Numerical simulation of turbulent flow over a cavity for fundamental and applied purposes

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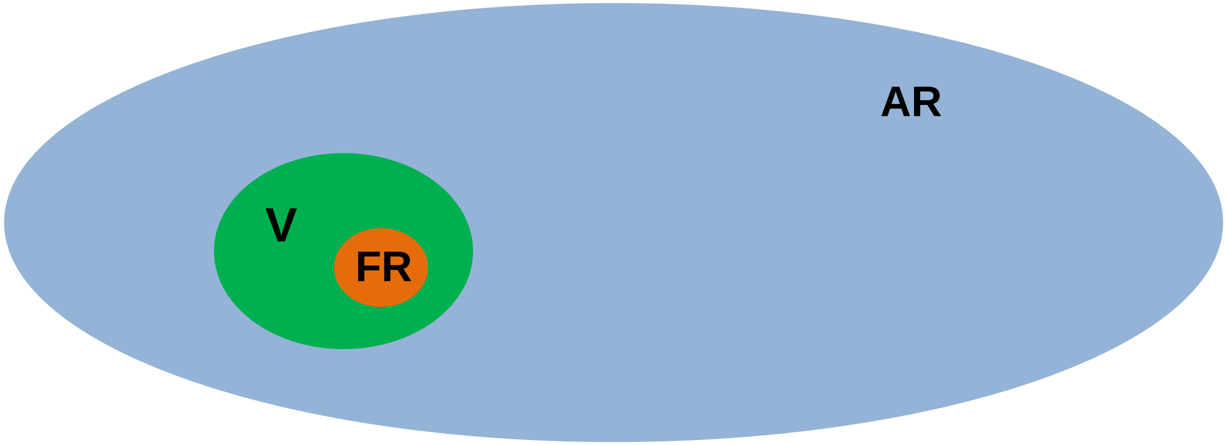
OUTLINE

- **Introduction**
- **Numerical algorithms**
- **Simulation of turbulent flow over cavity M219** as a case for validation
- **Analysis of numerical space-time data** for better understanding of flow physics
- **Prediction of turbulent flow over the cavity with a deflector** as an example of relevant industry-oriented problems
- **Concluding remarks**

INTRODUCTION

- **Computational experiment in aeroacoustics** is the main subject under consideration at the workshop
- **Validation (V) of numerical algorithms and the corresponding codes** is a crucial condition for making computational algorithm:
    - **a means of fundamental research (FR)** and deeper understanding of flow physics;
    - **a means of applied research (AR)** and solving industry-oriented problems



- In the talk we demonstrate this scheme on example of problems connected with **turbulent flows over a cavity**

NUMERICAL ALGORITHMS

- **Vertex-centered FV unstructured in-house code NOISEtte for solving CFD and CAA problems:**
  - turbulent flow simulation using scale-resolving approaches
  - unstructured meshes (tetrahedrons, pyramids, prisms, hexahedrons)
  - O(100K) cores parallel scalability
- **Recent modification [Shur et al., 2015] of hybrid RANS-LES DES method (with $\Delta=\Delta_{SLA}$, shear layer adapted LES length scale)** which accelerates RANS-to-LES transition in shear layers
- **The algorithm is based on higher-accuracy EBR (Edge-Based Reconstruction) scheme which exploits quasi-1D reconstruction of variables**
- **Remarkable details:**
  - hybrid CD-Upw adaptation of EBR scheme to solution;
  - adaptive change of EBR scheme stencil width depending on the mesh peculiarities (extended or compact stencils in “problem” regions)
- **Time integration: 2nd order implicit scheme (Newton iterations + BiCGStab solver)**
- **Immersed boundary conditions** for installed devices of complicated shapes and/or moving components

Quasi-1D framework for unstructured meshes

VALIDATION: M219 cavity, computational setup

Flow parameters:

$Re_H=1.37\cdot10^6$ $M_\infty=0.85$

$H=0.1016$ [м] $P_\infty=6.21\cdot10^4$ [Па]

Approach:

- IDDES ($\Delta=\Delta_{SLA}$) [Shur et al, 2015]
- Hybrid CD-Upw EBR vertex-centered scheme

Mesh:

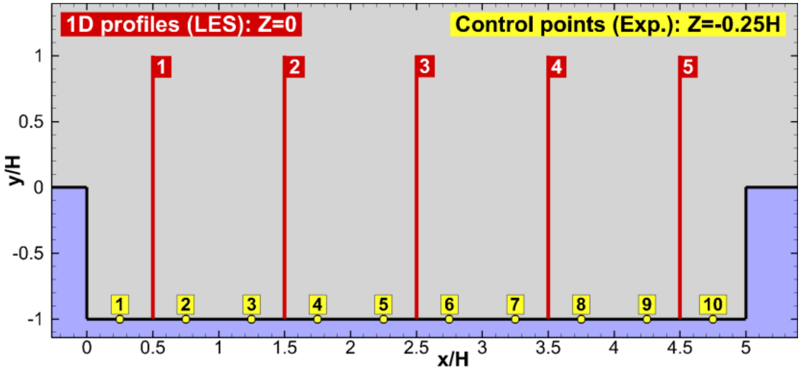
Hexahedral mesh

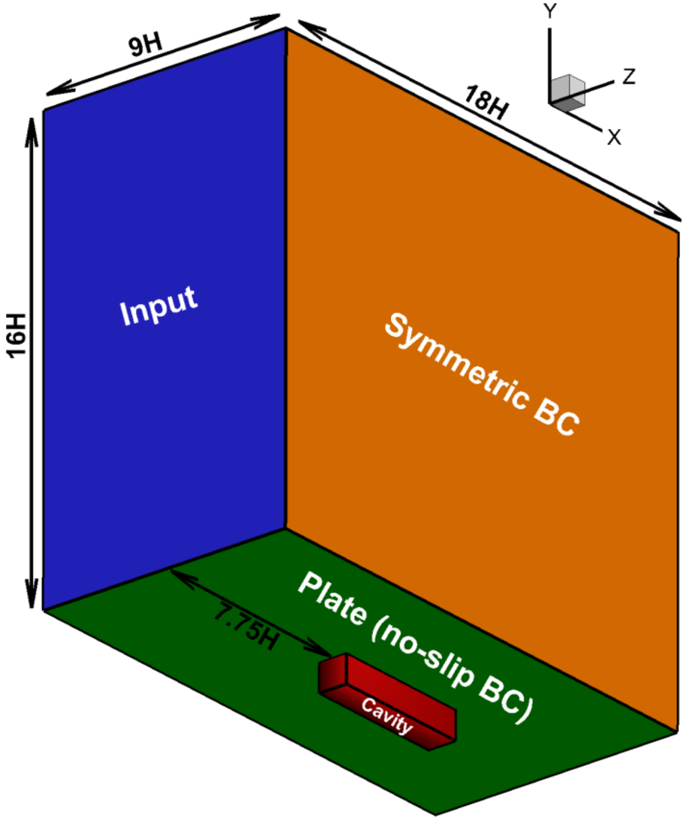
4M nodes

$\Delta_{LES} = H/33$

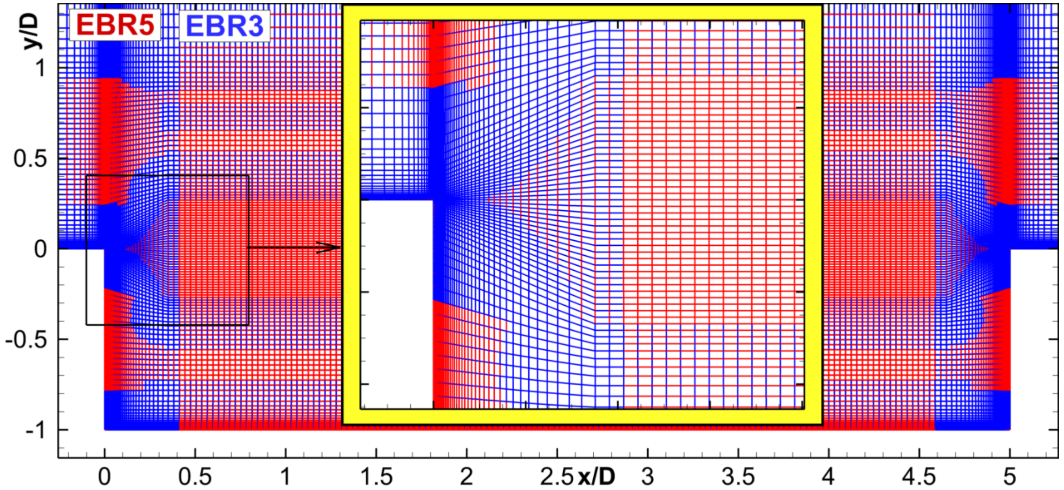
Reference data:

- Experiment: pressure history [de Henshaw et al., 2002]
- LES [Larcheveque et al., 2004]



