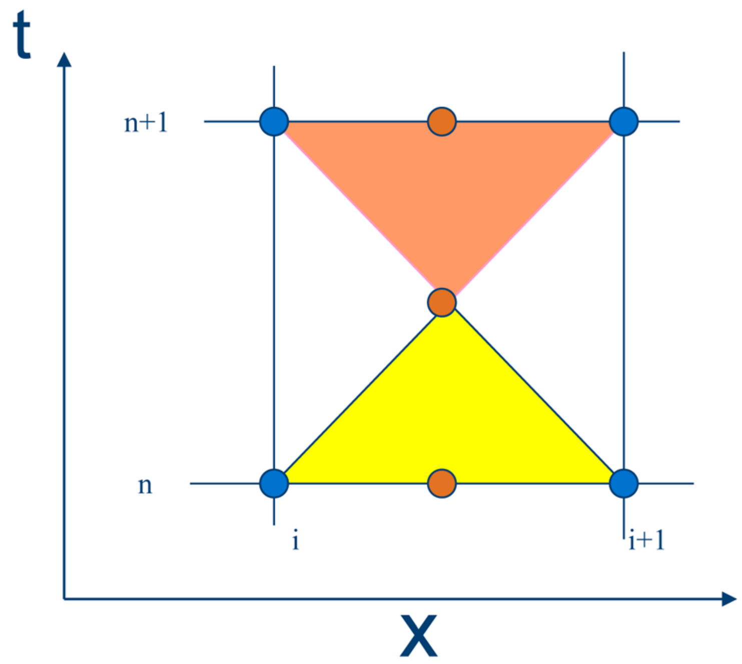
Conservative form

Compact one cell stencil in space & time

Nonlinear flux correction based on maximum principle

Nonlinear flux reconstruction based on the minimum solution variation

$$\frac{\partial \varphi}{\partial t} + c \cdot \frac{\partial \varphi}{\partial x} = 0$$



S.A. Karabasov and V.M. Goloviznin. "Compact Accurately Boundary Adjusting high-REsolution Technique for Fluid Dynamics", J. Comput.Phys., 228(2009), pp. 7426–7451.

Computational Cases

1) **CASE#1 BANC Workshop**

   DG FE – FRPM

   NACA0012, $c = 0.4$, $U_\infty = 56$ m/s

   $M = 0.1664$, $Re = 1.5$M

   $T_\infty = 281.5$K, $\rho = 1.181\ kg/m^3$,

   $P_\infty = 95429$ Pa, AoA = 0° sharp TE,

   untripped

2) **Experiment of Brooks, Pope and Marcolini (1989)**

   CABARET – LES

   NACA0012, $c = 0.1524$, $z = 3c$ exp.,

   $z = 0.1c$ sim.,

   $M = 0.1150$, $Re = 408$k

   AoA = 0° sharp TE,

   untripped

Computational Mesh – *Case 1*

C-grid hexahedron type in 2D incorporating a single element width in spanwise direction

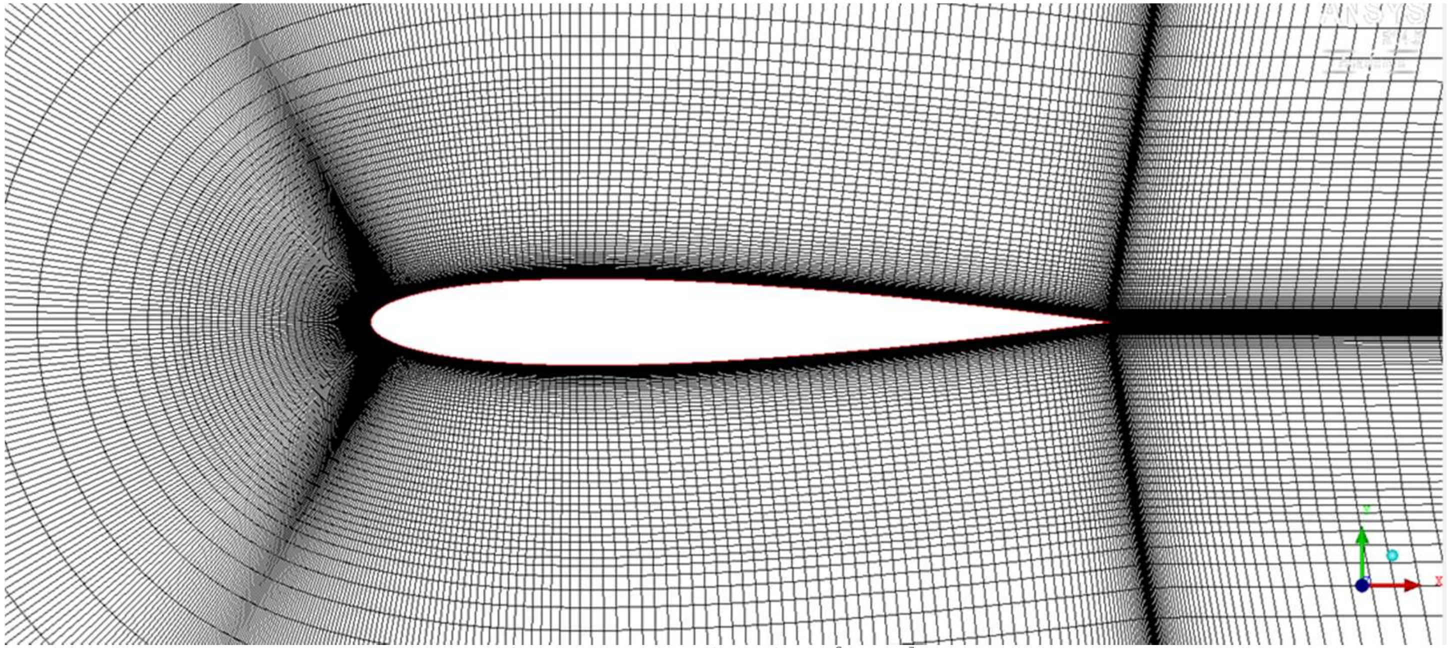
216 mesh points per side of the aerofoil ~80 of 216 on the LE per side (~5% of the chord)

