Cost reduction of supercomputer simulations in unsteady aerodynamics and aeroacoustics

Vladimir Bobkov, Alexey Duben, Andrey Gorobets, Tatiana Kozubskaya

Keldysh Institute of Applied Mathematics of RAS, Moscow, Russia

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Outline

Motivation

1. **Strategies of costs optimization**

   Models: multi-model approaches, hybrid RANS-LES methods, …

   Numerical methods: economic higher-accuracy/higher-resolution schemes, ..

   Meshes: multi-mesh technologies, composite meshes, sectors, adaptation, ..

   Parallel algorithms: hybrid parallel models

2. **Examples of supercomputer simulations**

   Aeroacoustics of swept wing

   Helicopter rotor noise

Concluding remarks

Motivation

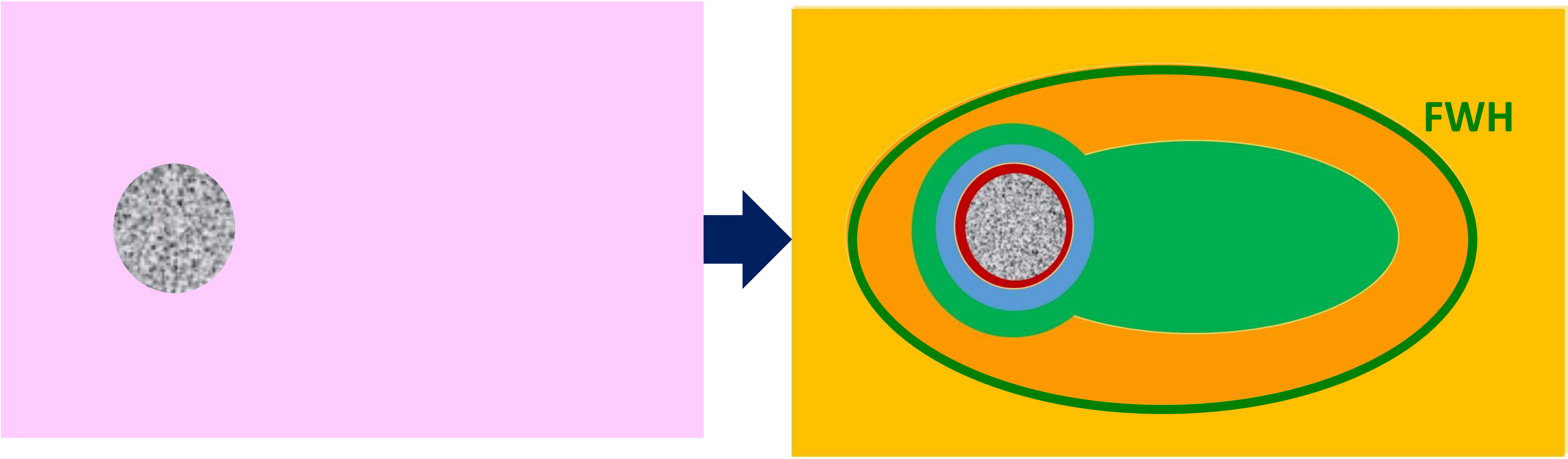
Direct Numerical Simulation (DNS)
based on solving the Navier-Stokes equations everywhere in the areas of interest
in aviation-industry oriented problems
is, unfortunately, **unachievable** neither today nor in the foreseeable future

If we want to provide the results required by the industry
we need to approach to **DNS** using different possible ways at different levels

Under different ways and levels we mean:
- **modeling:** multi-model and hybrid approaches
- **numerical methods:** efficient higher-accuracy schemes
- **meshing:** multi-mesh technologies, smartly generated meshes, adaptation, periodicity, sectors..
- **parallelization:** efficient hybrid parallel models for modern HPC architectures
- **different other** technologies, techniques, tricks,..

Nowadays we do not expect groundbreaking discoveries,
we need just **high quality in each above direction**
and the main gain as a result of **their efficient synthesis**

Strategies of cost optimization. Modeling



DNS

RANS

WMLES LES

LEE – Linearized Euler Eqs

Wave equation

Strategies of cost optimization. Methods

A proper choice of the method is always a compromise between **accuracy** and **costs**

As commonly recognized, **the high-order methods on rather coarse meshes** are generally more efficient than **the low-order methods on very fine meshes**

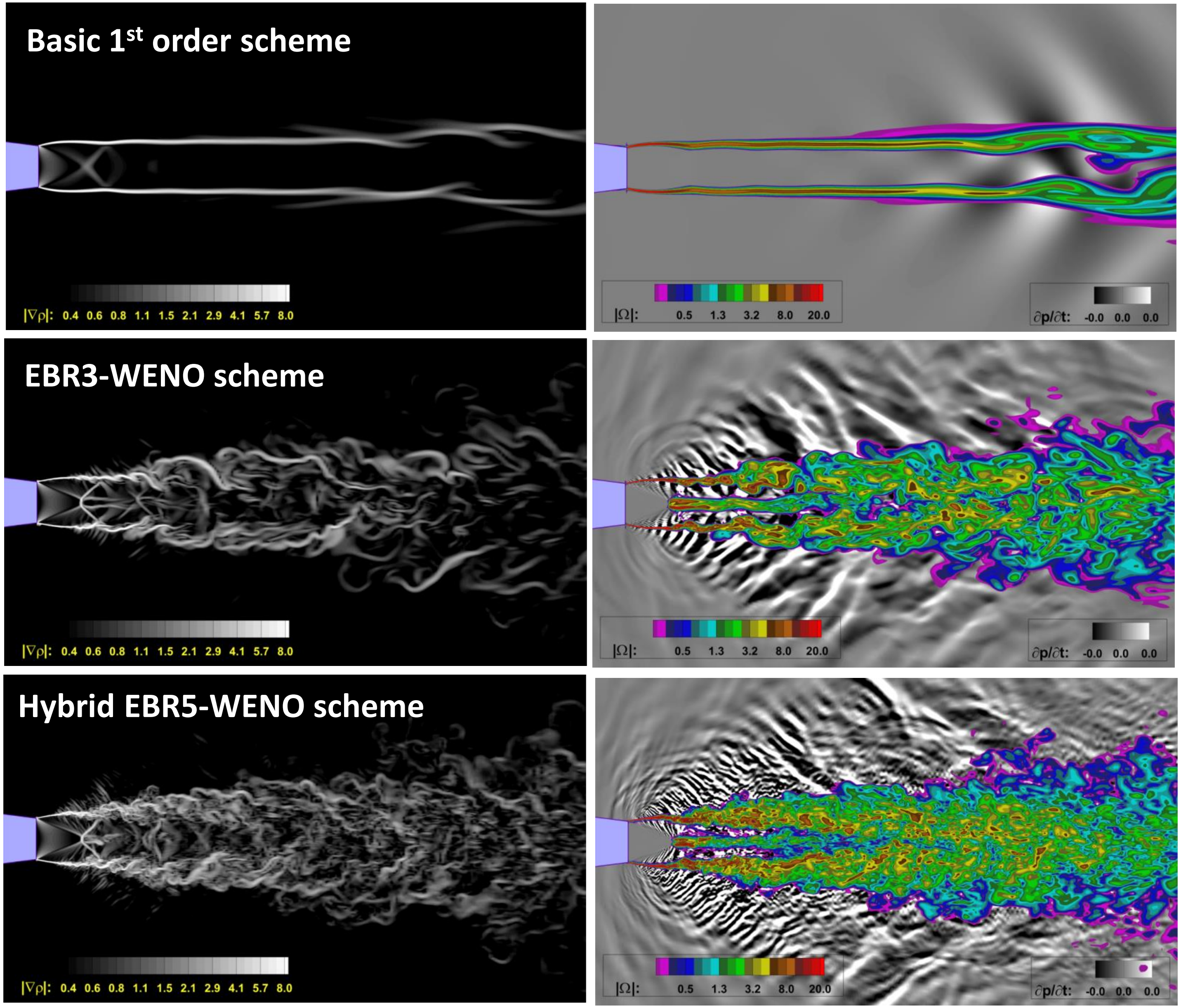
However, the choice is not so evident .
The high-order methods may be not so good for discontinuous solutions,
may be not so efficiently parallelized, the implementations may be too complicated and costly, especially for unstructured meshes

Moreover, on real meshes **the higher order may not guarantee the lower error**

Higher-accuracy higher-resolution methods may be an interesting candidate to providing a good compromise between accuracy and costs

Our choice is the **EBR (Edge-Based Reconstruction) schemes for unstructured meshes**
(in more details - tomorrow, October 8th)

EBR Schemes



~ 15-20% extra costs

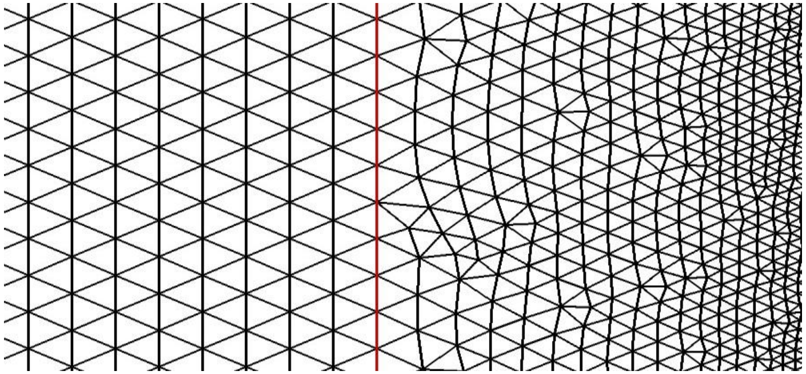
Strategies of cost optimization. Meshing

What do we want from meshes?

High consistency with the problem. Boundary layers, separation regions, etc, ..

High consistency with the model.
Different requirements on meshes for different models (RANS, LES, LEE, ..)

High consistency with the numerical method.
For instance, the meshes better meeting the EBR schemes properties are composite structured/TI-unstructured meshes



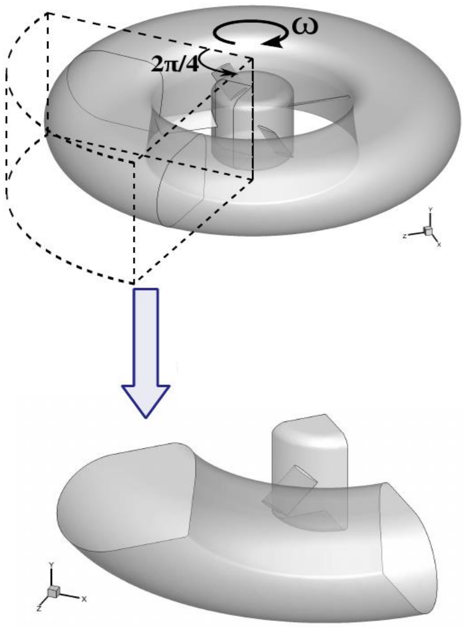
The good mesh is >50% of success ☺

Strategies of cost optimization. Meshing

A series of refined meshes used in one computations.
For instance, we start from RANS on a rather coarse mesh

A series of refined meshes for the data treatment.
Post processing, visualization, …

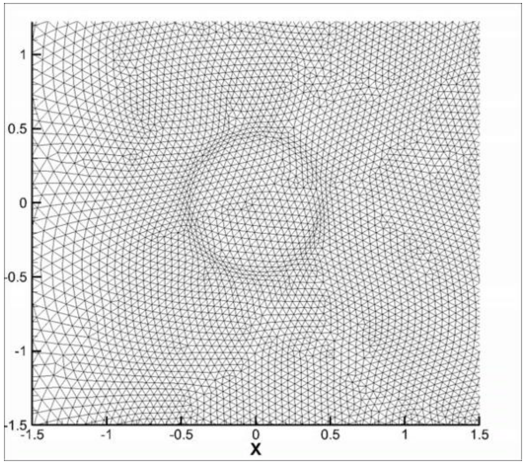
Topological consistency to provide the periodicity condition for unstructured meshes.
In particular, for sectors:



Dynamic adaptation for simply connected domains

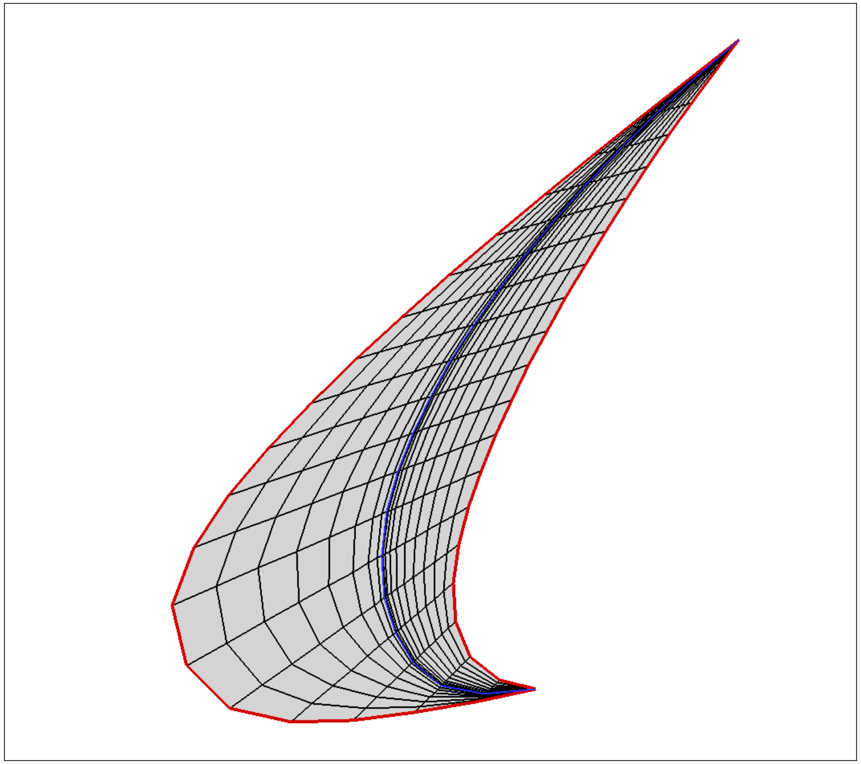
Strategies of cost optimization. Meshing

Dynamic adaptation for simply connected domains



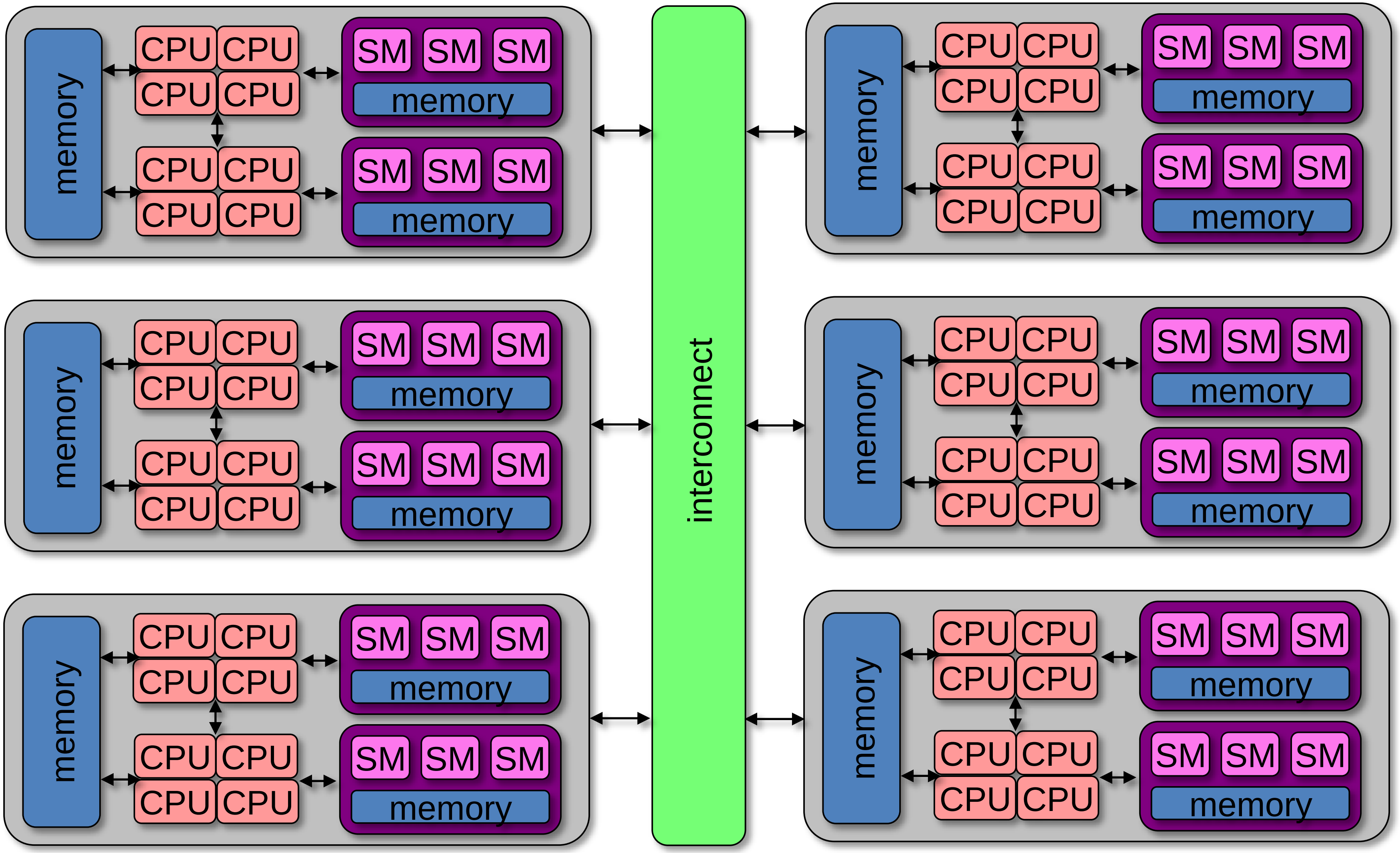
Strategies of cost optimization. Meshing

Mesh deformation



Strategies of cost optimization. Parallelization

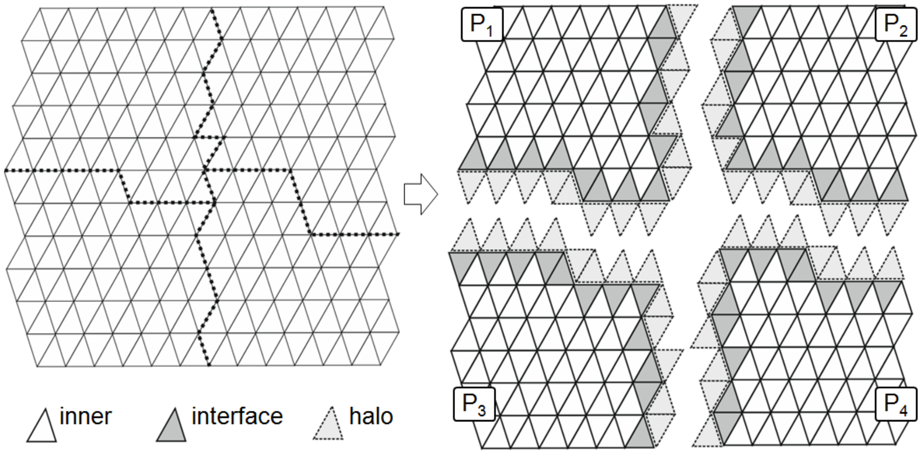
Typical configuration of hybrid HPC cluster



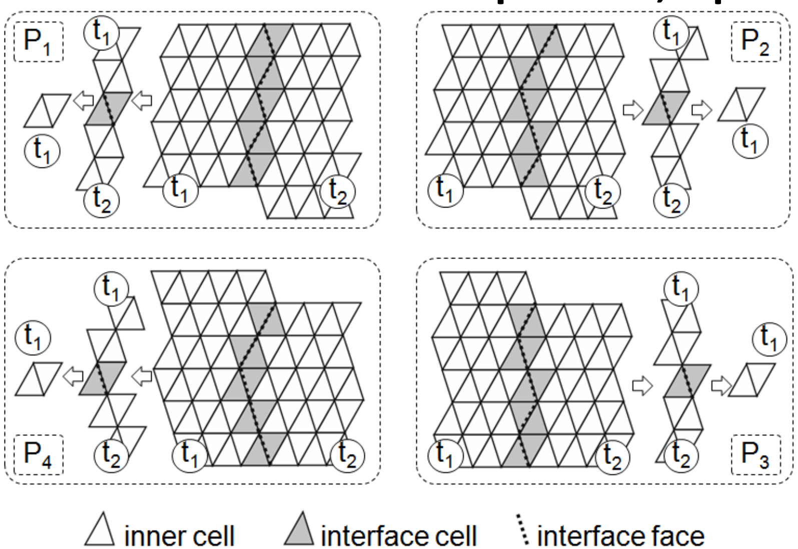
Strategies of cost optimization. Parallelization