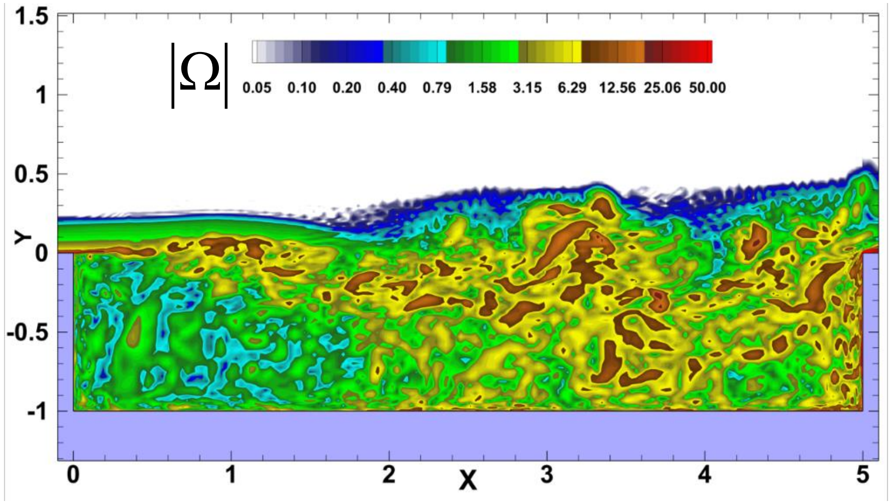


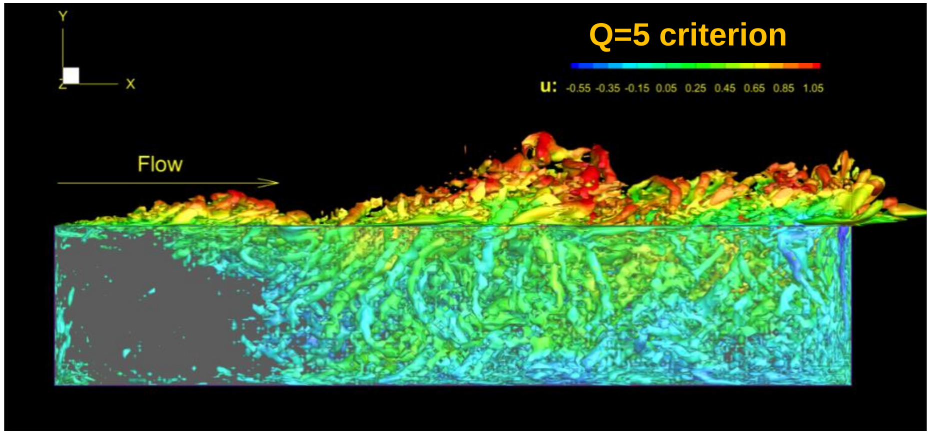
Computational domain

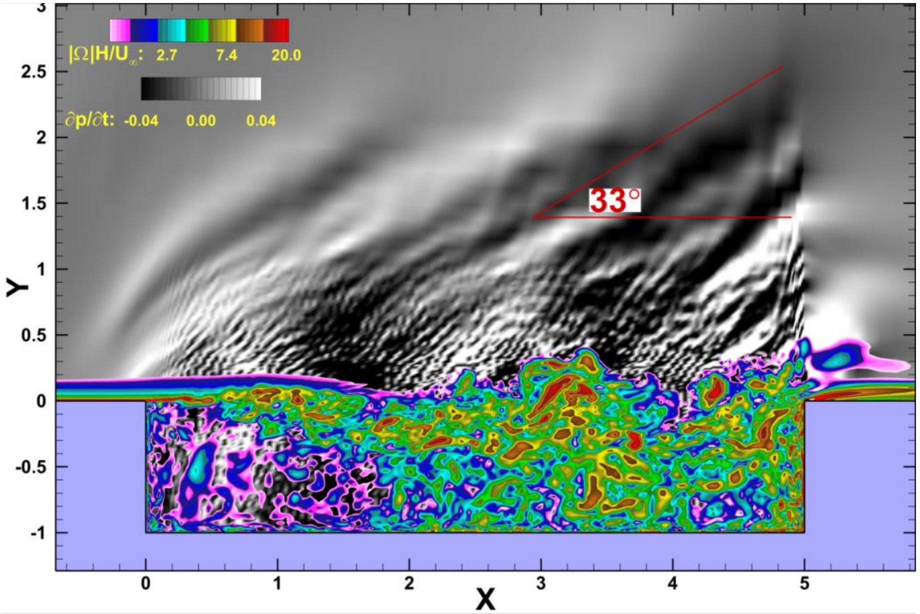


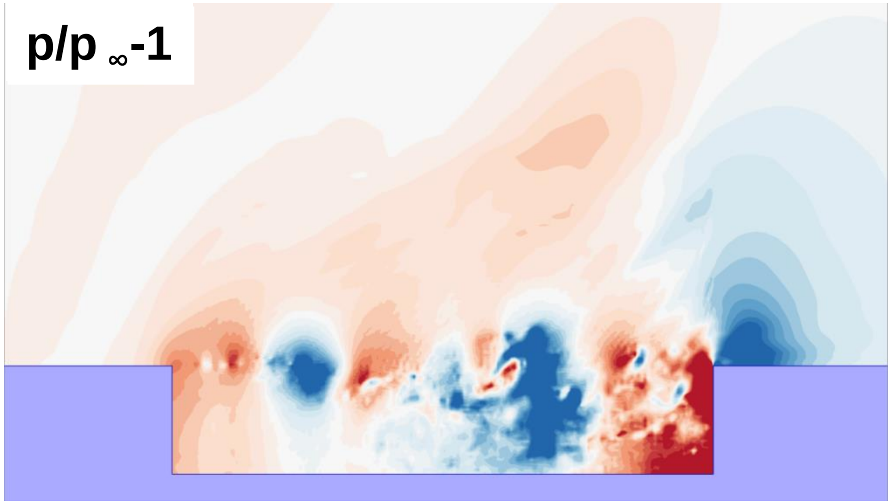
Computational mesh pattern

VALIDATION: M219 cavity, instantaneous fields

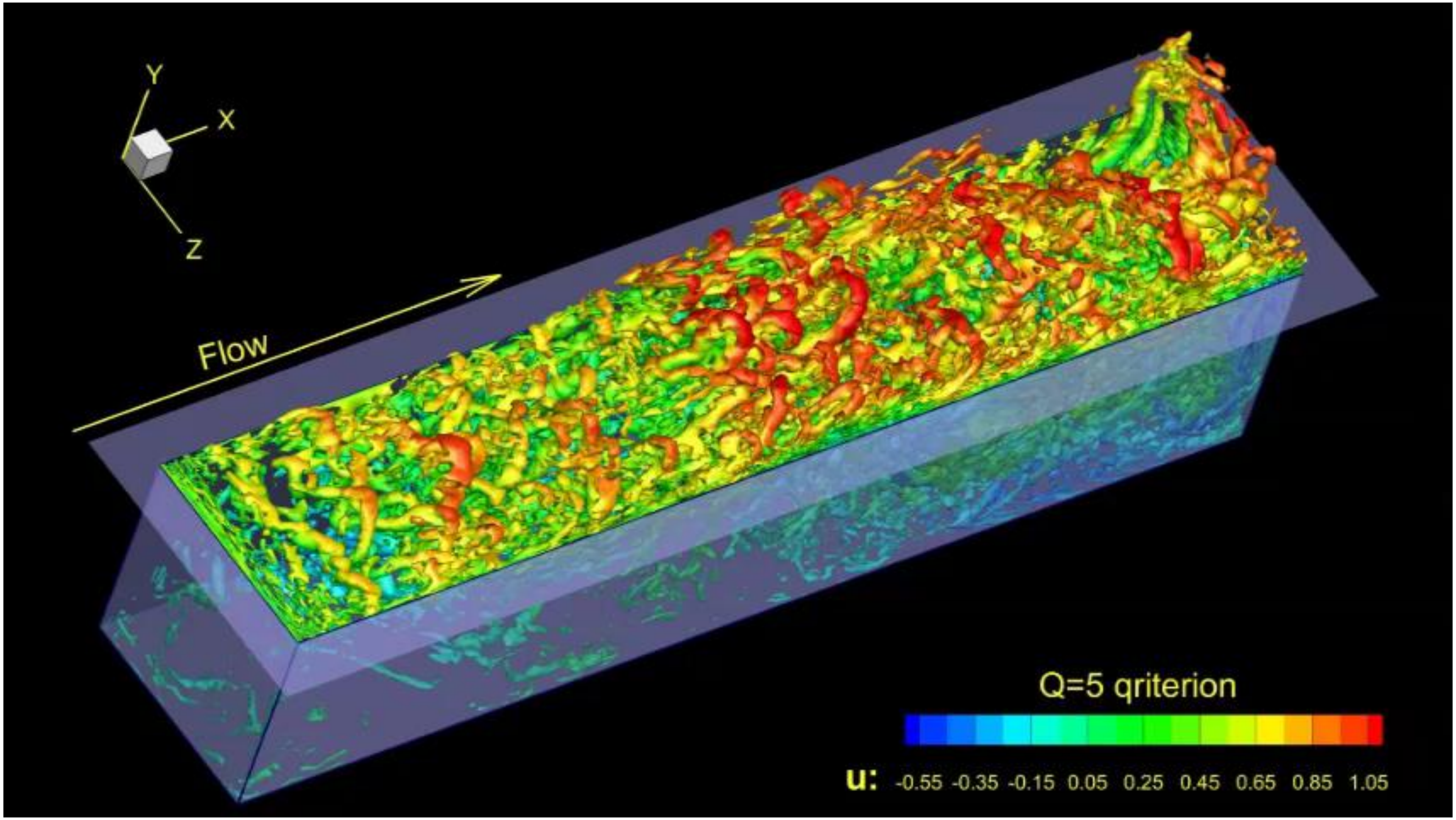




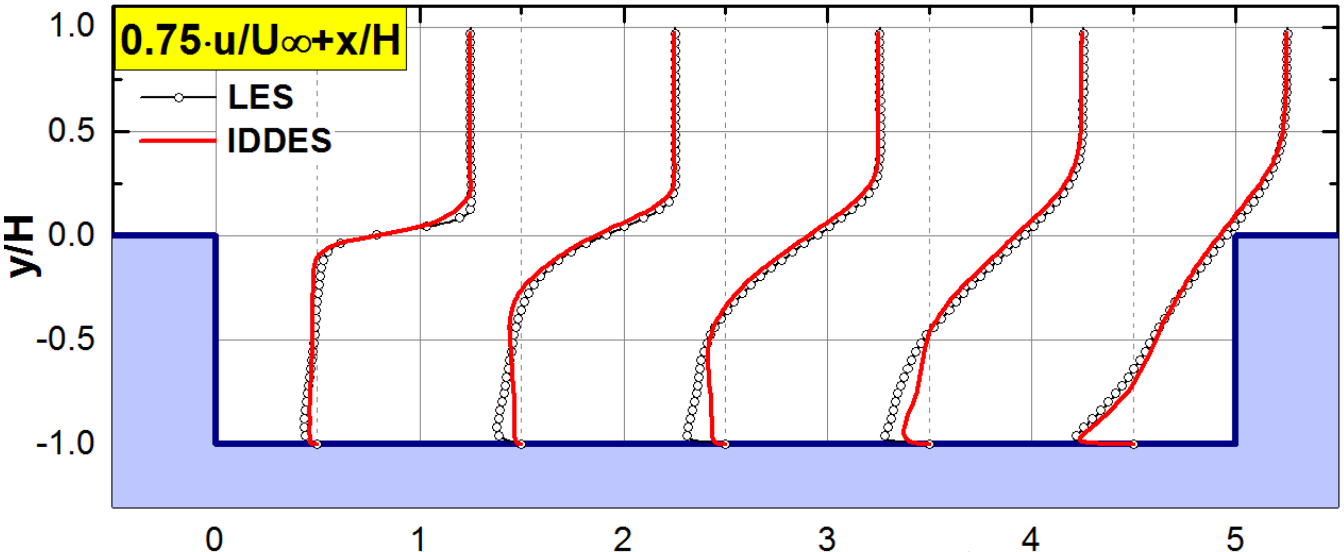




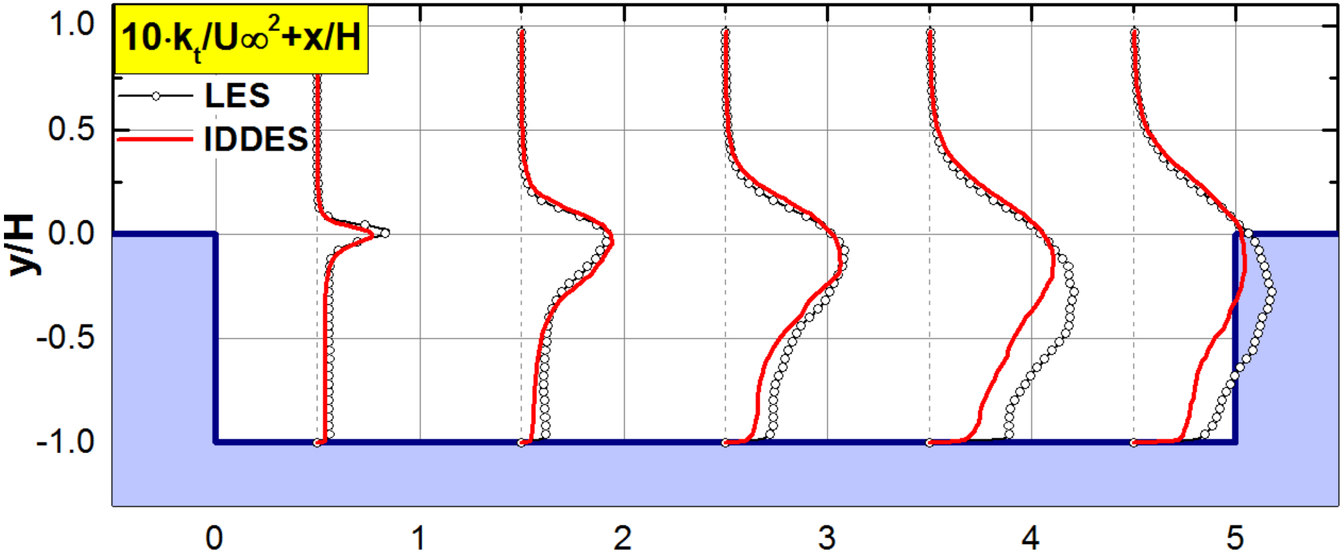
VALIDATION: M219 cavity, flow visualization