117 mesh points in the far-field (normal direction) Target y+ of 1

Far-field boundaries 25c away from the aerofoil

Maximal element expansion ratio
~5-10% on the aerofoil surface
up to 30% in the far-field

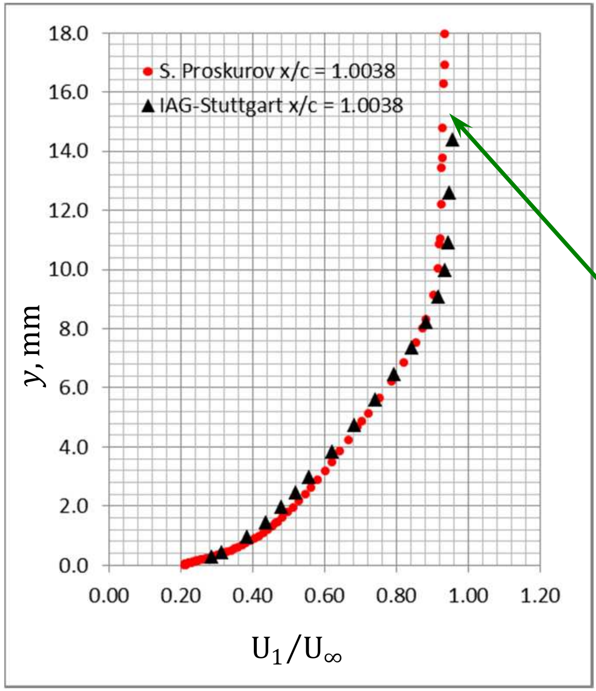
68k elements in total per 2D layer



Computational Cases

Resources comparison

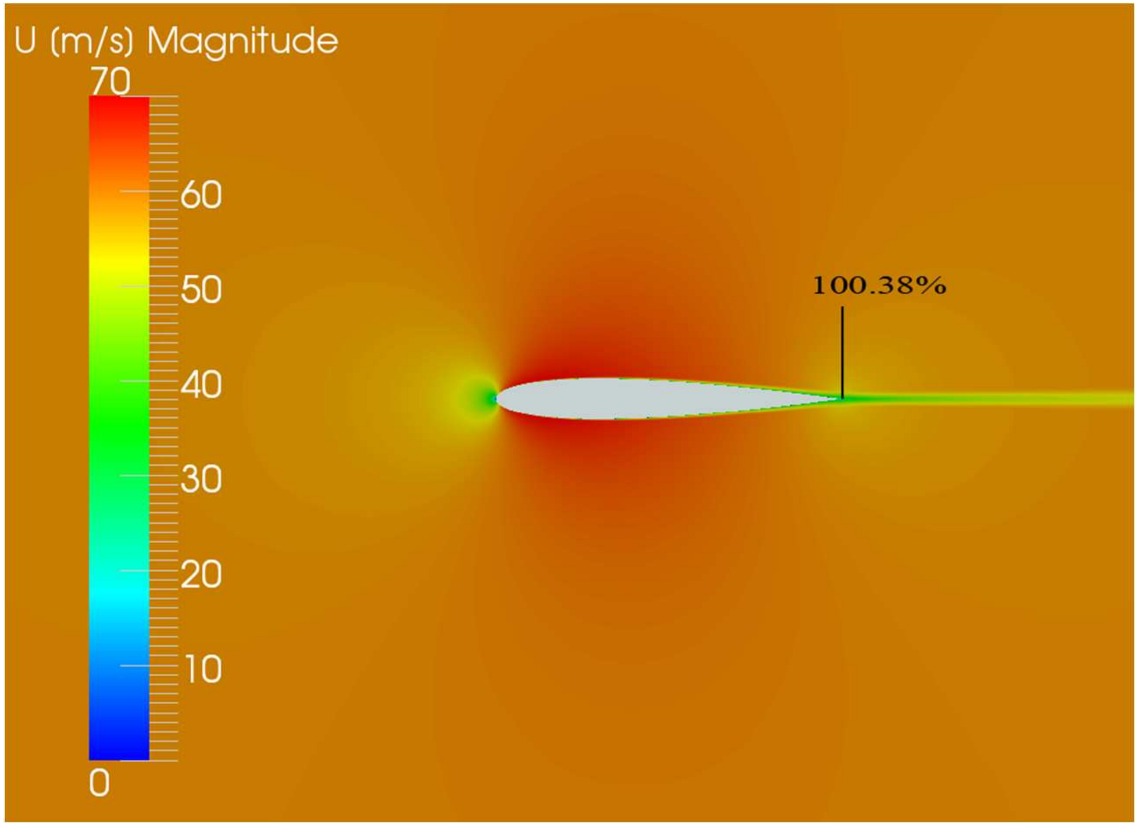
	Case 1	***Case 2***
CFD	RANS $k-\omega$ SST	LES
Mesh	68,000 cells (2D)	8.2 M cells
	single core	2880 cores (HECToR)
Time (wall clock)	10 min.	240 hours
CAA	32 cores (4 assigned to FRPM and 28 to CAA)	
	~24 hours	