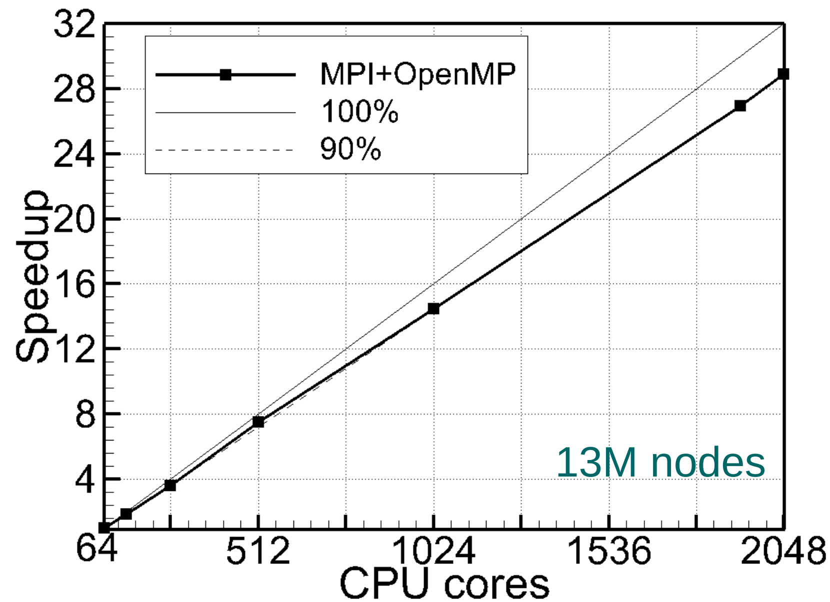
Multilevel MPI+OpenMP parallelization

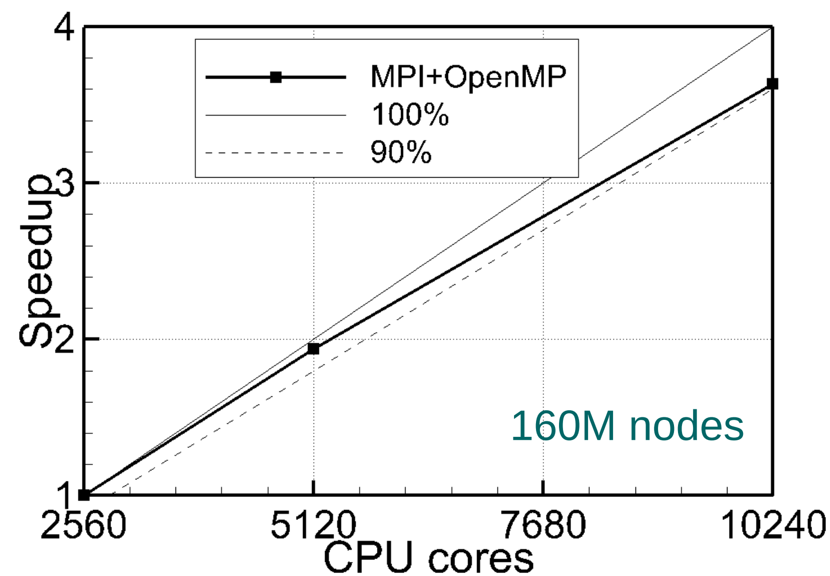
Upper level domain decomposition, MPI



Intra-node domain decomposition, OpenMP



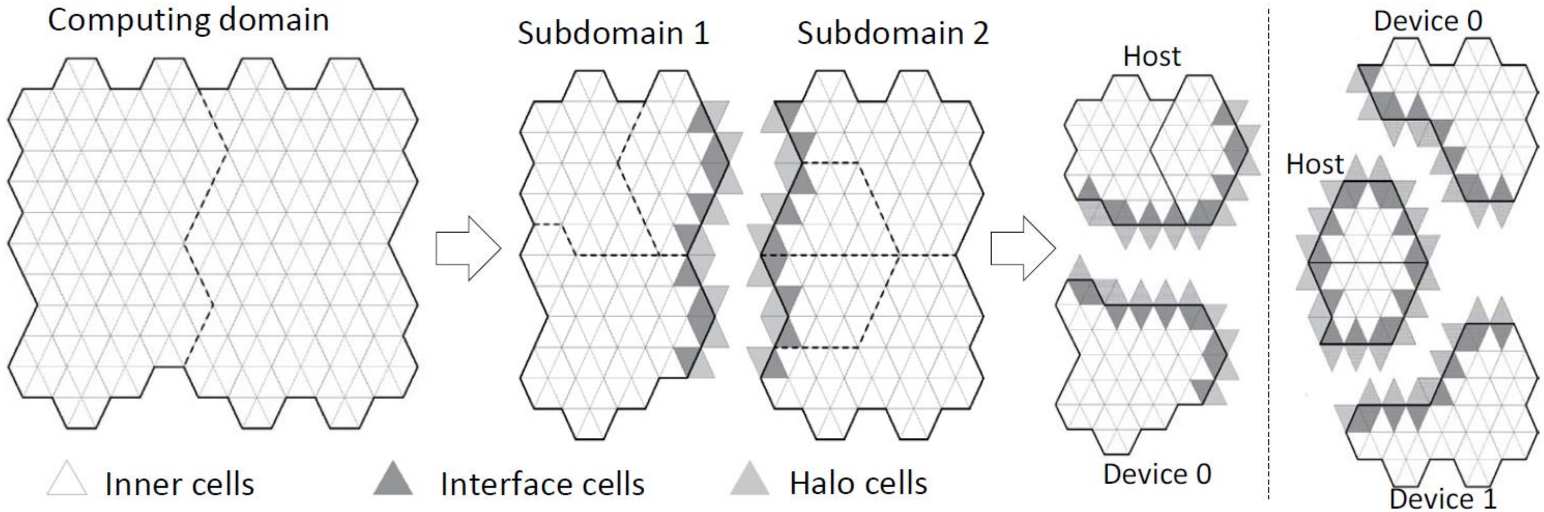


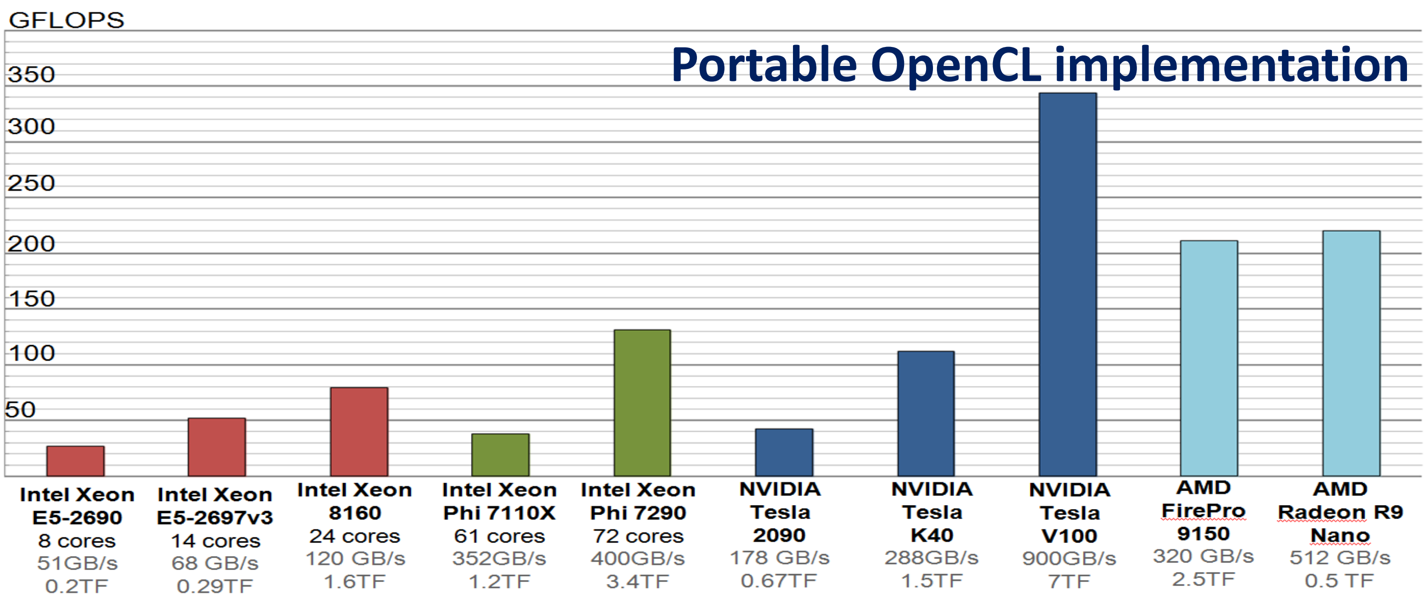


Gorobets, A. Parallel Algorithm of the NOISEtte Code for CFD and CAA Simulations. Lobachevskii J Math (2018) 39: 524. https://doi.org/10.1134/S1995080218040078

Strategies of cost optimization. Parallelization

Multilevel decomposition for heterogeneous computing

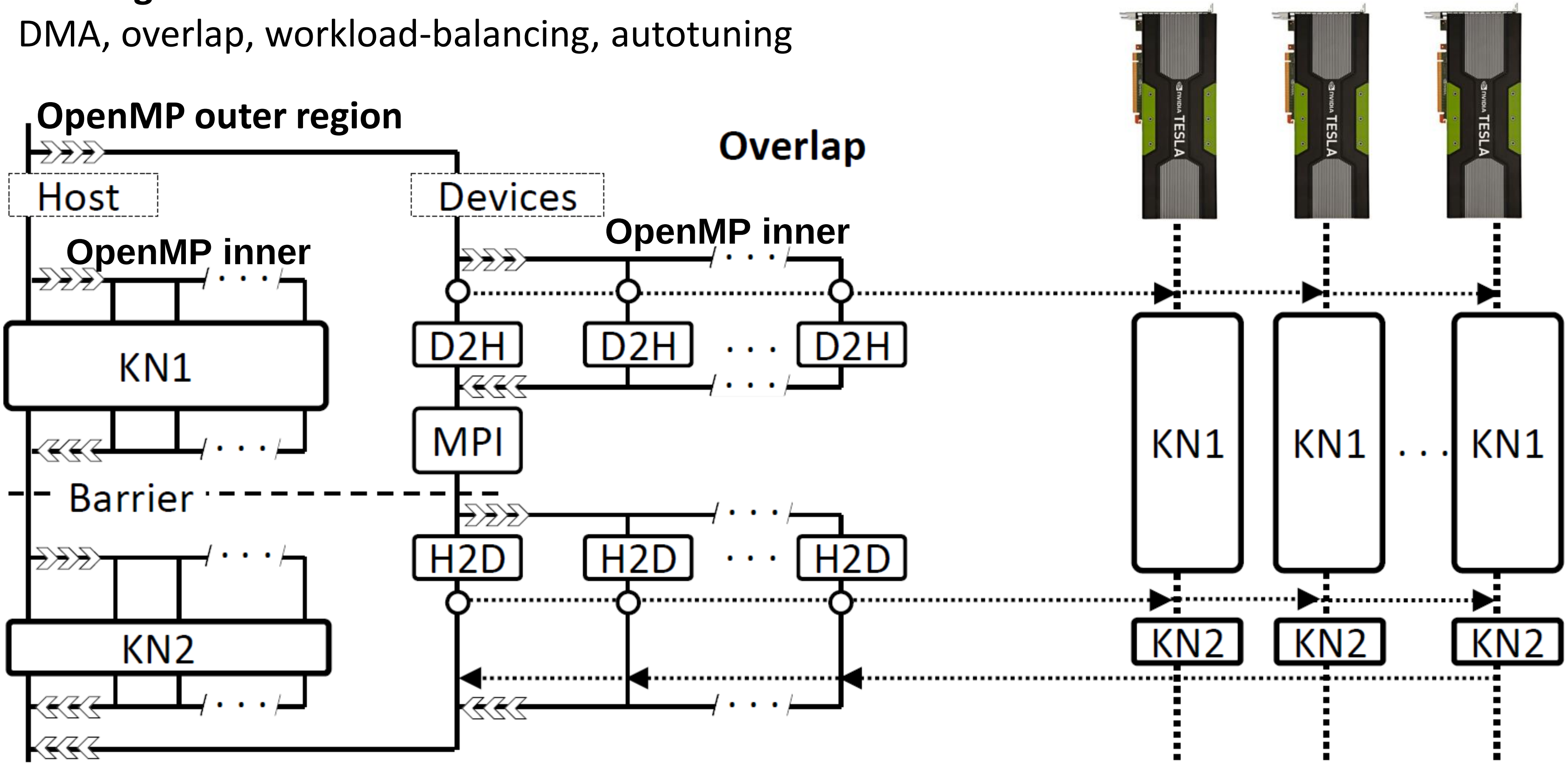




Efficient heterogeneous implementation

Heterogeneous execution scheme

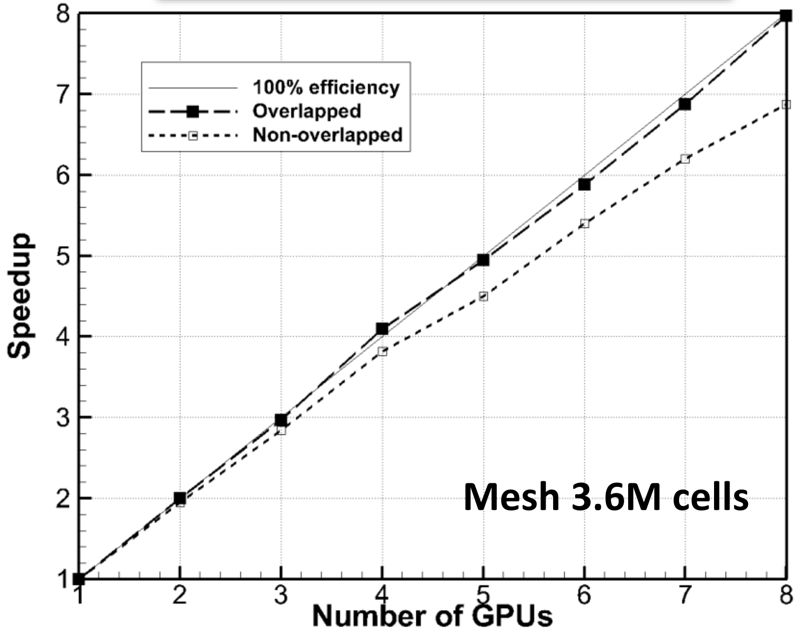
DMA, overlap, workload-balancing, autotuning