VALIDATION: M219 cavity, comparison with the reference LES



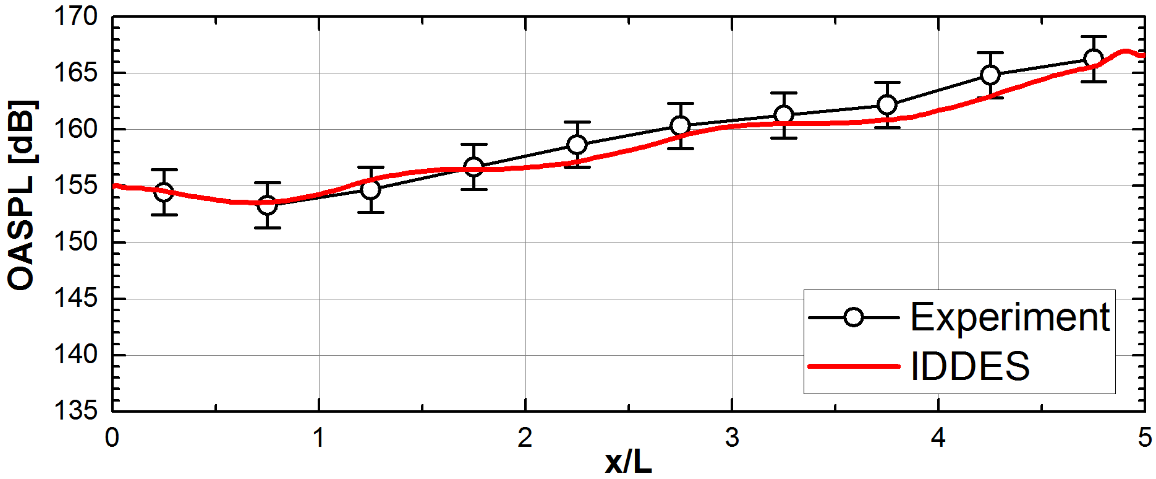
Mean longitudinal velocity profiles



Resolved turbulent kinetic energy profiles

LES [Larcheveque et al., 2004]

VALIDATION: M219 cavity, OASPL and Rossiter modes



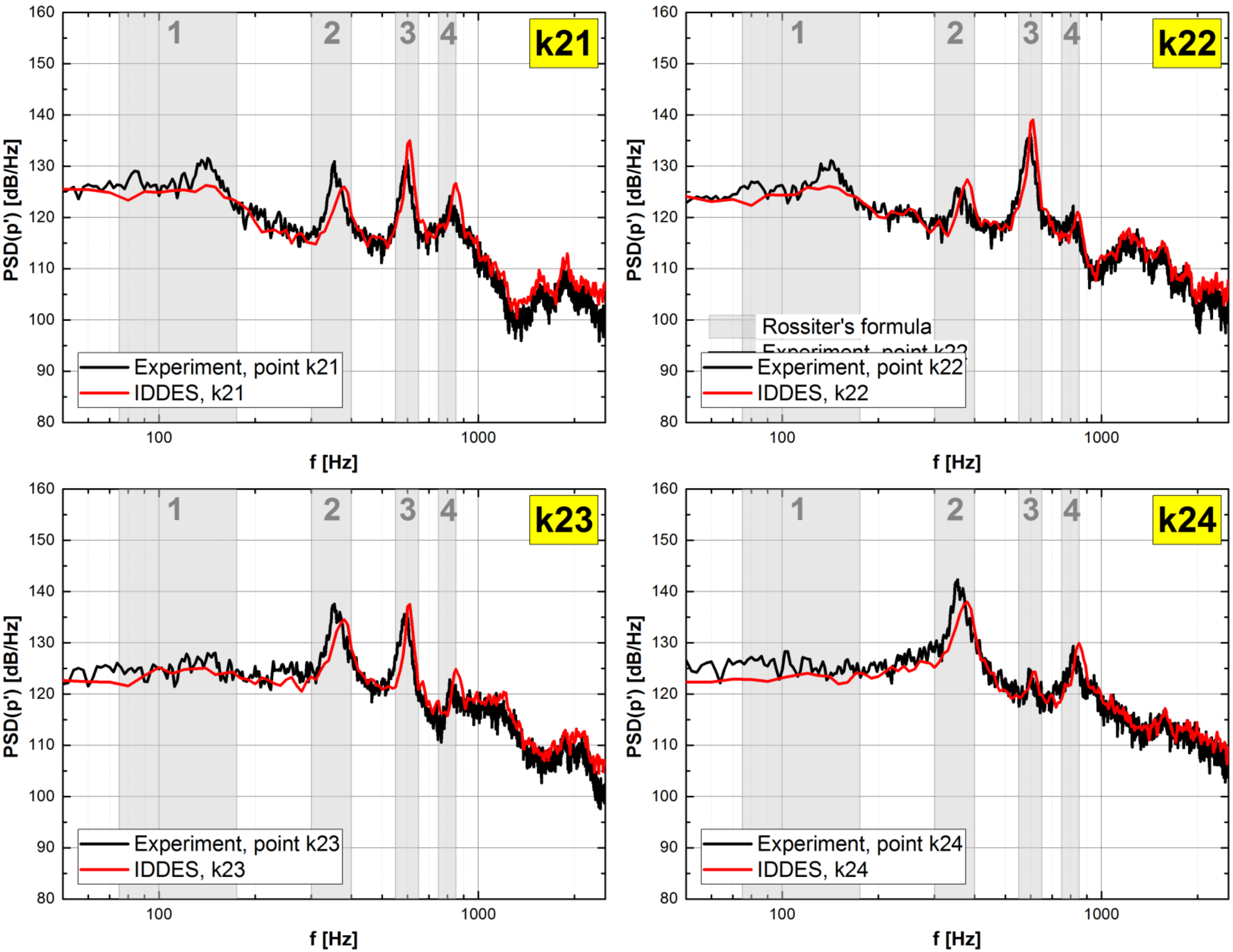
PSD estimation:

- Periodogram method, Hanning window, overlap 50%
- Sample length: experiment: 3.4 [s], IDDES: 1 [s]