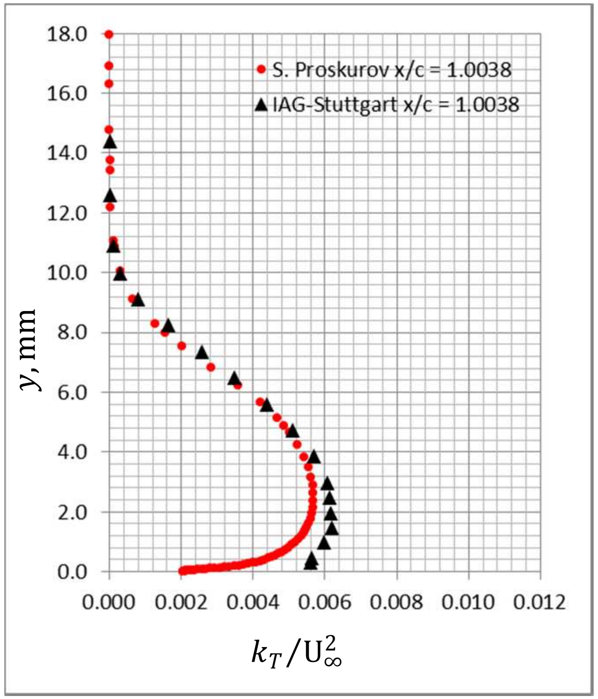


Results

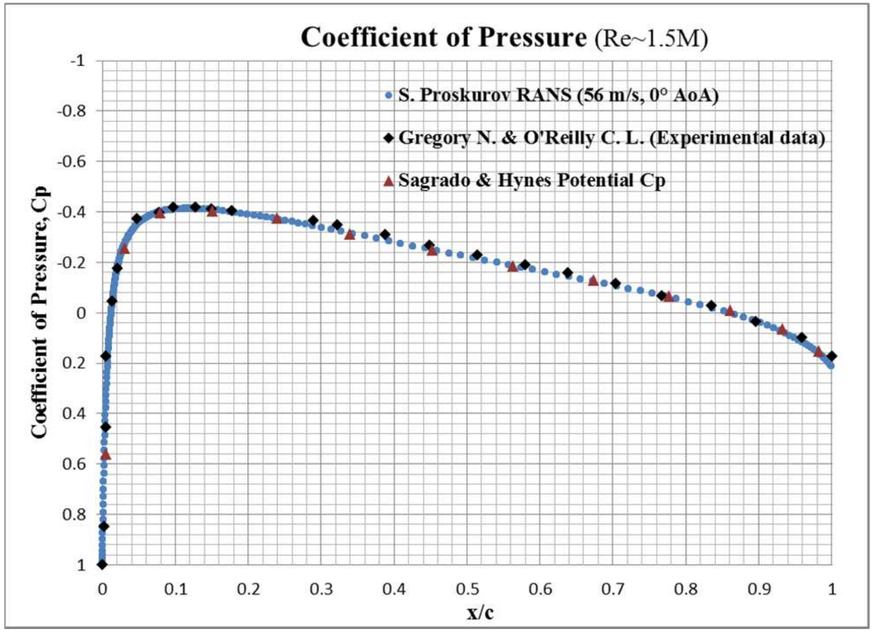
Near-field results – *Case 1*

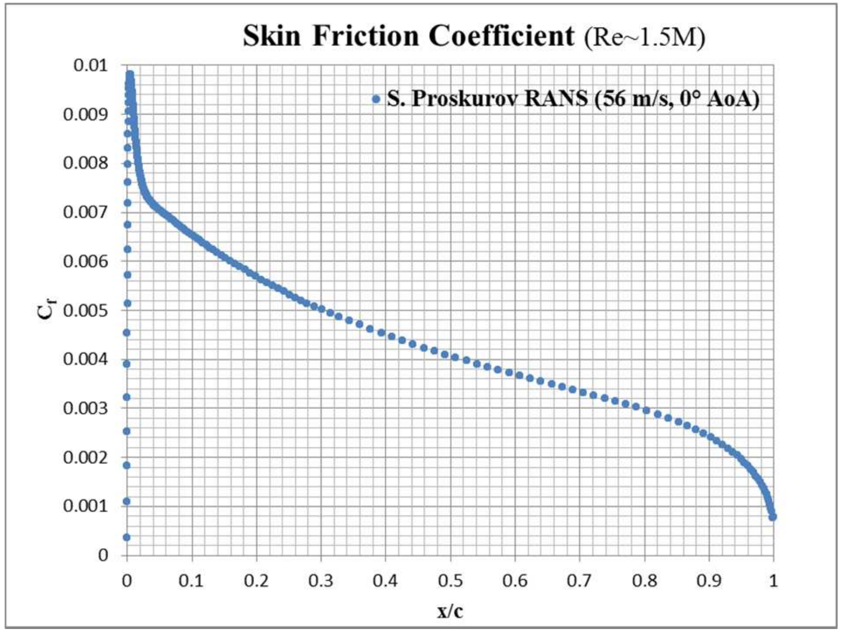
Inflection point at *y* ~14-16 mm





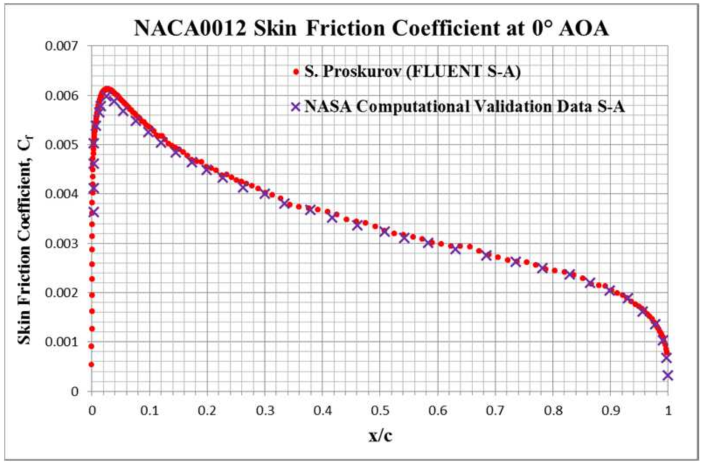
Results