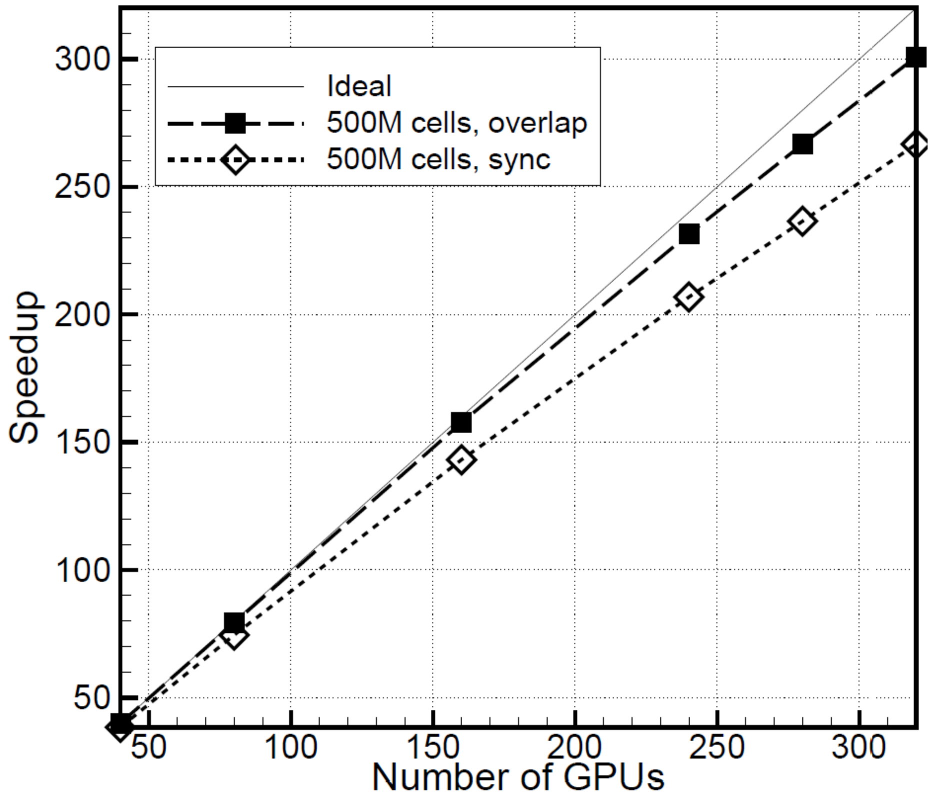
A.Gorobets, S.Soukov, P.Bogdanov. Multilevel parallelization for simulating turbulent flows on most kinds of hybrid supercomputers. Computers&Fluids. (2018) 173:171. https://doi.org/10.1016/j.compfluid.2018.03.011

Overlap of communications and computations

"Fat node" 8 GPU (NIISI RAS, P.Bogdanov):
NVIDIA GTX Titan 288GB/s, 1.5TF, PCI-E 3



HPC5 (KIAE):
2x 8C Xeon E5-2650v2,
2x NVIDIA K80, IB FDR

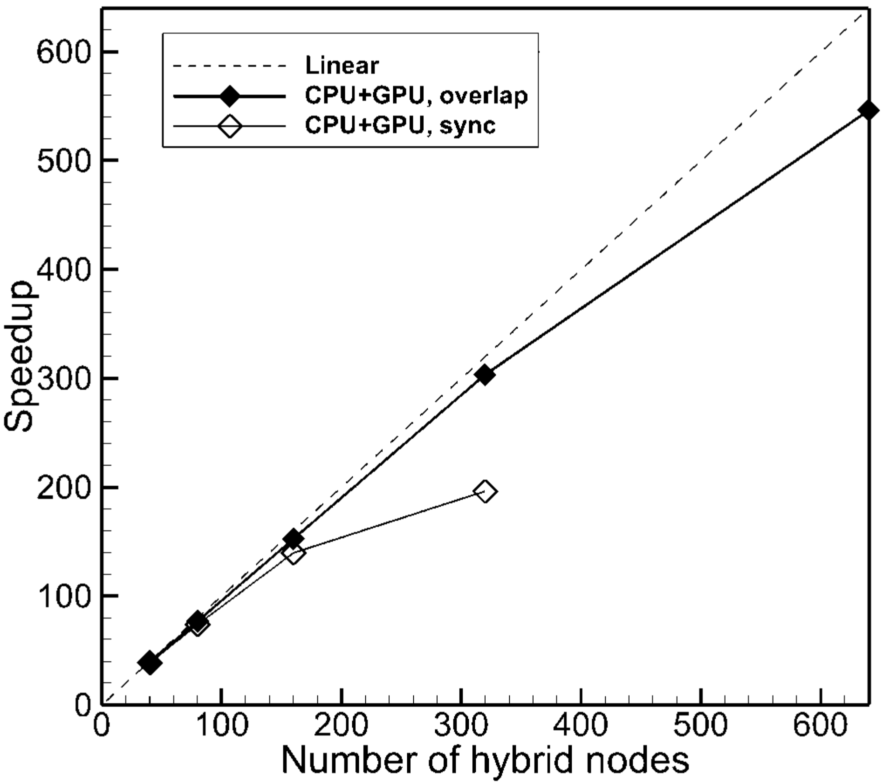


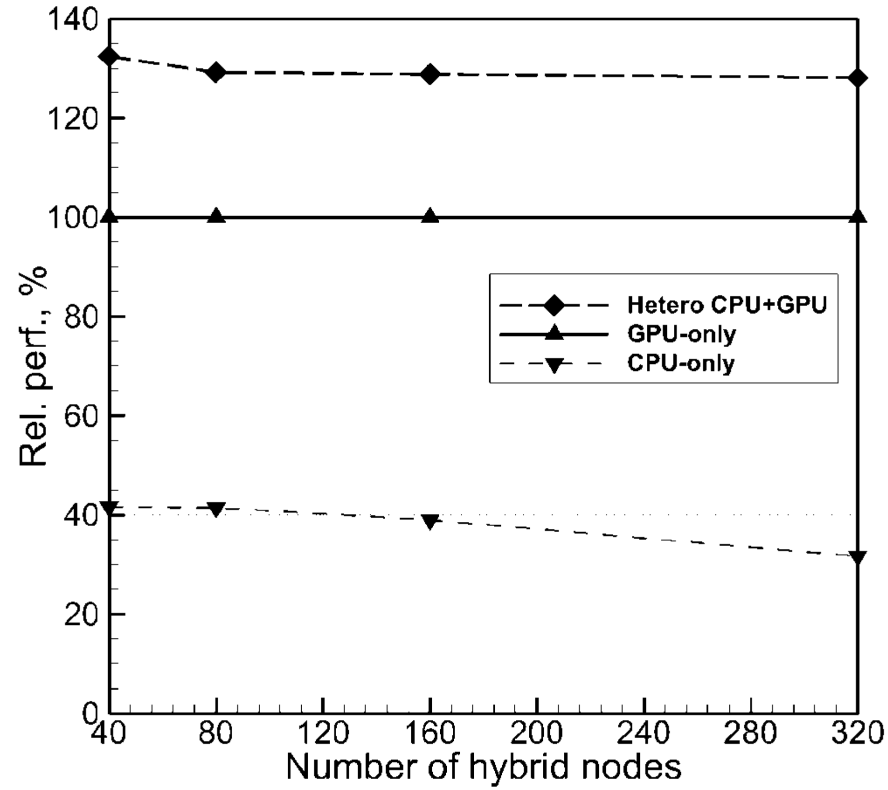
Strategies of cost optimization. Parallelization

Heterogeneous computing: MPI+OpenMP+OpenCL

Lomonosov-2 nodes:

14-core Xeon E5 v3 + GPU NVIDIA K40M





S. A. Soukov, A. V. Gorobets. Heterogeneous Computing in Resource-Intensive CFD Simulations. Doklady Mathematics, 2018, Vol. 98, No. 2, pp. 1–3. DOI: 10.1134/S1064562418060194

Two examples of supercomputer simulations:

Aeroacoustics of swept wing

Helicopter rotor noise

Aeroacoustics of swept wing

Airframe noise has become one of the dominated acoustic sources generated by aircrafts **at the stage of landing**

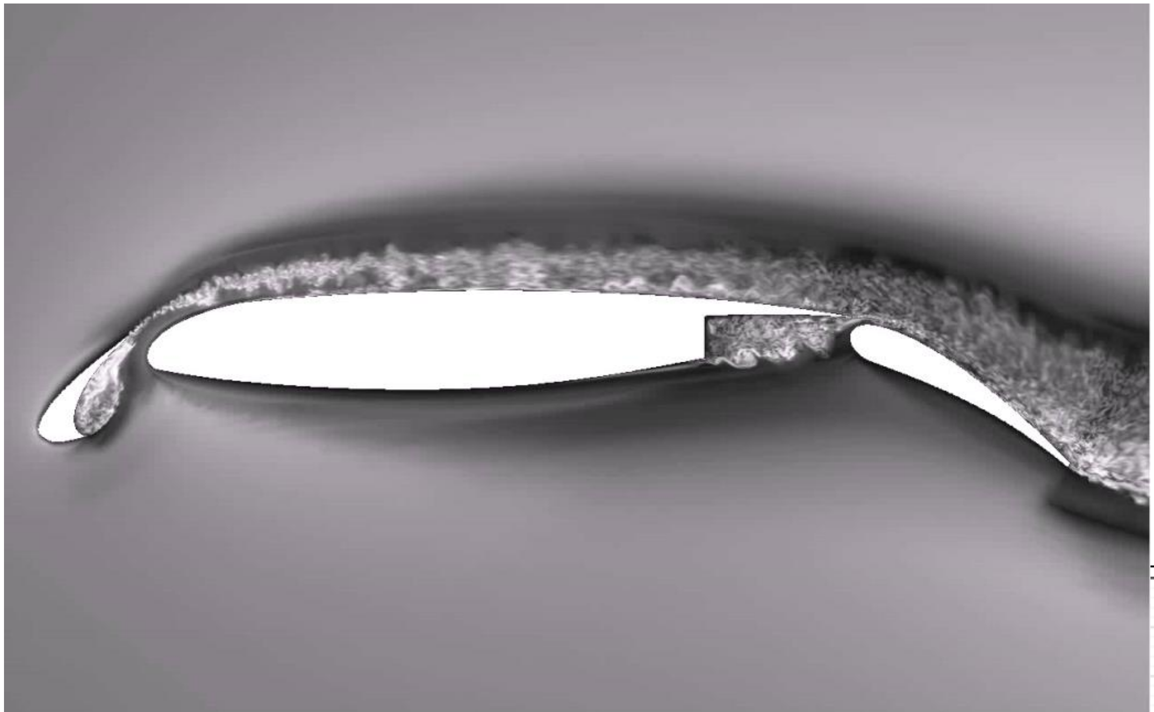
The high lift devices present the main source of airframe noise.

The optimization of HLD configuration, first of all, **slat-wing-flap configuration with no aerodynamic penalties** is one of the hot problems in aircraft design.