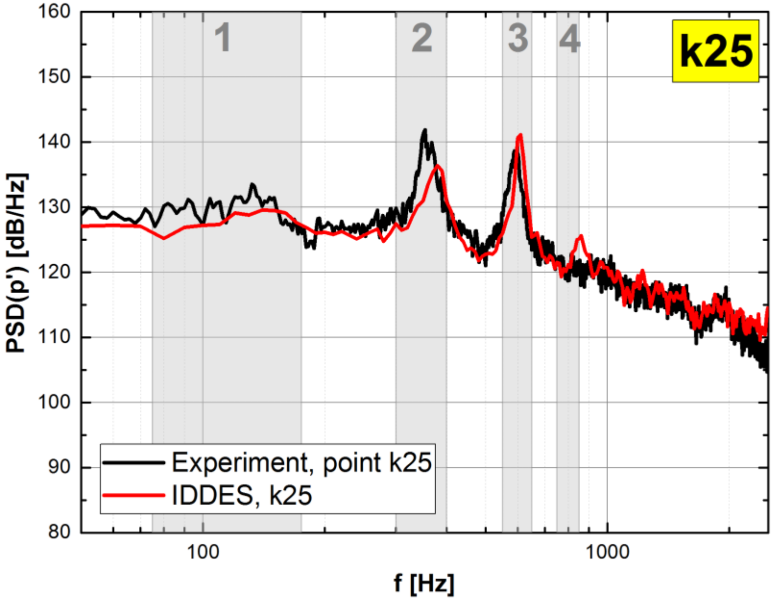
Comparison of Rossiter modes values

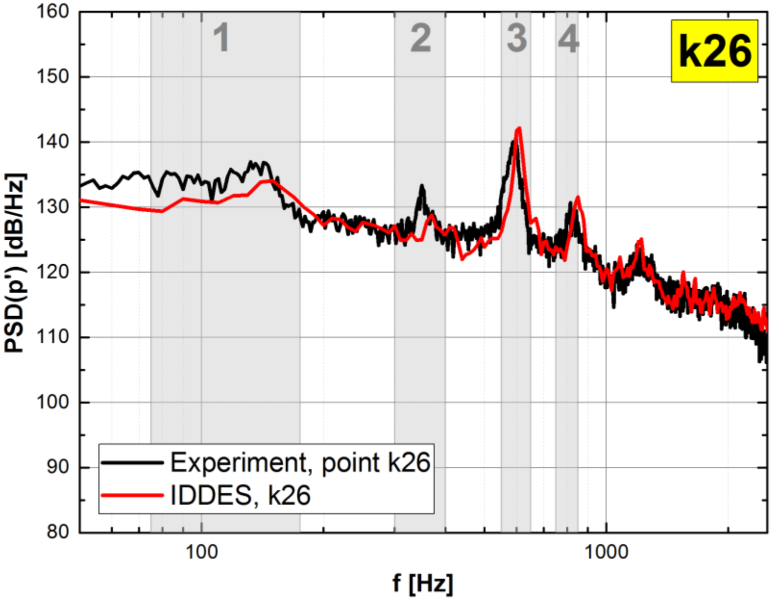
Mode	1	2	3	4
Experiment (Hz)	**135**	**350**	**590**	**820**
Rossiter formula (Hz)	**148**	**357**	**566**	**775**
LES (Hz)	**125**	**360**	**585**	**825**
IDDES (Hz)	**140**	**375**	**595**	**835**

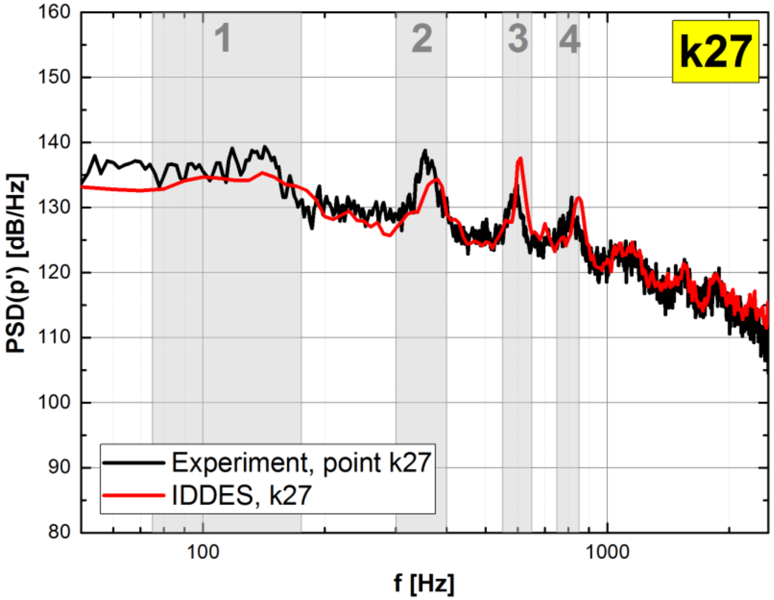
VALIDATION: M219 cavity, PSD(p’) (1/2)

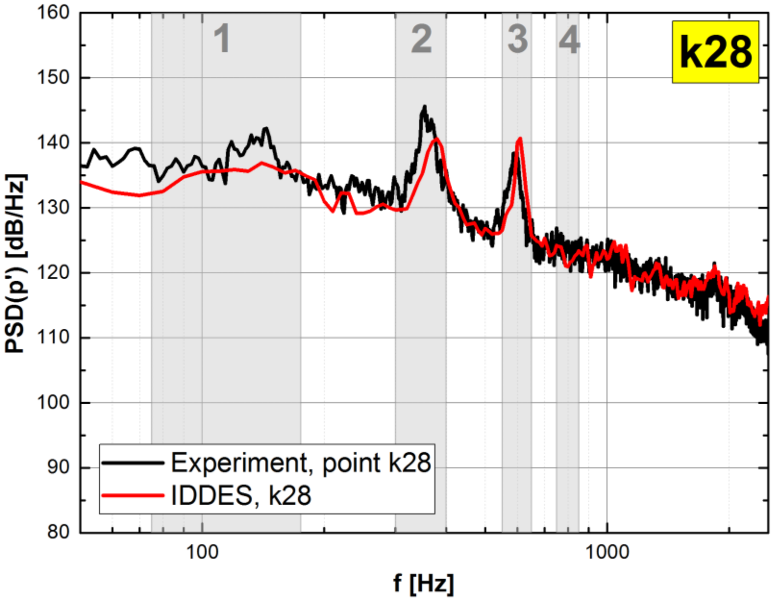


VALIDATION: M219 cavity, PSD(p’) (2/2)

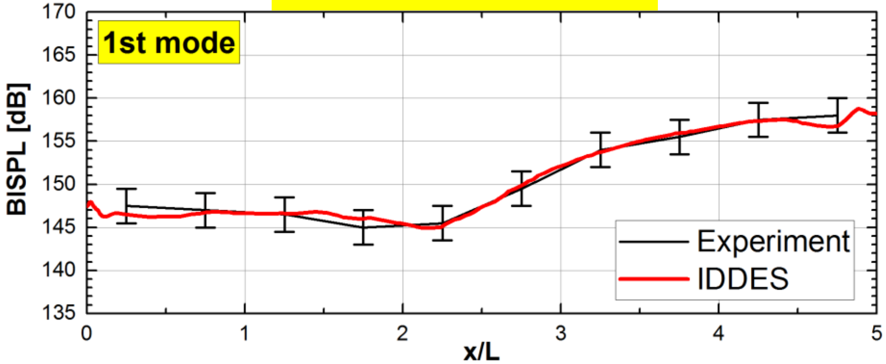


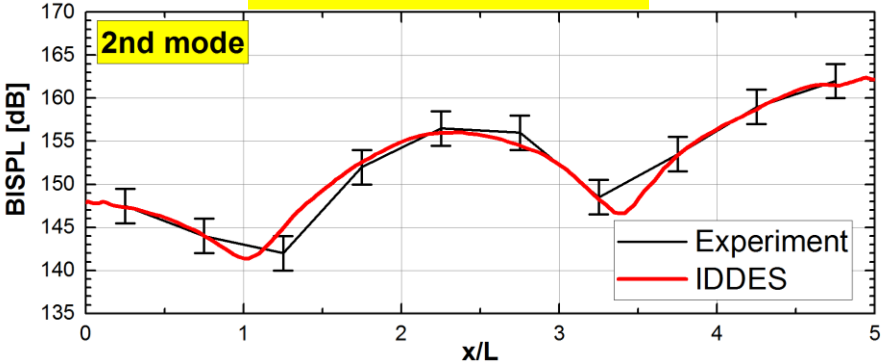


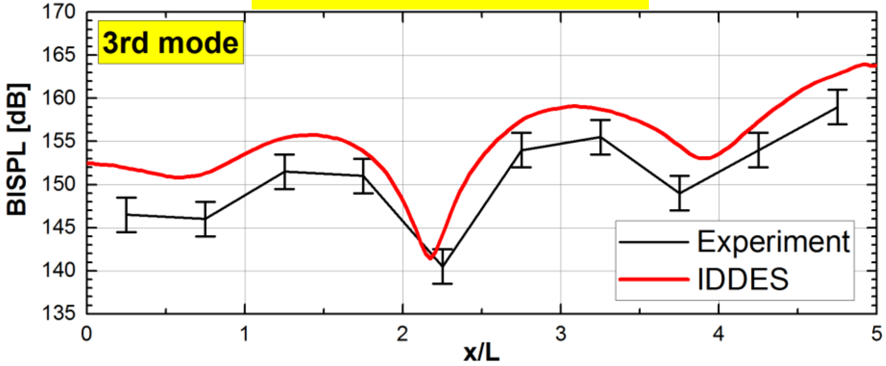


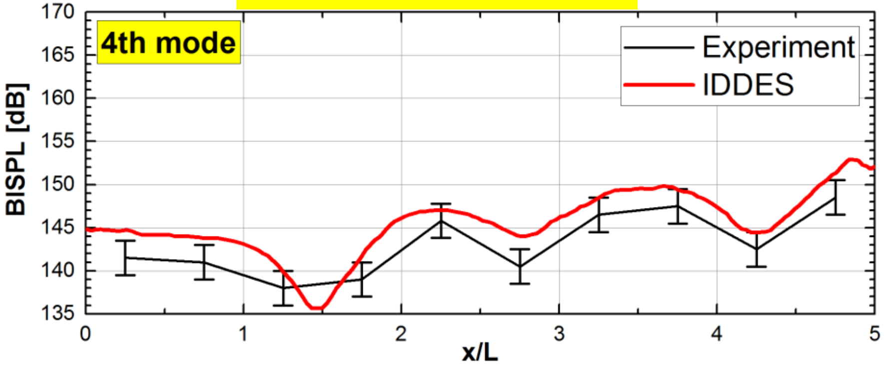


VALIDATION: M219 cavity, BISPL


75 Hz < f < 175 Hz


300 Hz < f < 400 Hz


550 Hz < f < 650 Hz


750 Hz < f < 850 Hz

- Results of IDDES are in a good agreement with the experimental data
  which lets us consider the numerical data **valid**
  So, basing on this background, we can do further steps
  in the directions of **fundamental** and **applied** research