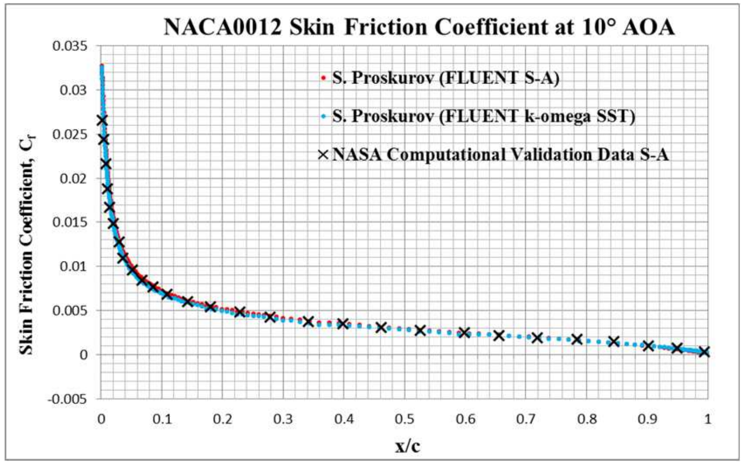




C_f NASA validation case:

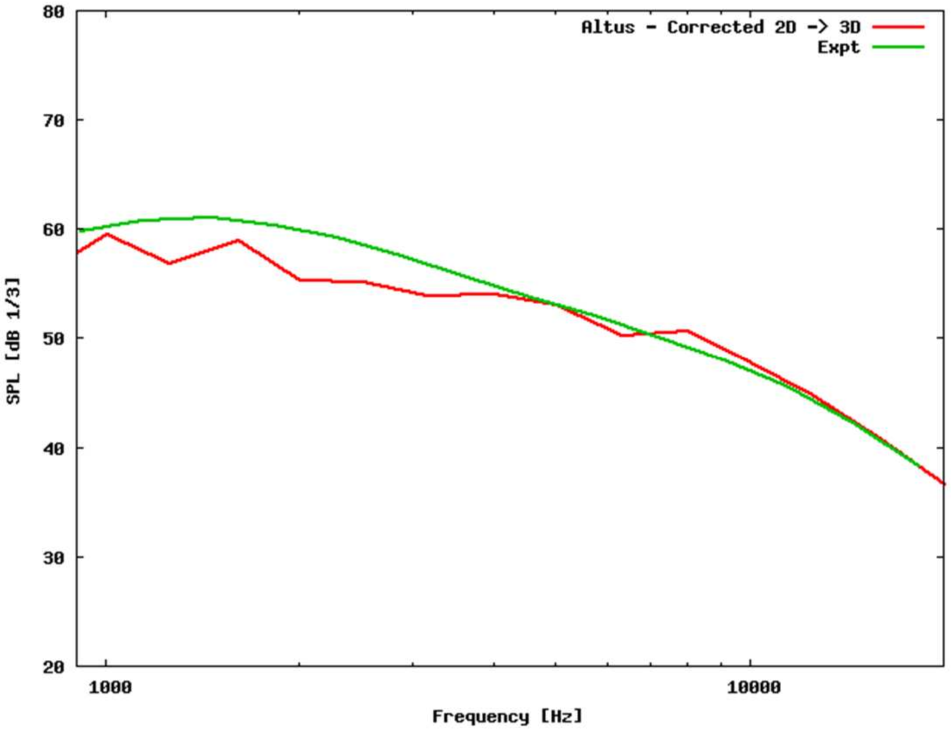
NACA0012,
c = 1.52, U_∞ = 59 m/s
M = 0.17, Re = 5.97M
$T\infty$ = 288.16 K,
ρ = 1.225 kg/m^3,
μ = 1.7894 × 10^{-5},
<u>sharp TE</u>