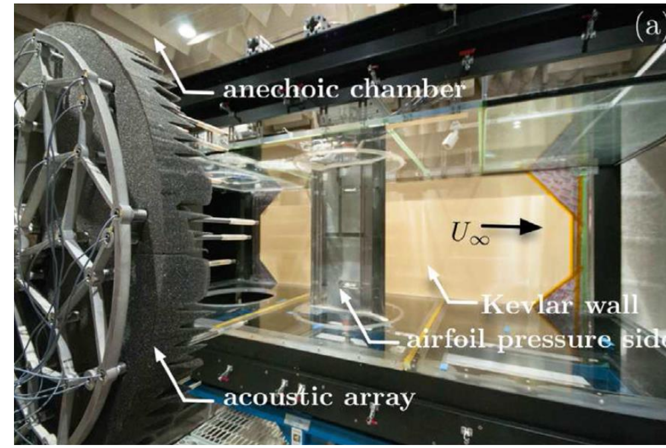
Aeroacoustics of swept wing

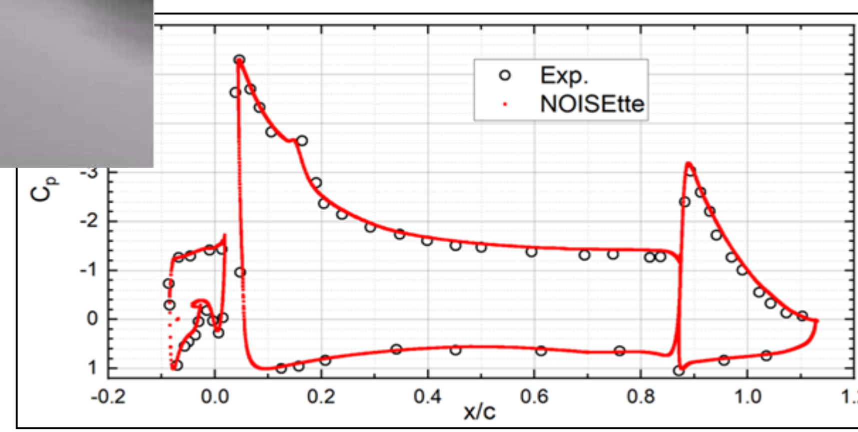
Validation: HLD case (Re$_c$=1.7·10^6, M$_\infty$=0.17, α=5.5°)

IDDES model, two-component hybrid EBR5 scheme, FWH method for far field



Turbulent viscosity



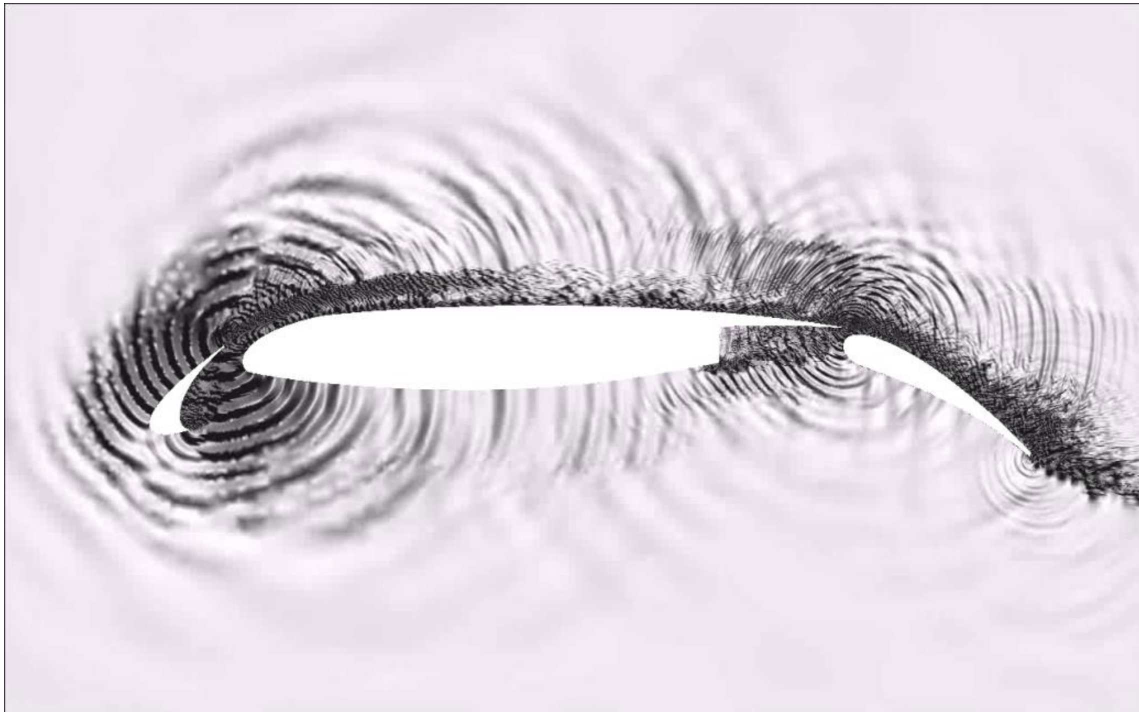


V. Bobkov, A. Gorobets, A. Duben, T. Kozubskaya, V. Tsvetkova. Towards affordable CAA simulations of airliner's wings with deployed high-lift devices // *Book of abstracts of CEAA 2018 Workshop, 2018*

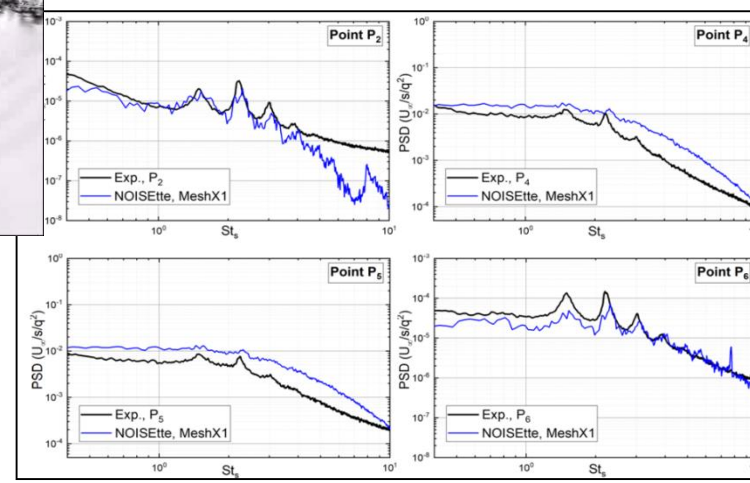
Aeroacoustics of swept wing

30P30N HLD case (Re_c=1.7·10^6, M_∞=0.17, α=5.5°)

IDDES model, two-component hybrid EBR5 scheme, FWH method for far field



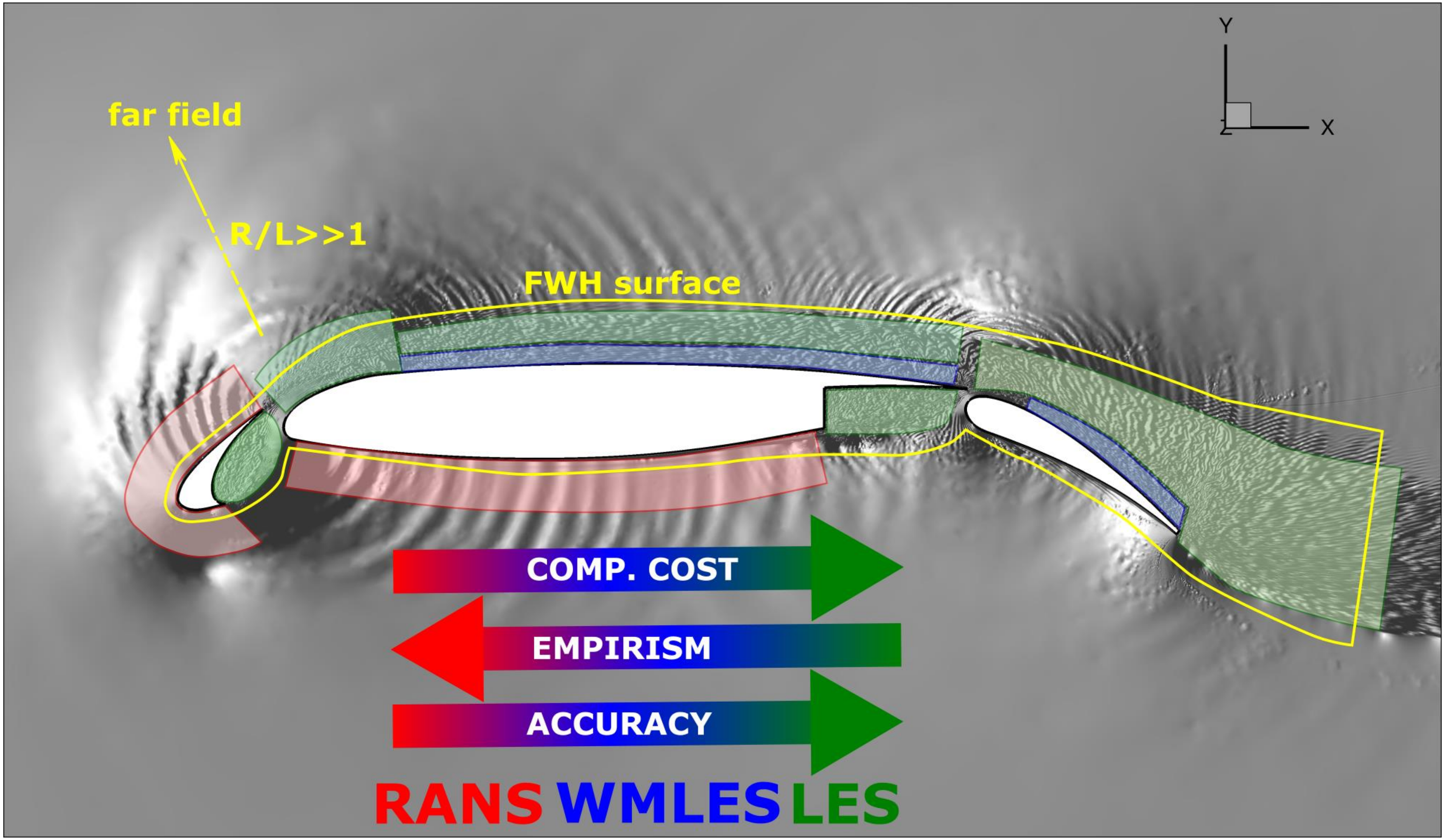
Pressure time derivative



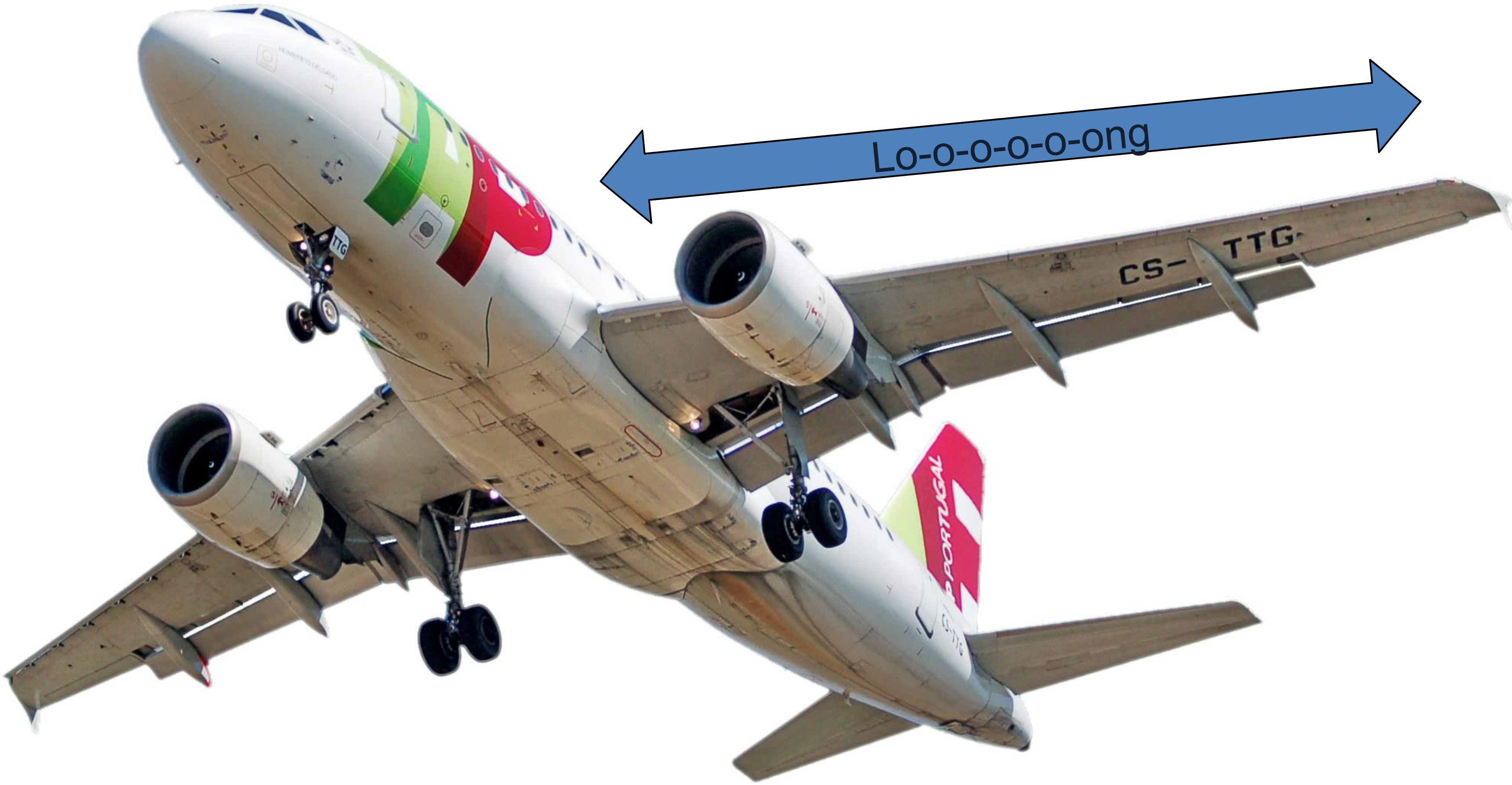
V. Bobkov, A. Gorobets, A. Duben, T. Kozubskaya, V. Tsvetkova. Towards affordable CAA simulations of airliner's wings with deployed high-lift devices // *Book of abstracts of CEAA 2018 Workshop, 2018*