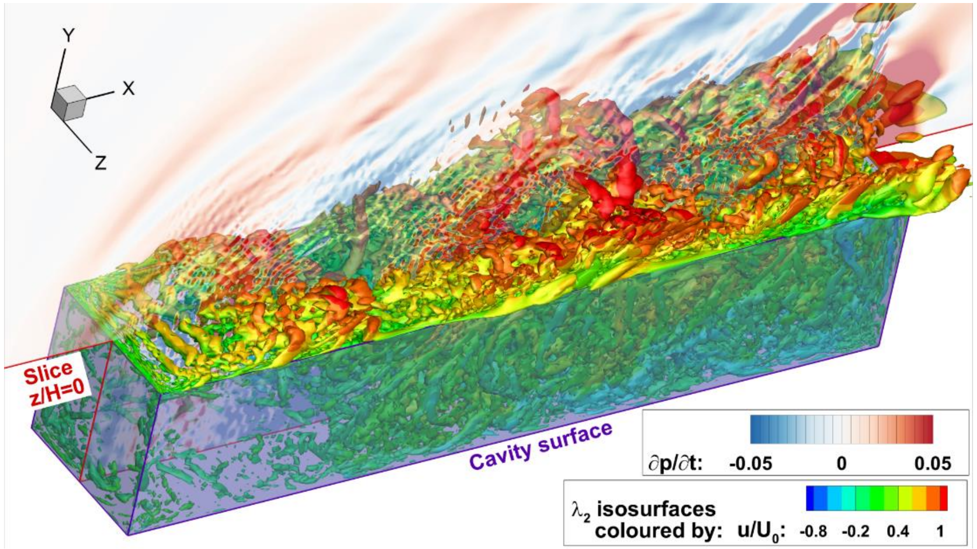
TOWARDS FUNDAMENTAL RESEARCH: M219 cavity, analysis

- In [Larcheveque et al., 2004] the detailed analysis of unsteady data accumulated in the process of computation is presented:
    - ○ shear layer mean properties with description of coherent structures dynamics
    - ○ spectral, cross-spectral and bispectral analysis of shear layer
    - ○ pressure spectra analysis on the cavity bottom
    - ○ joint time-frequency analysis to charactirize the “mode switching” phenomenon
- In [T. Knacke & F. Thiele, AIAA 2013-2162] the slat noise generation is analyzed

- 1 sec of unsteady data (ρ’, u’, v’, w’, p’) at slice z/H=0 and cavity surface has been accumulated during the IDDES computation
- The analysis is mostly based on normalized space-time cross-correlation function

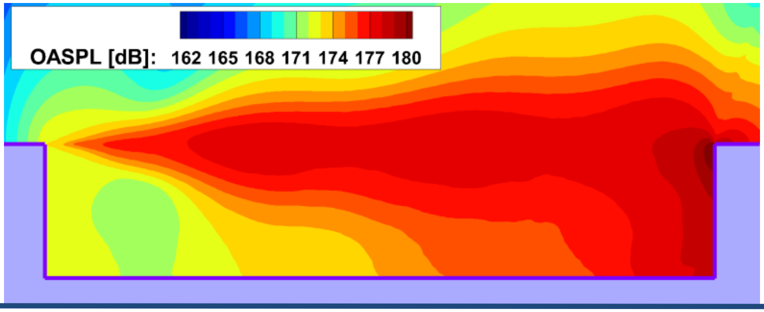
$$R_{pp}\left(\mathbf{x}_0,\mathbf{x},\tau\right)=\frac{\left\langle p'(\mathbf{x},t)\cdot p'(\mathbf{x}_0,t+\tau)\right\rangle}{p'_{\mathrm{rms}}(\mathbf{x})\cdot p'_{\mathrm{rms}}(\mathbf{x}_0)}$$

- ○ $\mathbf{x}_0$ – observer position
- ○ $\mathbf{x}$ - varying position
- ○ τ – time delay



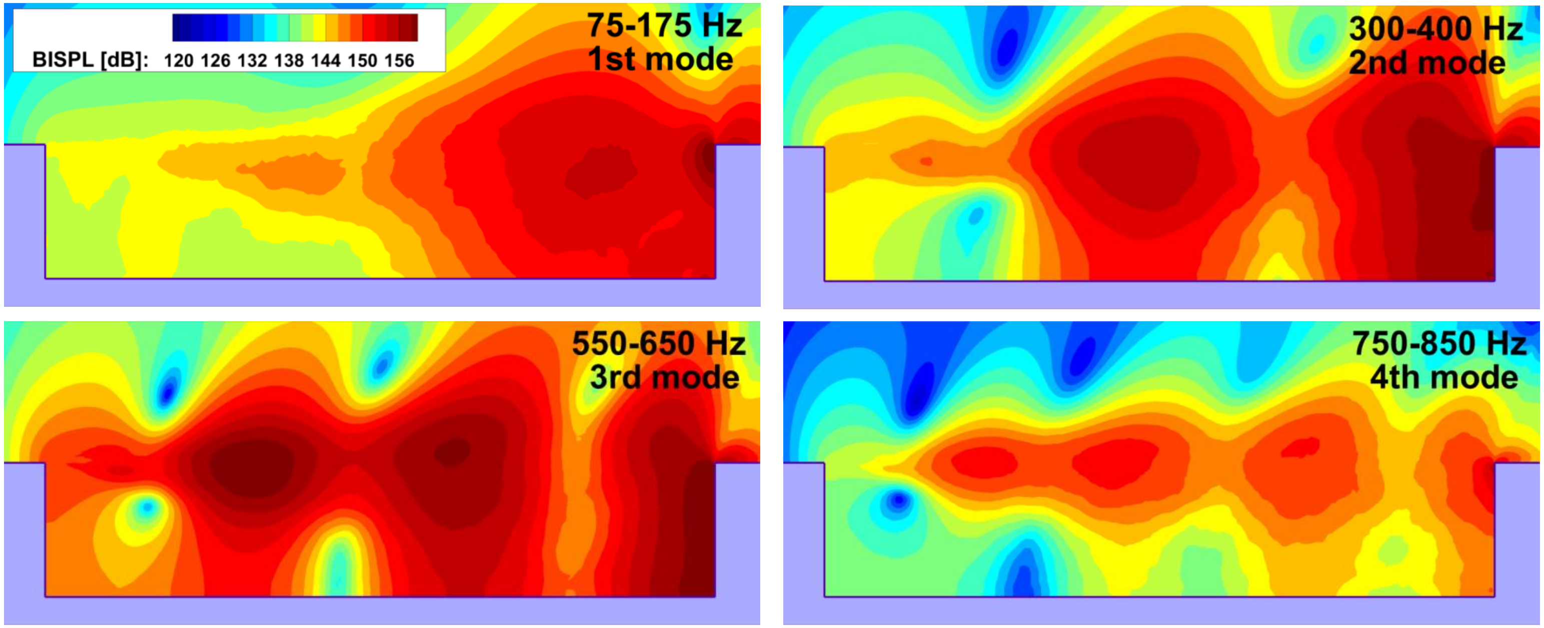
TOWARDS FUNDAMENTAL RESEARCH: M219 cavity, BISPL analysis