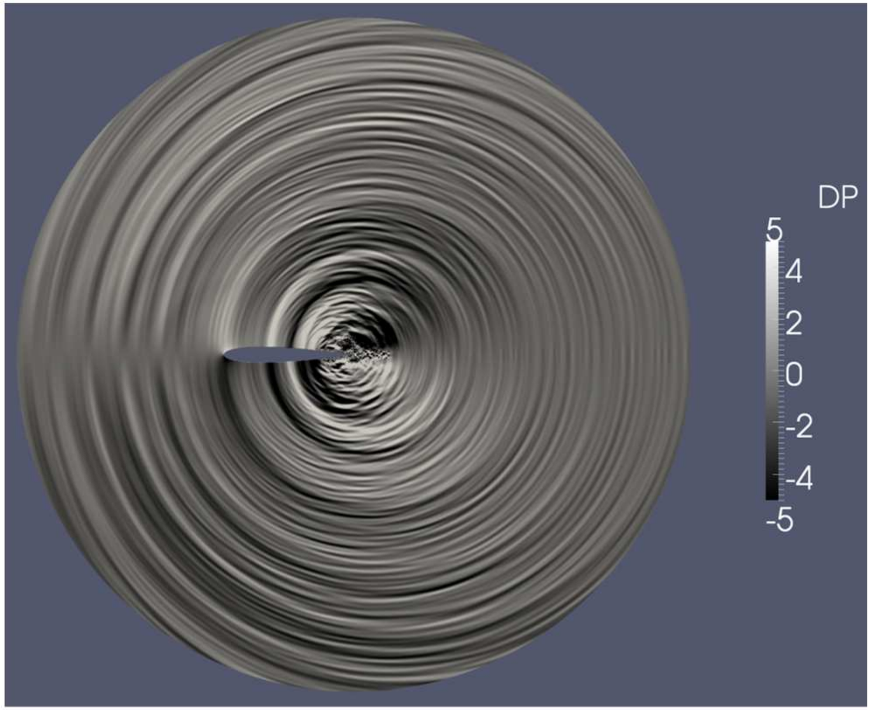




Results

Acoustic results – *Case 1*



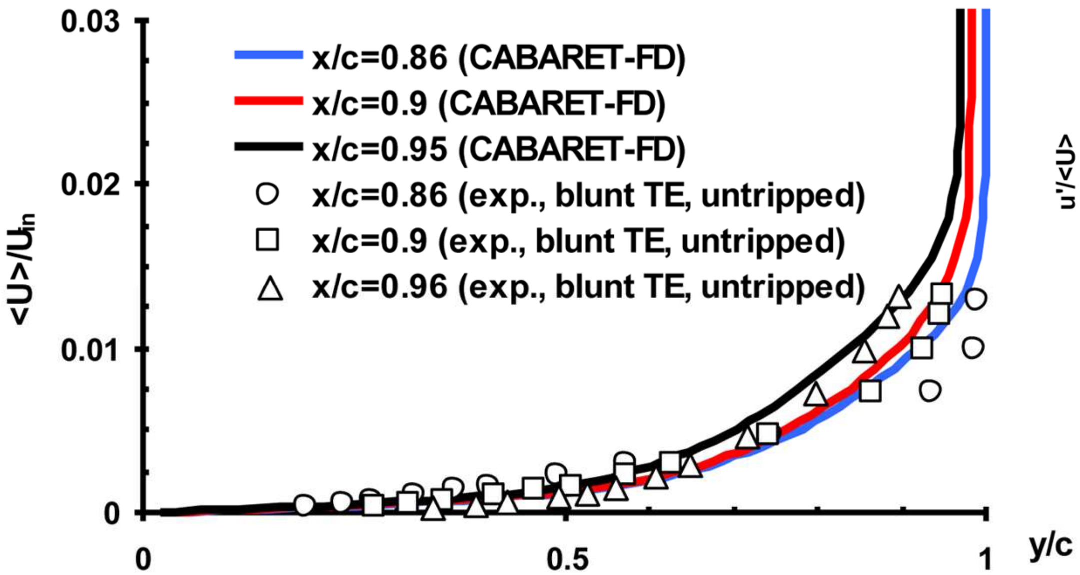


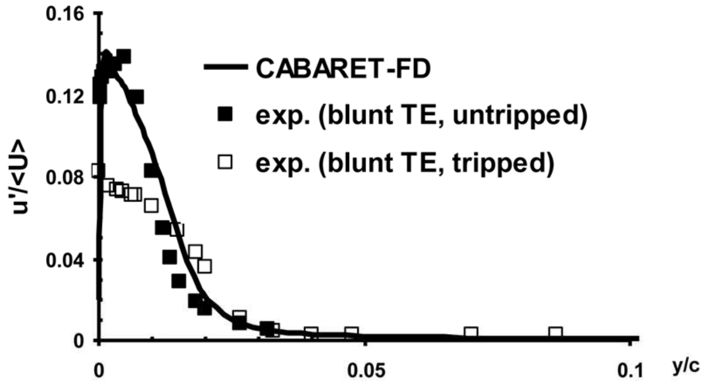
Instantaneous acoustic pressure field

green - DLR 60 m/s, *red* - our 56 m/s

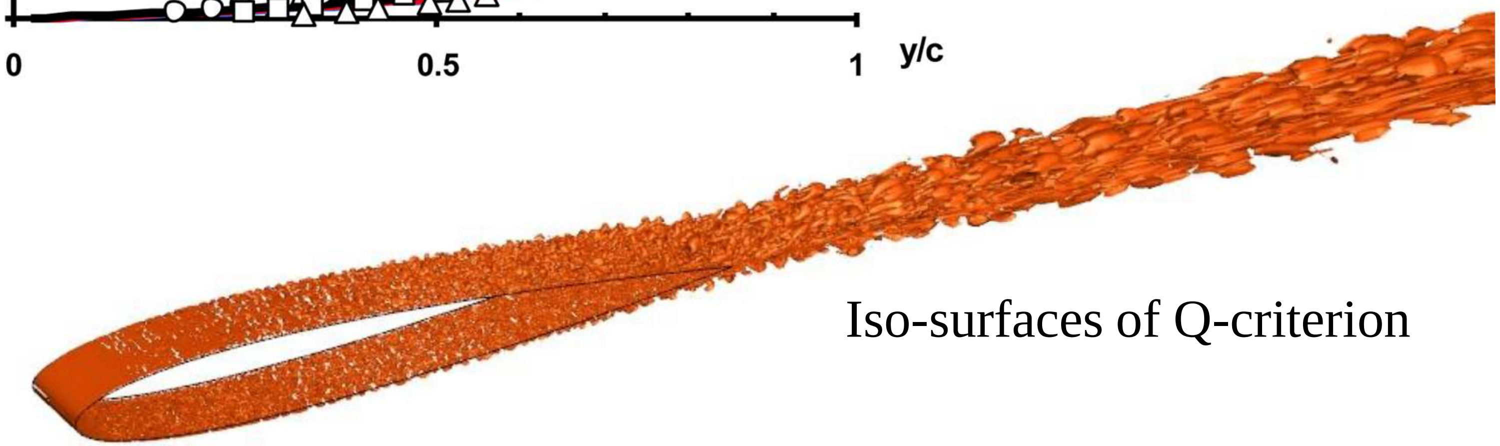
Results

Near-field results – *Case 2*



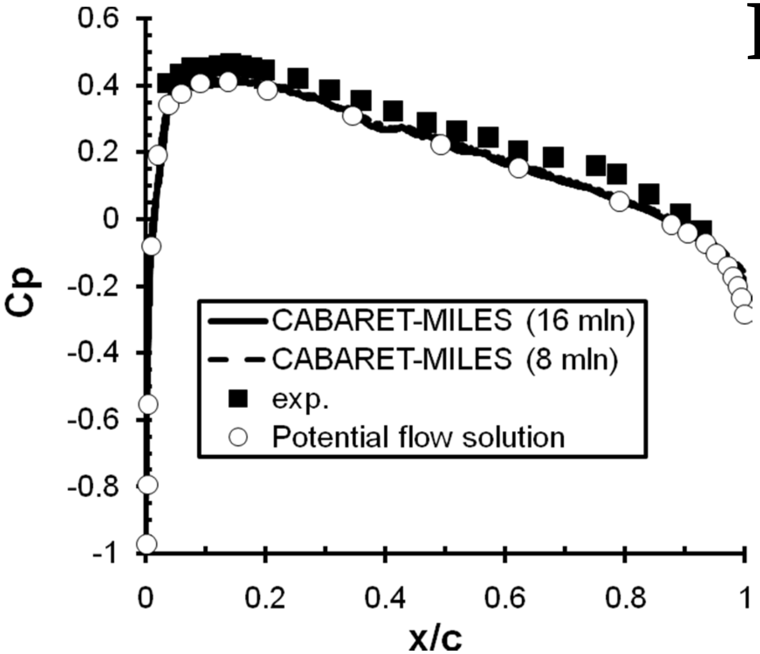


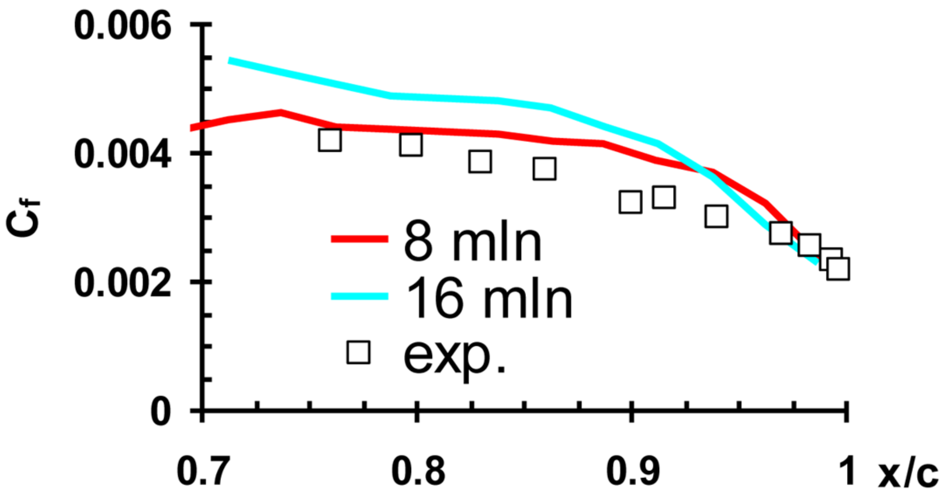
$x/c = 0.9$