Aeroacoustics of swept wing

Implementation of multi-model approach

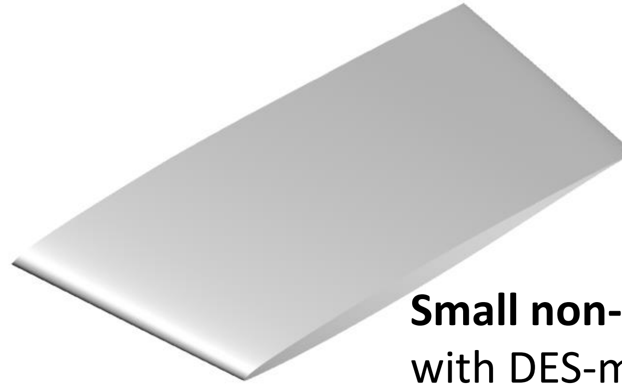


Aeroacoustics of swept wing

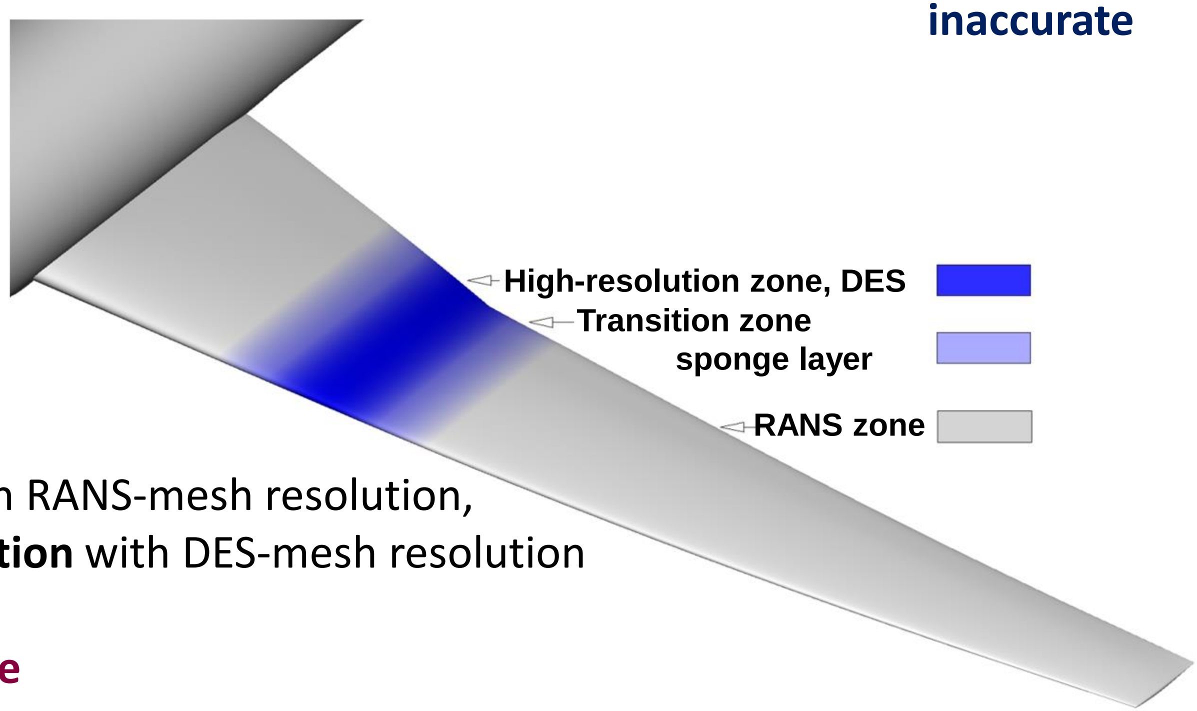


Aeroacoustics of swept wing

Whole-wing
with DES-mesh resoluti
too expensive
accurate



Small non-swept section
with DES-mesh resolution
cheap
inaccurate



Whole wing with RANS-mesh resolution,
Small swept section with DES-mesh resolution
cheap
not so inaccurate