Overall sound pressure level in slice z/H=0



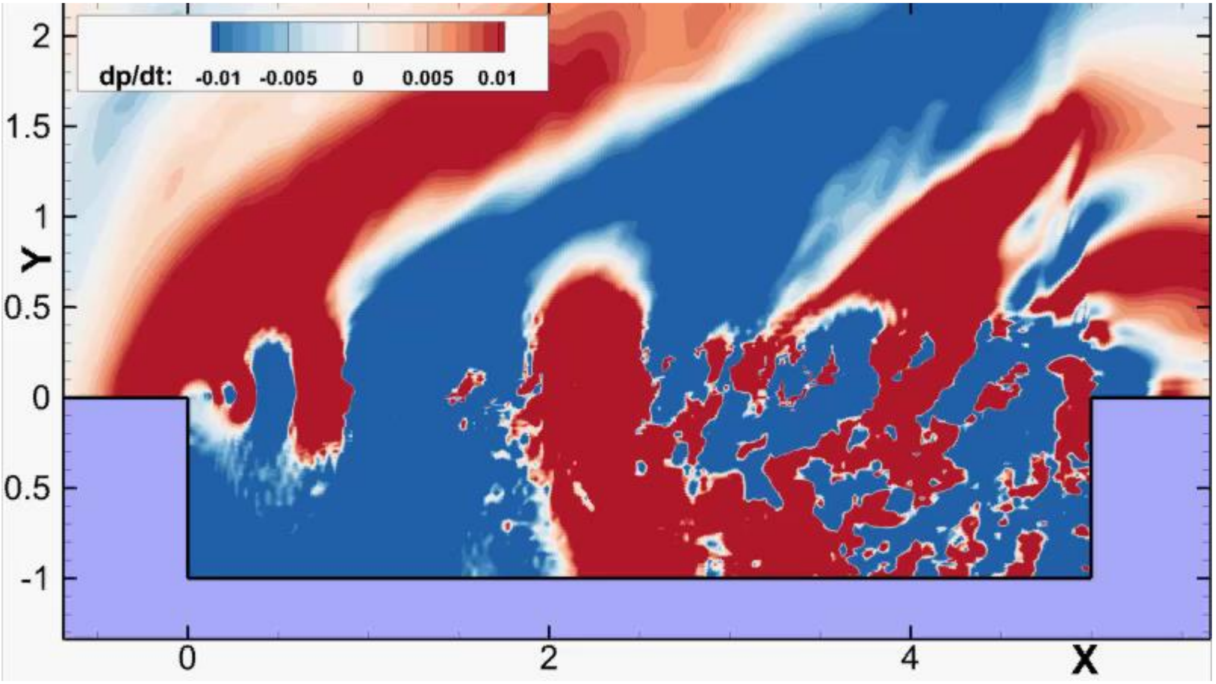
- Includes both turbulent (high frequency) perturbations and acoustic (low frequency) pulsations → identification of acoustics loads is not clear

Band-integrated sound pressure level in slice z/H=0



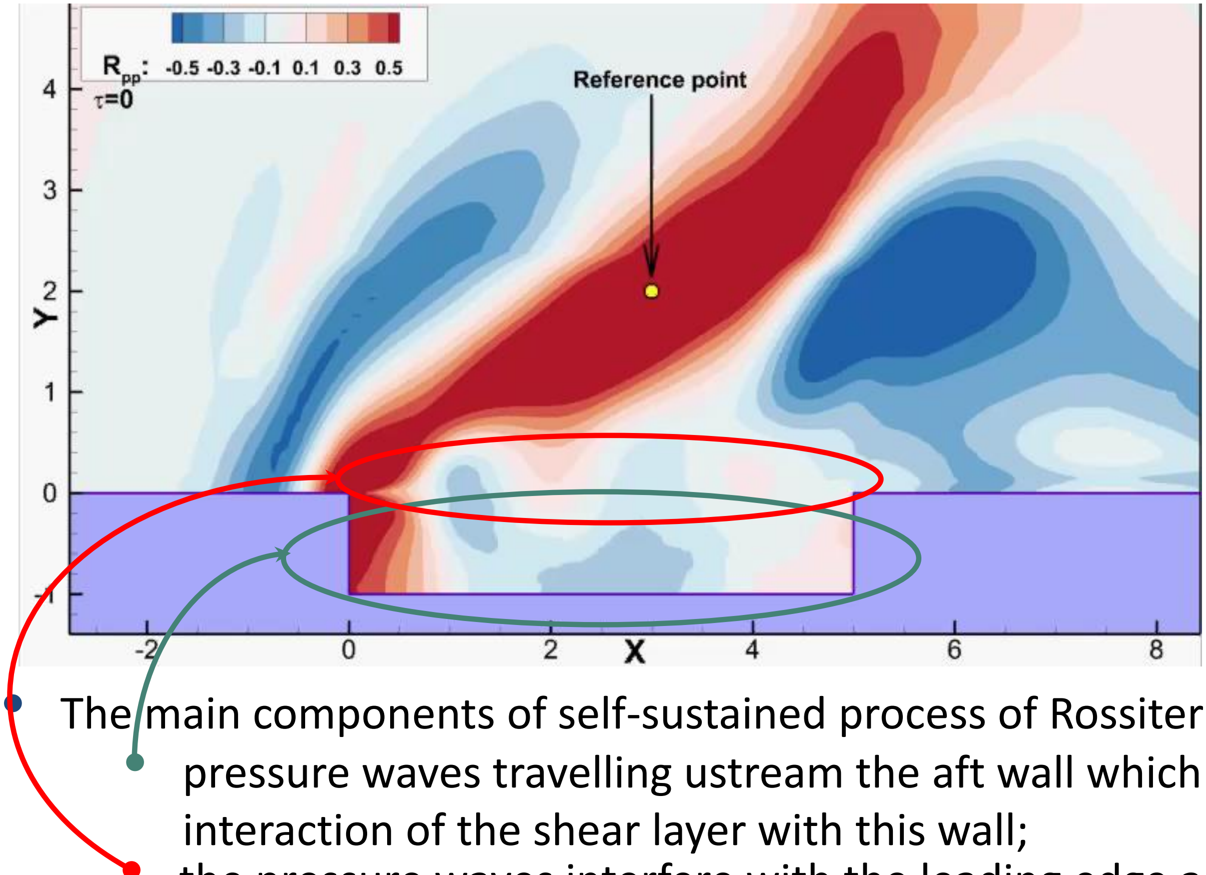
- BISPLs show bright spots in the shear layer. They correspond to the Rossiter modes and their quantity depends on the mode numbers
- It looks like standing waves influenced by the shear layer

TOWARDS FUNDAMENTAL RESEARCH: M219 cavity, pressure time derivative



- Evolution of instantaneous pressure time derivative field is commonly considered as good enough to examine acoustic waves propagation outside main turbulent interaction area. However:
    - in the cavity nearfield acoustic waves (propagating to the farfield) and turbulent disturbances (decaying in the nearfield) are mixed → it’s difficult to separate one from another
    - different scales and amplitudes of acoustic and turbulent disturbances also complicate the identification of noise generation mechanisms

TOWARDS FUNDAMENTAL RESEARCH: M219 cavity, correlation analysis



$$R_{pp}\left(\mathbf{x}_0,\mathbf{x},\tau\right)=\frac{\left\langle p'(\mathbf{x},t)\cdot p'(\mathbf{x}_0,t+\tau)\right\rangle}{p'_{\mathrm{rms}}(\mathbf{x})\cdot p'_{\mathrm{rms}}(\mathbf{x}_0)}$$

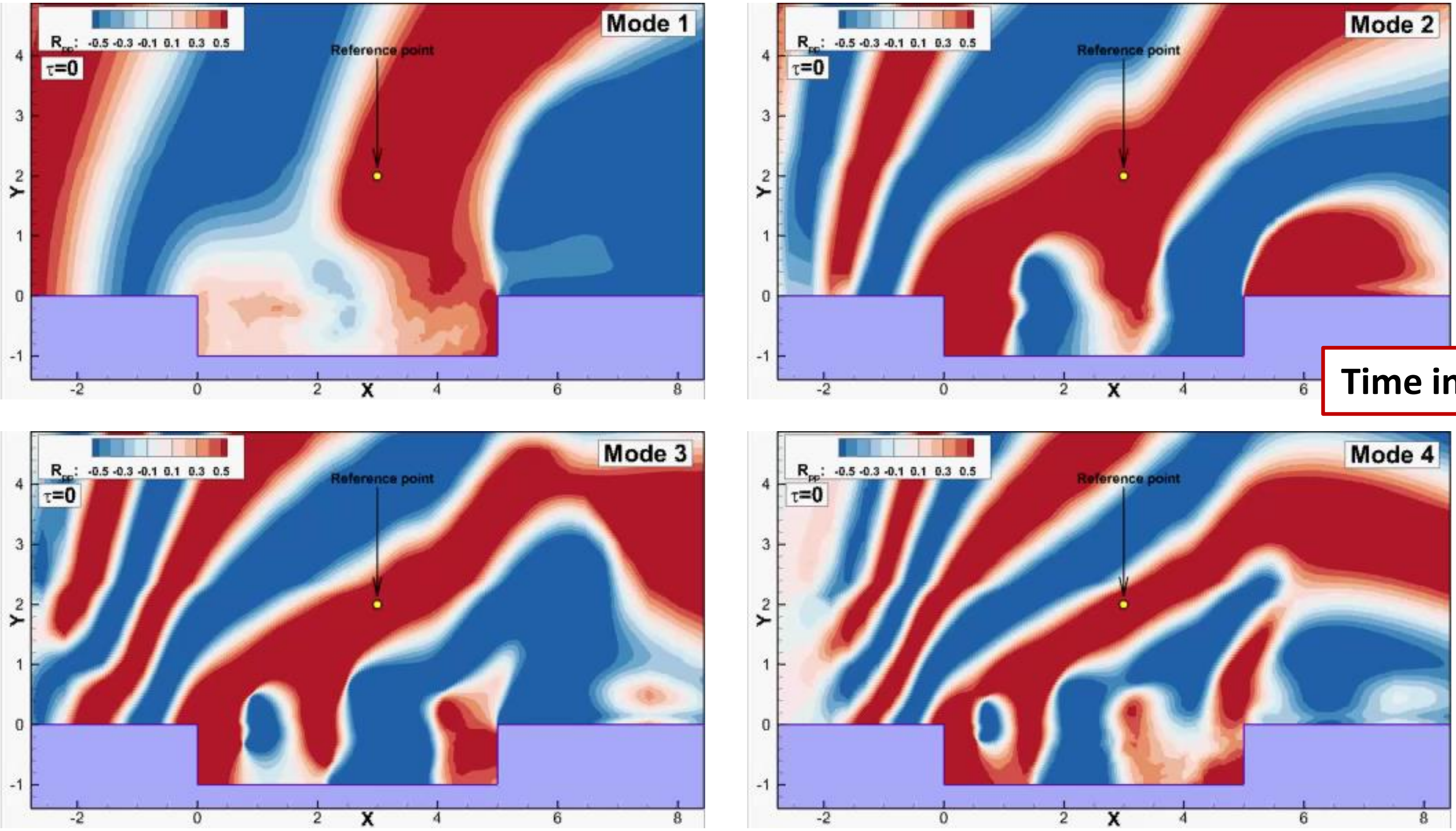
- High values of R_{pp} (red or blue) correspond to the regions strongly correlated with reference point ($\mathbf{x}_0$) at time delay τ