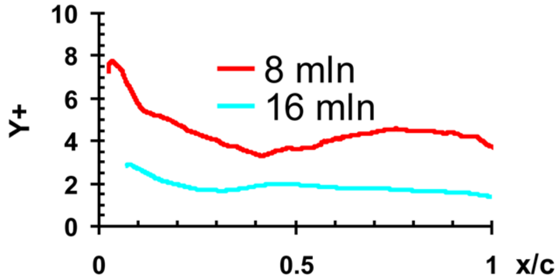


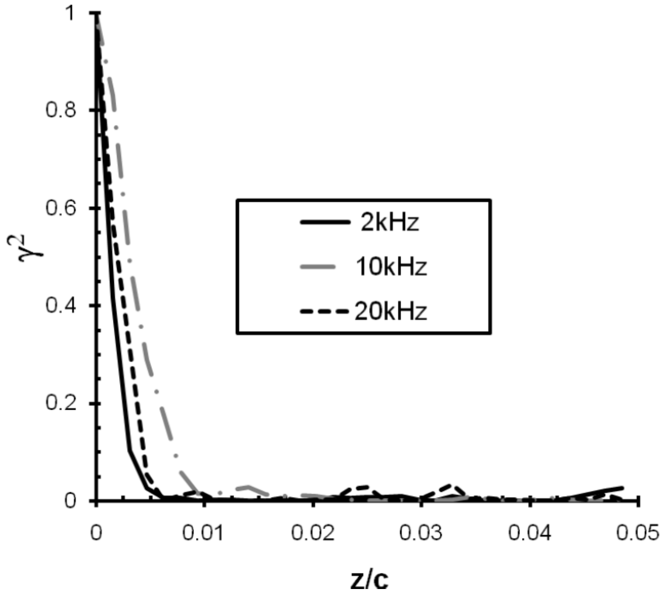
Iso-surfaces of Q-criterion

Results







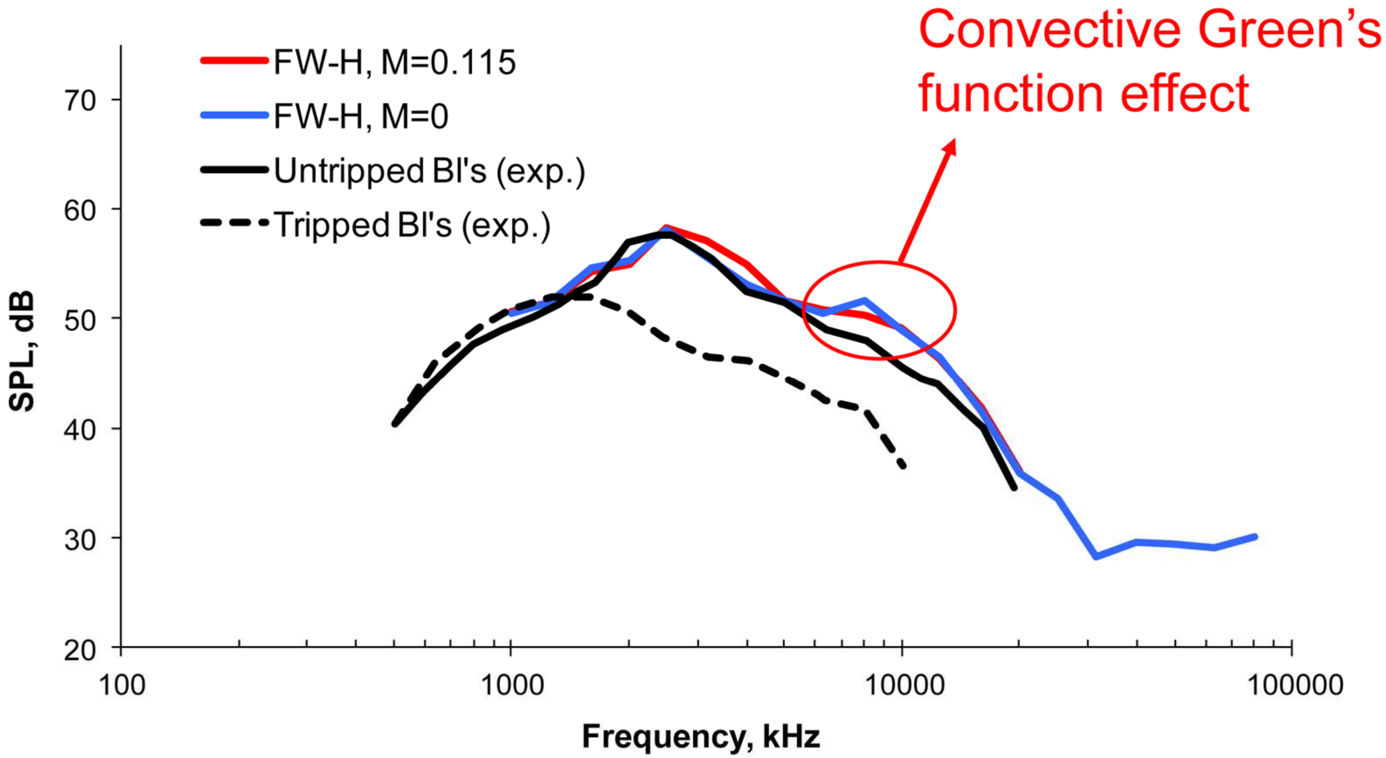


Pressure coherence function at *x*/c = 0.95

Fluctuations become uncorrelated quickly in spanwise direction, typical of high Re number flows

Results

Acoustic results – *Case 2*



Sound pressure level at observer location x = c, y = 8c, z = 0.5c