Aeroacoustics of swept wing

Research plan

Straight wing section, periodicity

30P30N: validation

Case 1p

→

Straight wing section, sponge layers

Case 1s

↓

Skew wing section, periodicity

Case 2p

→

Skew wing section, sponge layers

Case 2s

↓

Swept wing section, periodicity

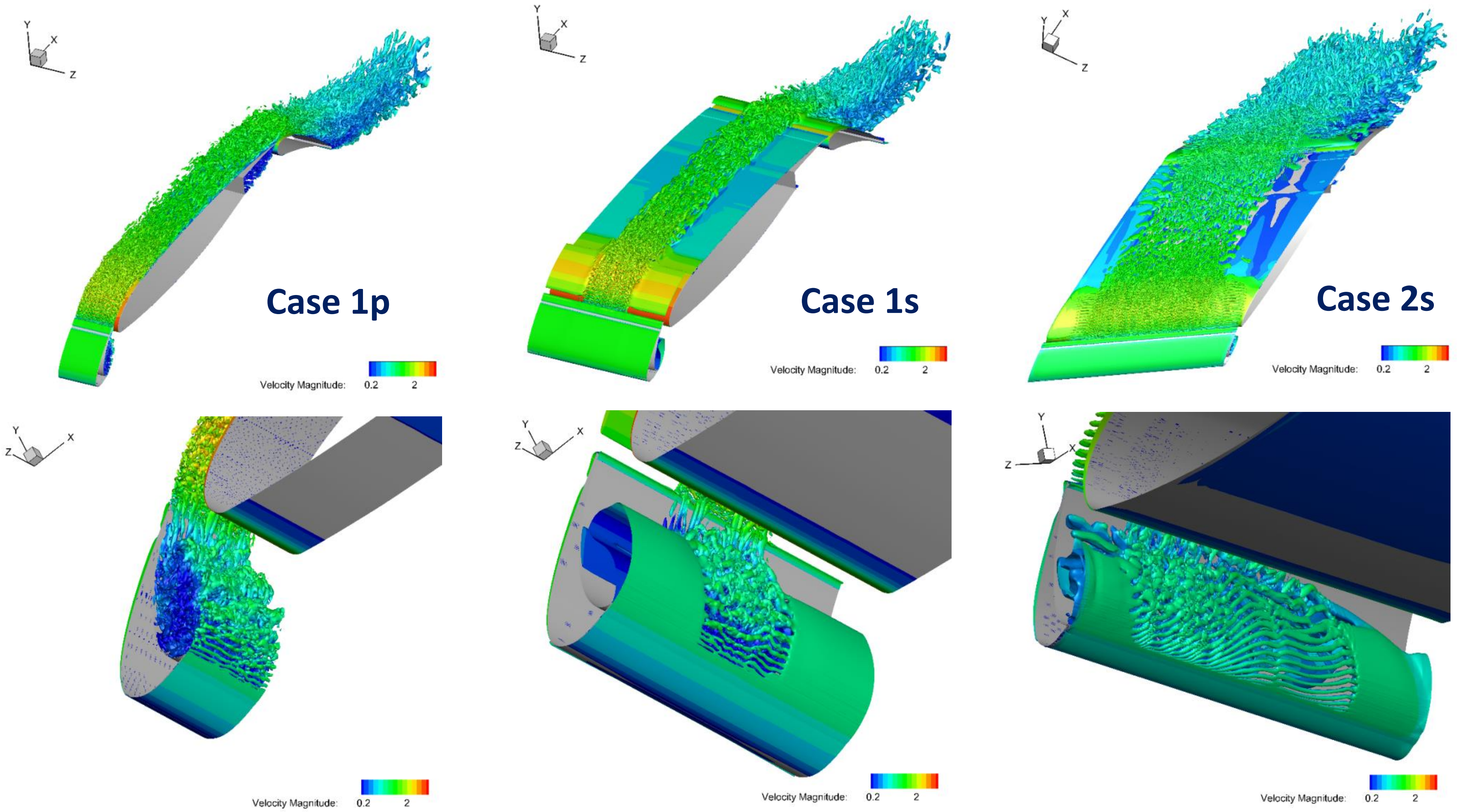
×

Swept wing section, sponge layers

Case 3s

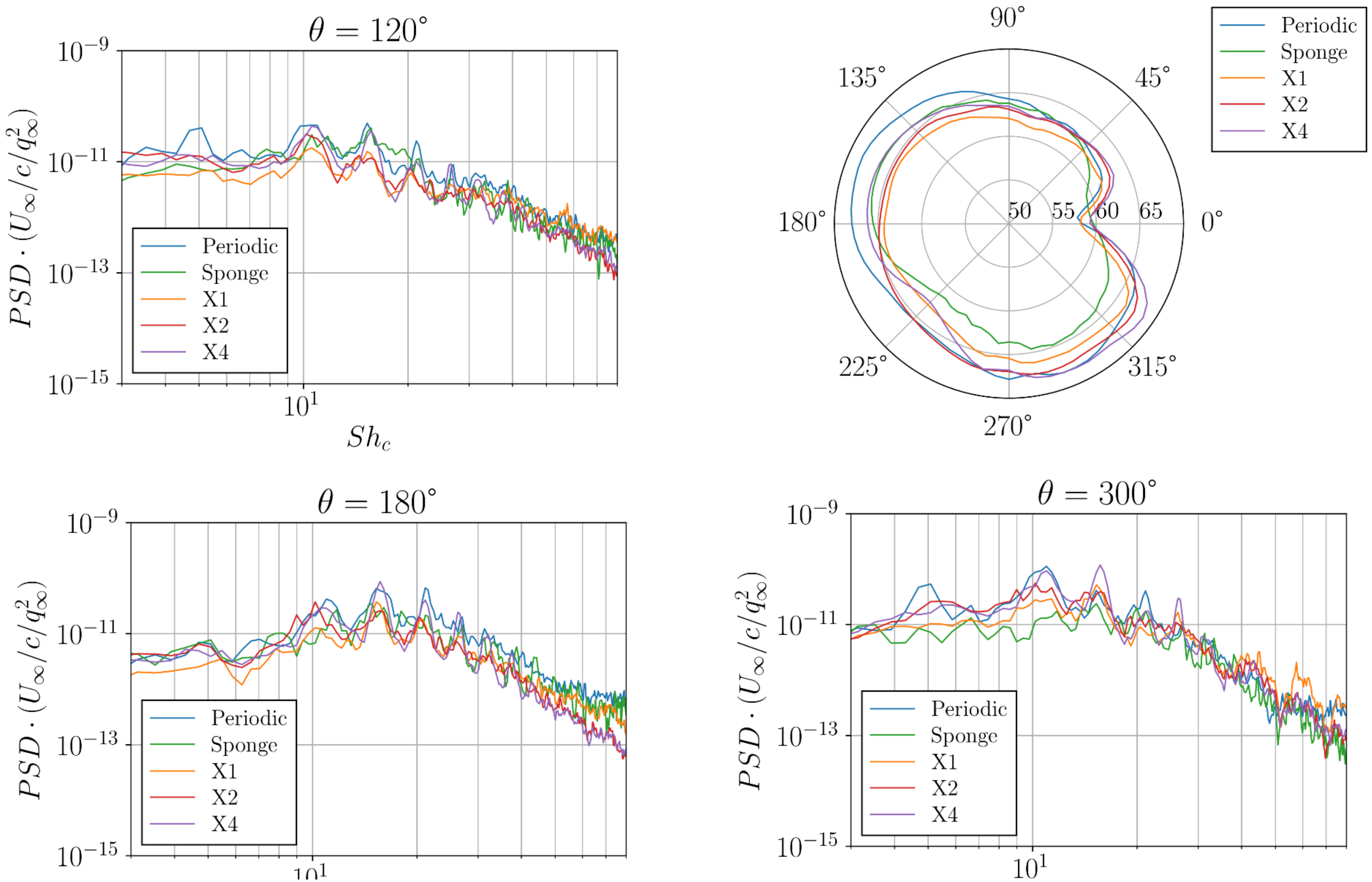
Aeroacoustics of swept wing

Vorticity magnitude in different cases



Aeroacoustics of swept wing

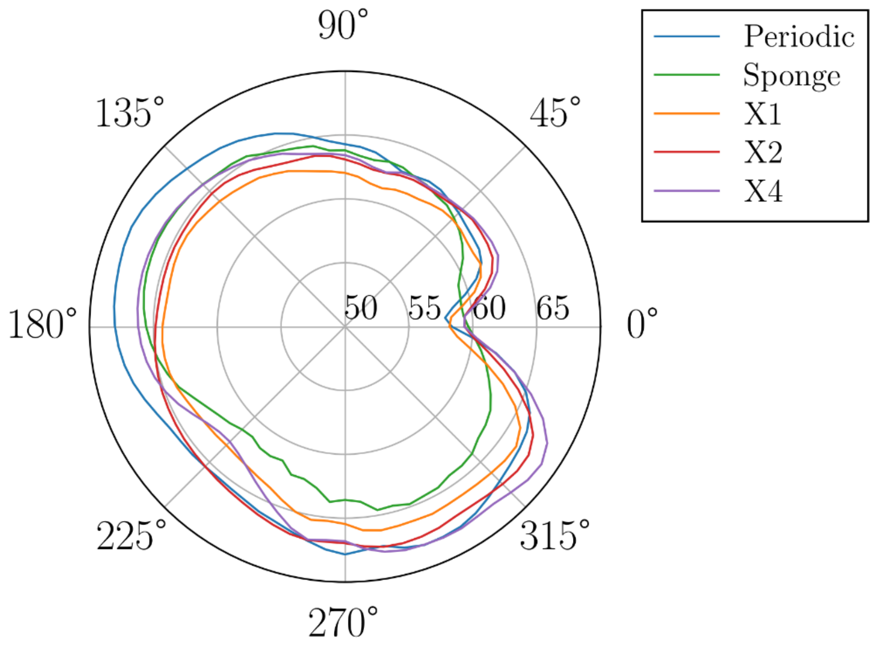
Spectra in control points and directivity diagram



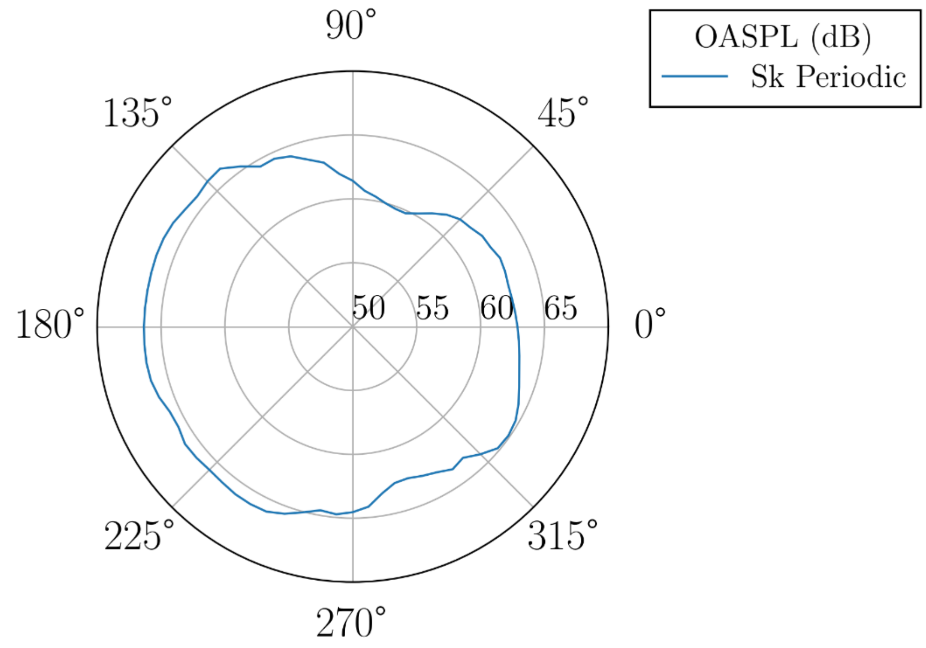
The developed sponge-layer technology does not distort significantly the spectral results

Aeroacoustics of swept wing

Diagram of acoustic-radiation directivity



Straight wing section



Skew wing section

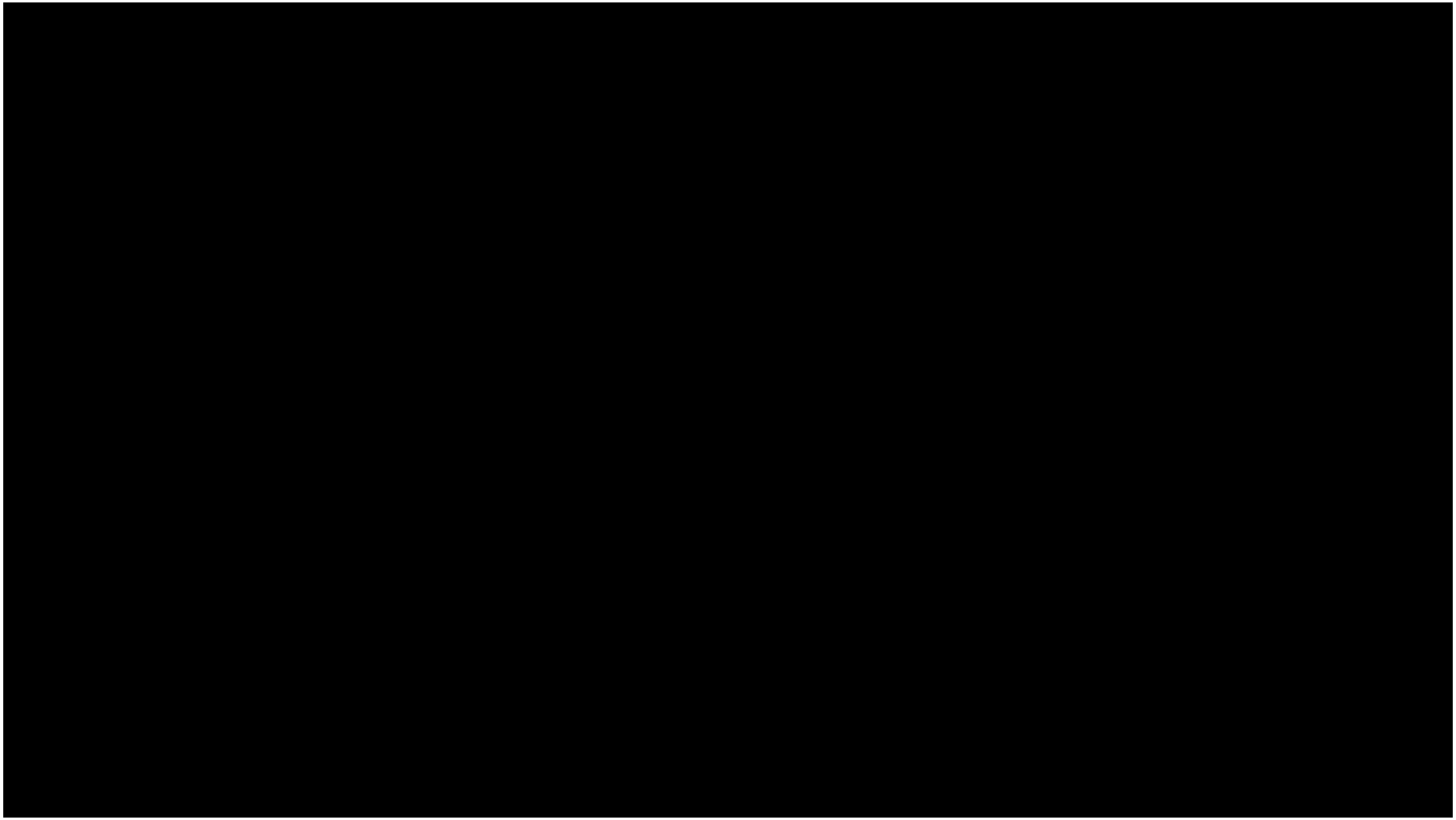
Two examples of supercomputer simulations:

Aeroacoustics of swept wing

Helicopter rotor noise

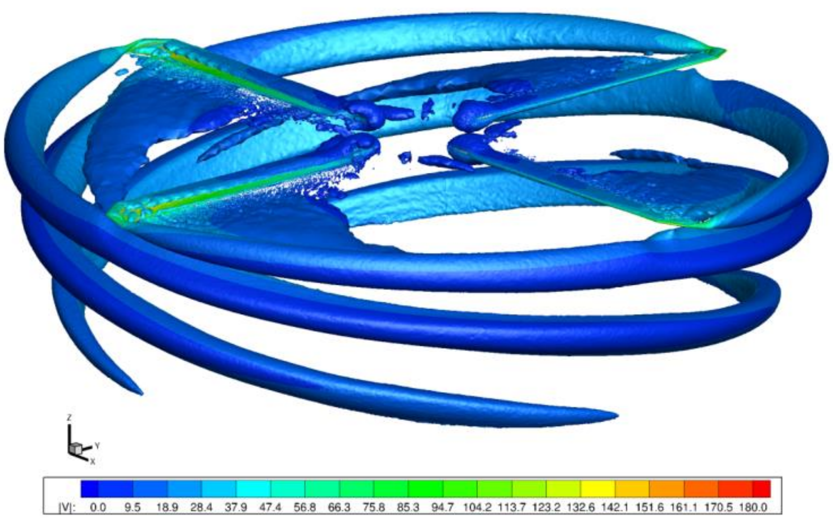
Helicopter rotor noise

Movie

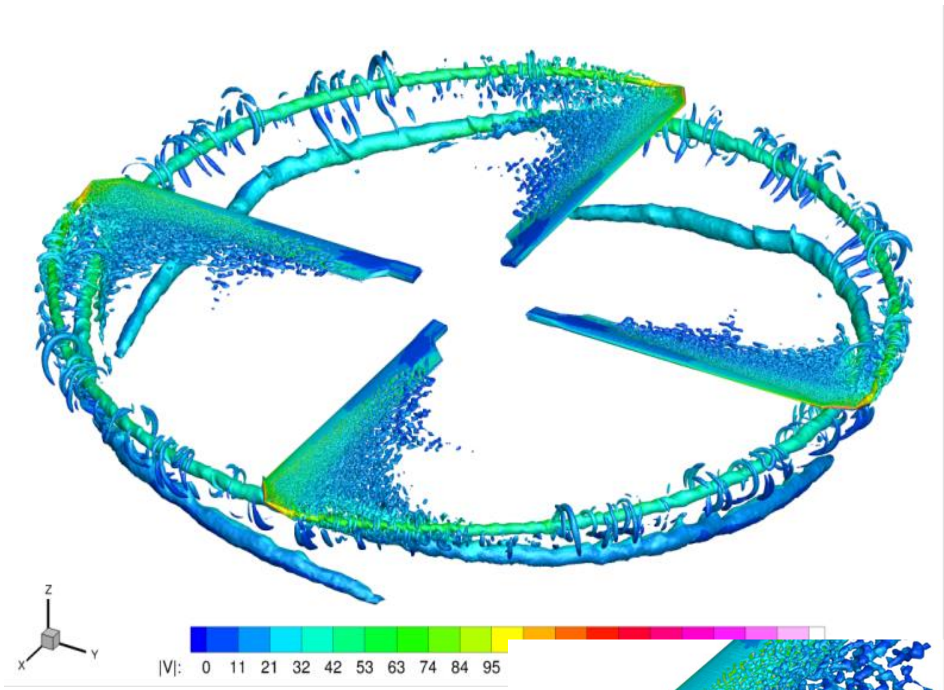


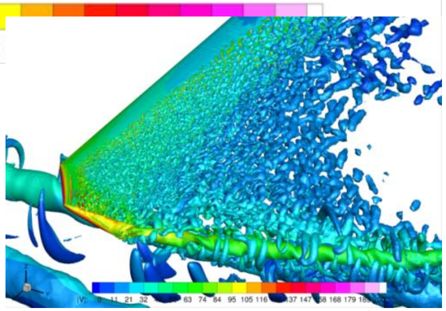
Helicopter rotor noise

RANS vs DES



RANS

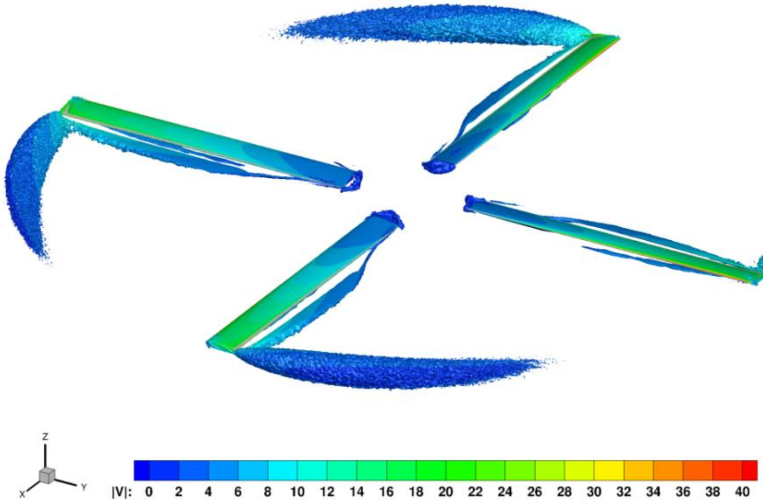




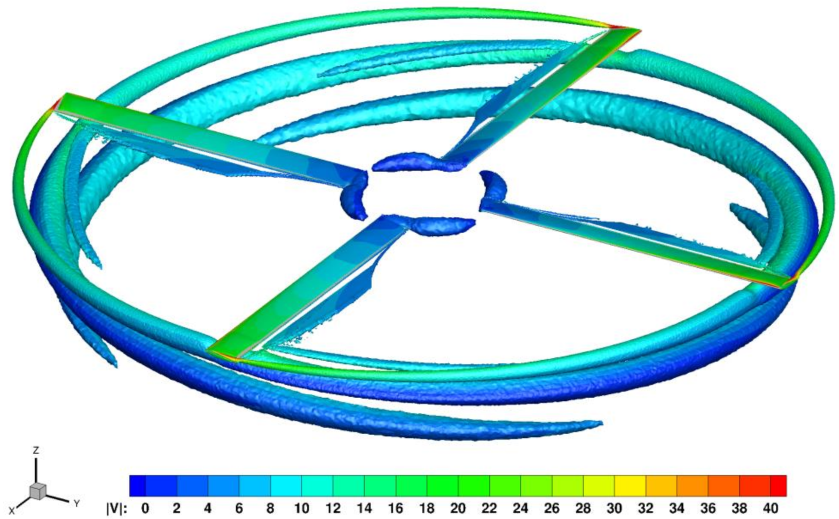
DES

Helicopter rotor noise

Basic FV scheme vs EBR scheme



RANS

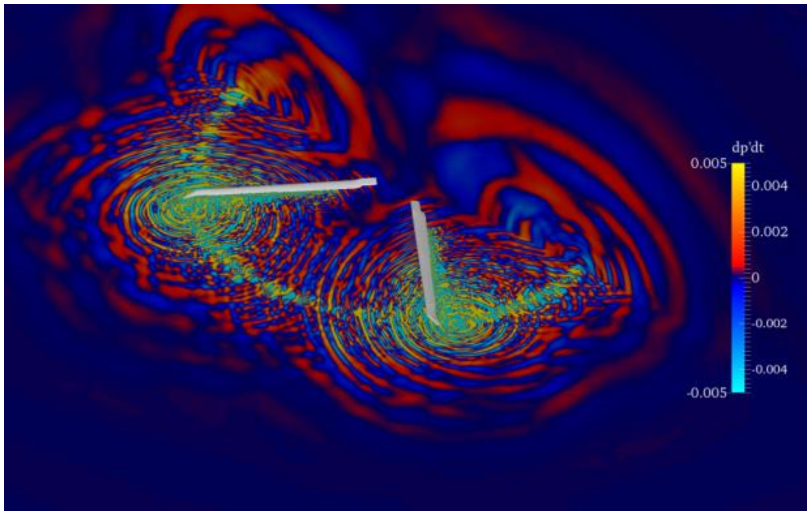


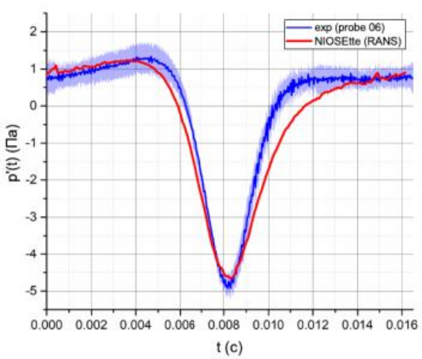
RANS

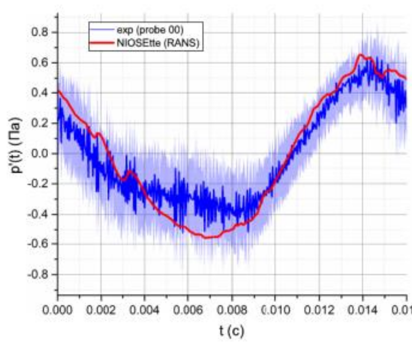
The same mesh

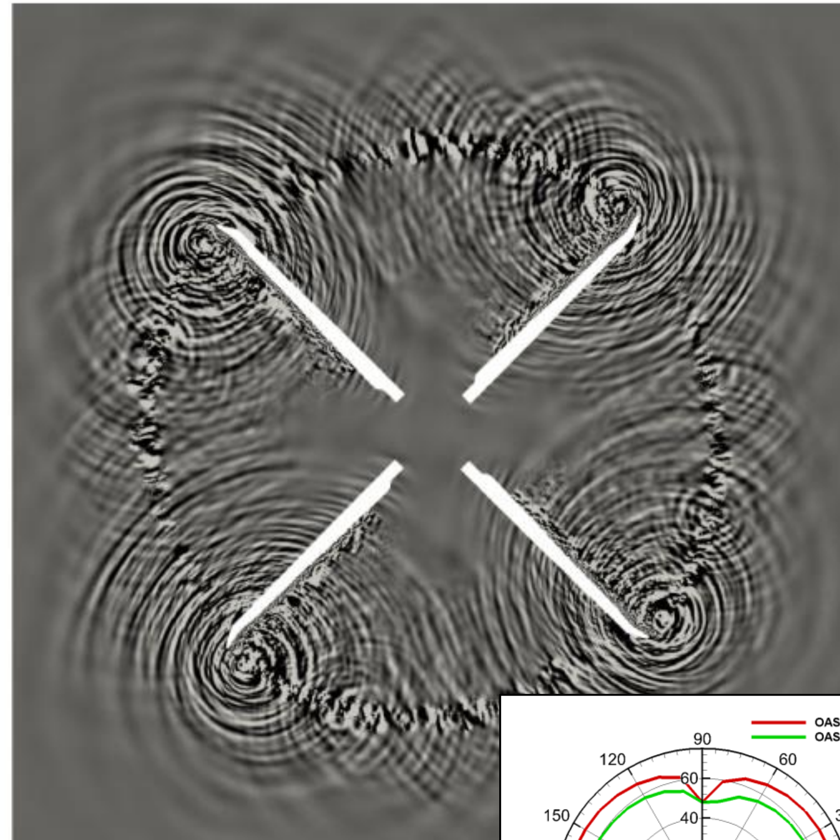
Helicopter rotor noise

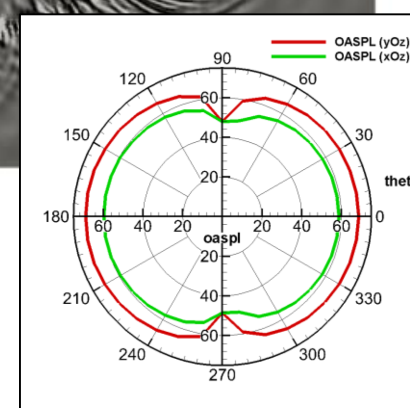
Aeroacoustics







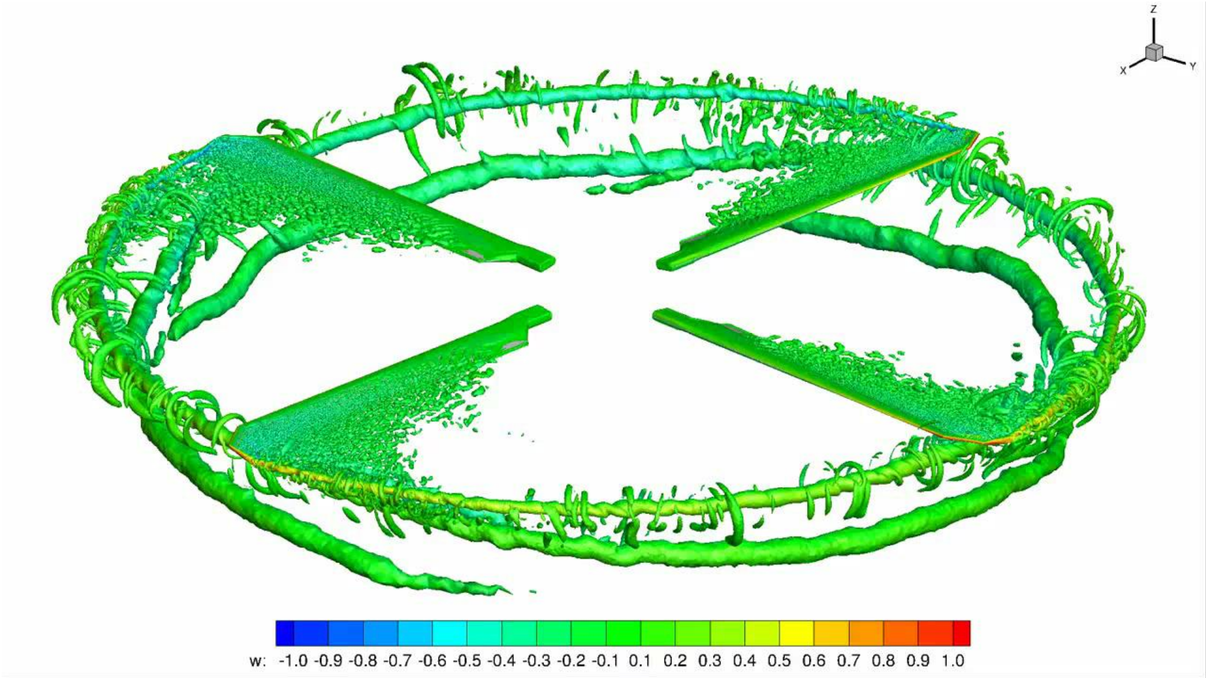




I.V. Abalakin, V.G. Bobkov, P.A. Bakhvalov, A.V. Gorobets, T.K. Kozubskaya.
Simulation of aerodynamics and aeroacoustics of helicopter main rotor on unstructured meshes. – Proceedings of ECCM 6/ ECFD 7, 11–15 June 2018, Glasgow, UK, p1887

Concluding remarks

Unsteady aerodynamics and aeroacoustics problems
become more and more important in modern aviation industries.
Simulations of unsteady aerodynaics and aeroacoustics problems for real configurations are still **very complicated and too computationally expensive**.
However some good results can be obtained and to make the “DNS era” closer
by using **different smart saving technologies**.



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Thank You!