Time in reverse

- The main components of self-sustained process of Rossiter modes generation can be seen:
  - pressure waves travelling ustream the aft wall which are generated by the interaction of the shear layer with this wall;
  - the pressure waves interfere with the leading edge and provoke instability waves in the shear layer
- The movie shows that the outer region and the area inside the cavity are highly correlated, all the flow pattern is involved in the modes generation mechanism
- The decay of correlation in time (the colors become not so bright with time delay) can be explained by floating of Rossiter modes frequencies due to instability of the shear layer

TOWARDS FUNDAMENTAL RESEARCH: M219 cavity, correlation analysis

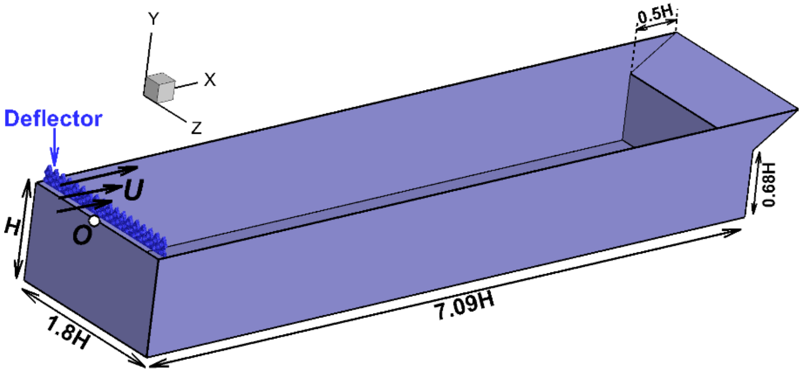
- Band filtered fields provide the information of Rossiter modes generation mechanism much better



Time in reverse

- The movies illustrate well the Rossiter's theory saying that the modulation of the acoustic waves (narrow band noise is amplified) is related with the phase correlation of pressure waves coming upstream from the aft wall and instability waves in shear layers (provoked, in their turn, by upstream pressure waves)

TOWARDS APPLIED RESEARCH: Cavity with/without deflector, setup



Flow parameters

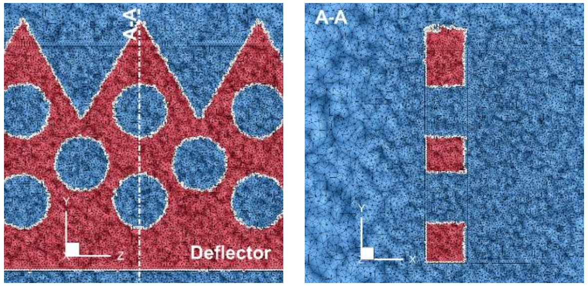
- $Re_H = 7 \cdot 10^6$ (H – cavity depth)
- M = 0.8

Approach:

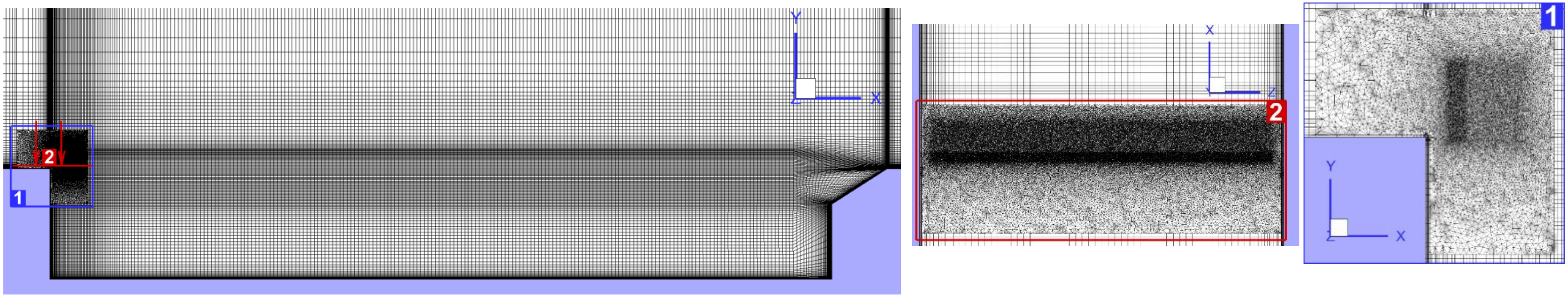
- IDDES ($\Delta = \Delta_{SLA}$) [Shur et al, 2015]
- Hybrid CD-Upw EBR vertex-centered scheme
- Deflector: Immersed Boundary Conditions (IBC) method
- Plate and cavity surfaces: wall functions

Meshes

- Cavity without deflector: hexa mesh, 5.07M nodes
- Cavity with deflector: hexa, tetra, pyramids 14.09M nodes
- Cell size:
    - on deflector surface: $8.5 \cdot 10^{-3}$h (h=0.215H)
    - downstream deflector: ≤ h/30
    - inside cavity: ≤H/30

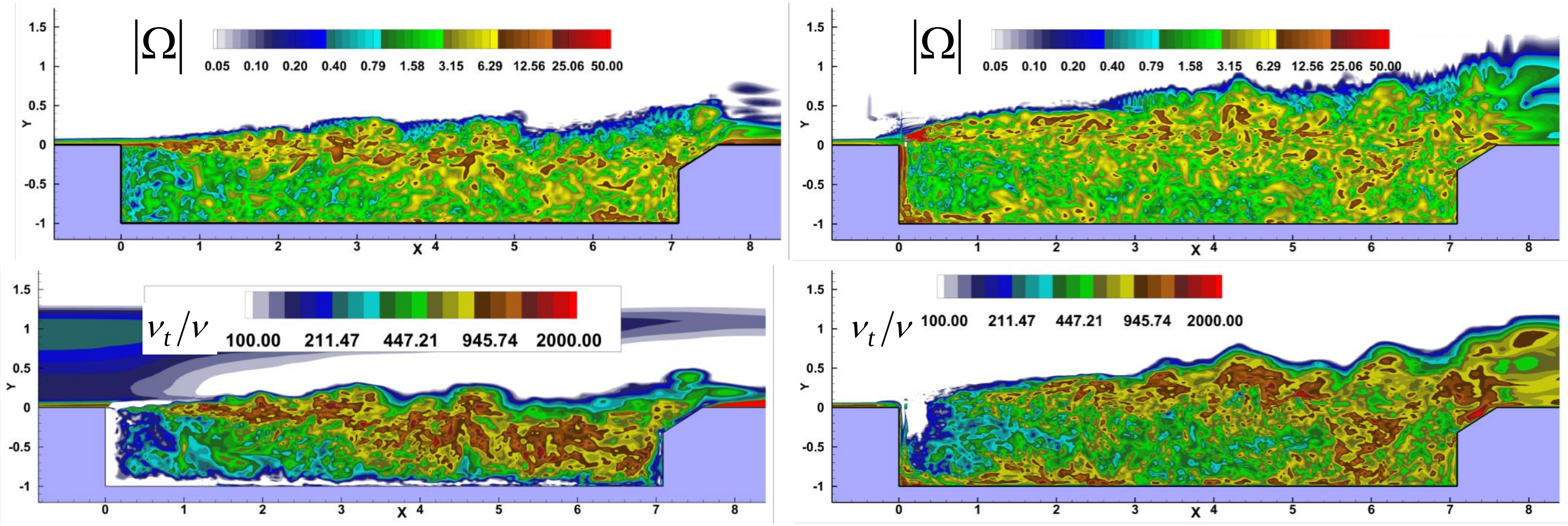


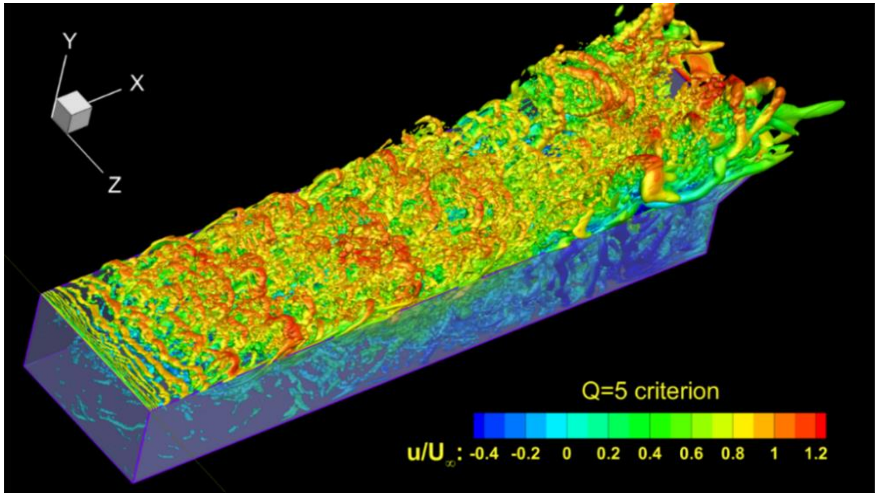
Deflector modelled by IBC (red)