V.A. Semiletov and S.A. Karabasov, "CABARET scheme for computational aero acoustics: extension to asynchronous time stepping and 3D flow modelling", Int. J. Aeroacoustics, 13 (3-4): 321 – 336, 2014.

Conclusions

FRPM method provides the quick prediction of broadband noise levels that showed the similar trend as experimental results for the *trailing edge noise* case

FRPM method has a great potential to study design optimisation

LES simulation can be used to verify the noise levels of the final design.

Confidence in modelling is gained by using:

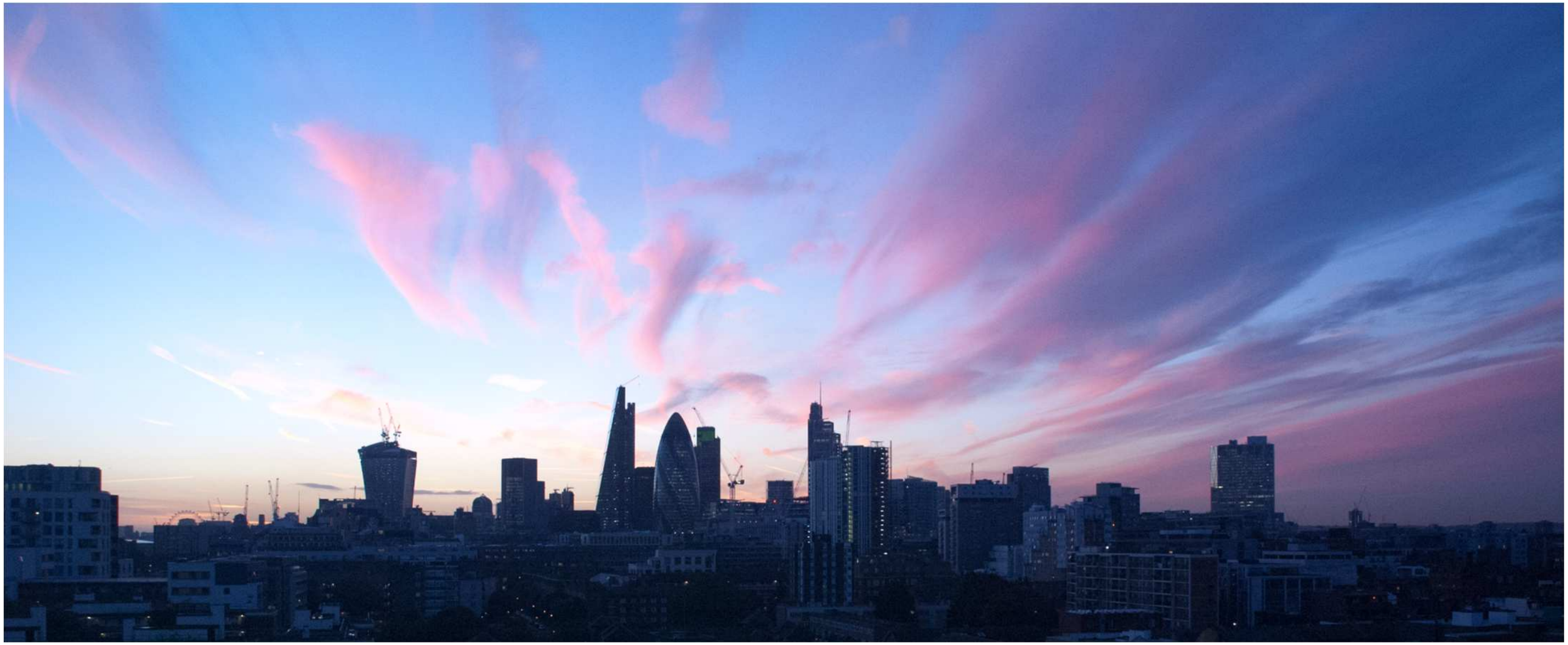
Two different CFD approaches

Two different acoustic source models

Two different acoustic codes & equations

High-fidelity LES may be used to provide realistic correlations / turbulence energy spectra / length scales to improve the FRPM method

Thank you!



Questions?