TOWARDS APPLIED RESEARCH: Cavity with deflector, instantaneous fields

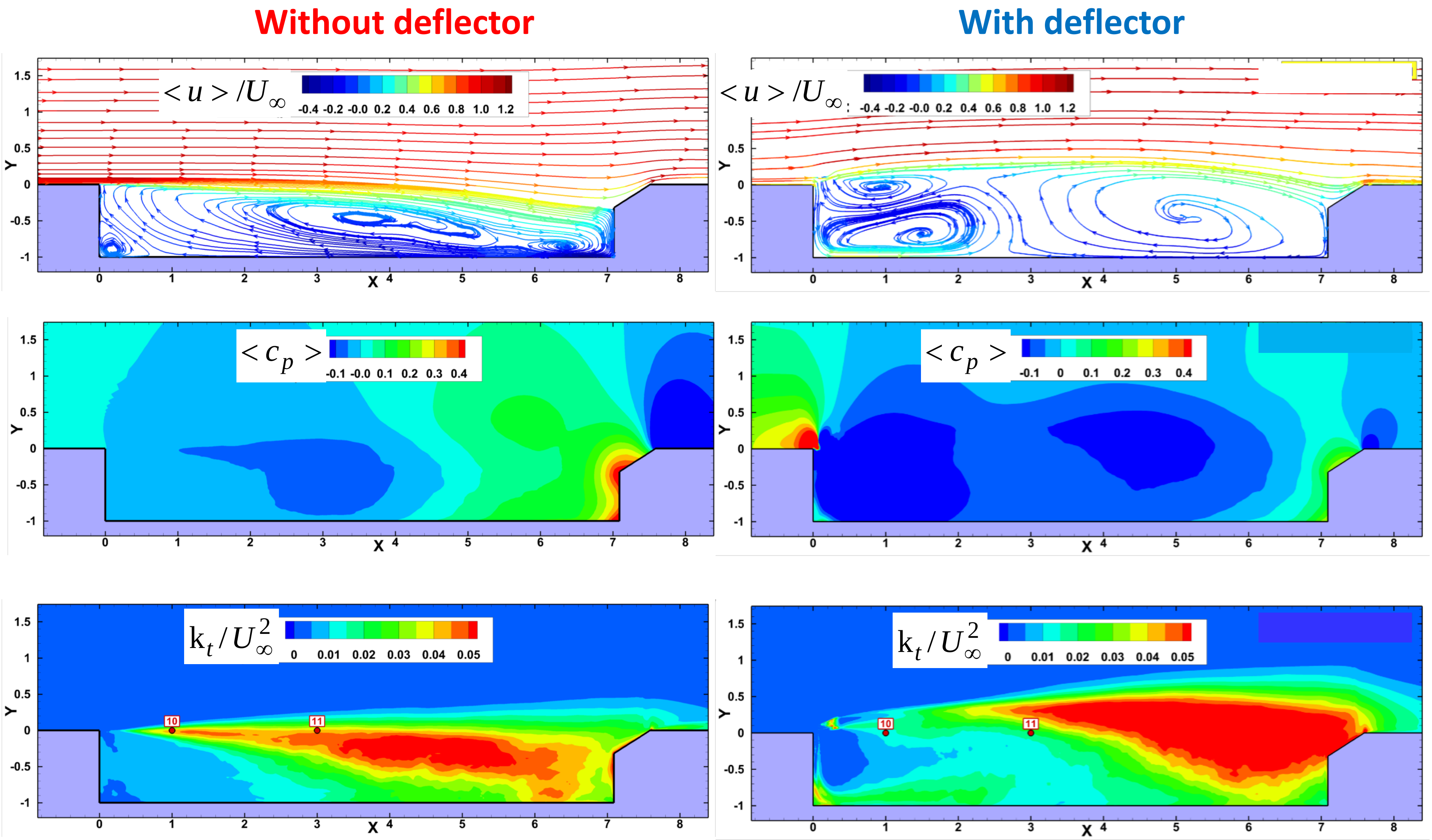
Without deflector **With deflector**





- The RANS-to-LES transition is rather fast in both computations
- The deflector acts as a turbulizer and produces a noticeably thicker developed shear layer

TOWARDS APPLIED RESEARCH: Cavity with deflector, averaged flow fields



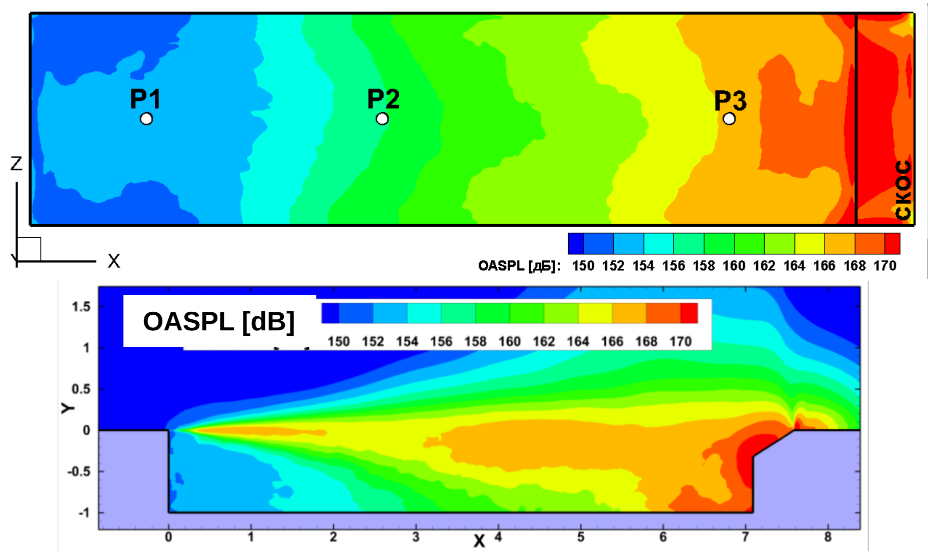
Without deflector

With deflector

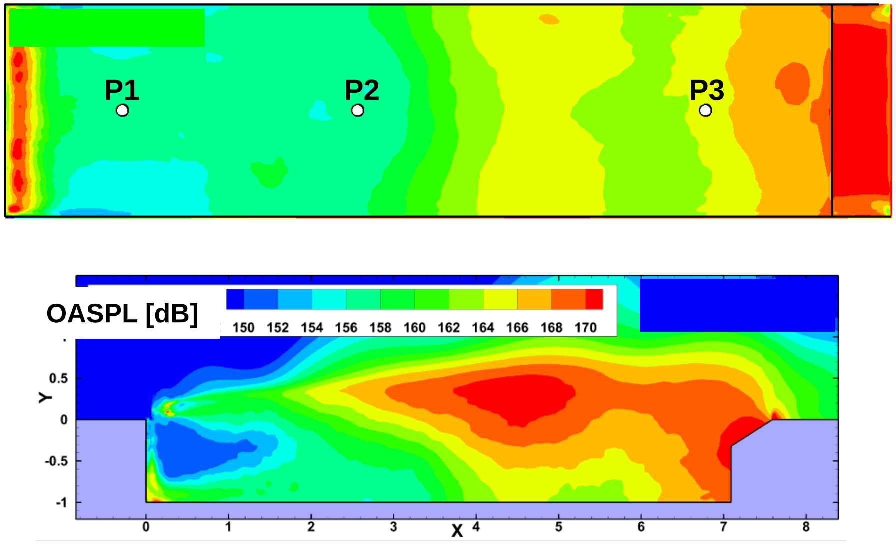
- The deflector changes the flow structure: additional recirculation regions appear
- The deflector lowers pressure coefficient on the cavity surface, especially at the aft wall

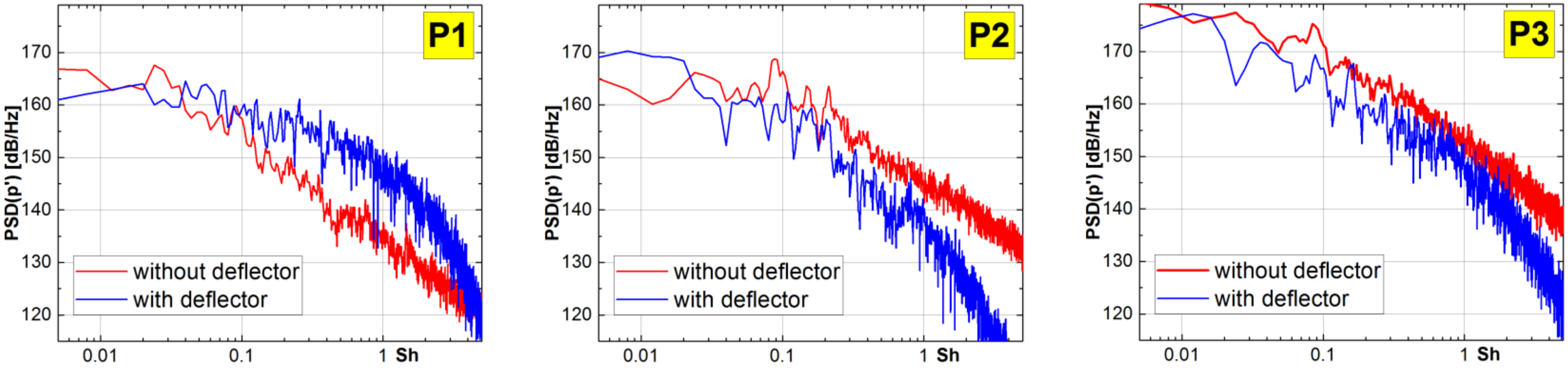
TOWARDS APPLIED RESEARCH: Cavity with deflector, acoustic loads

Without deflector



With deflector





- The deflector changes the distribution of acoustic loads, however not significantly
  - reducing near cavity floor and aft wall edge
  - increasing of SPL near forward vertical wall (flow through the gap between deflector and cavity leading edge)

CONCLUDING REMARKS

- We have developed and validated a numerical approach for the prediction of turbulent flow over a cavity using unstructured algorithms
- From fundamental hand side, it opens a possibility for a deeper investigation of cavity flow physics basing on big numerical data analysis. It seems that we are far from the end of this resource and it would be interesting to continue
- From applied hand side, it allow us to carry out predictions for engineering purposes in a certain (even if not so wide) range of problem parameters as long as the next validation step is not needed
- In our case both directions are not completed. So far the presentation can be considered more as a demonstration of ways of computational experiment

Thank you !