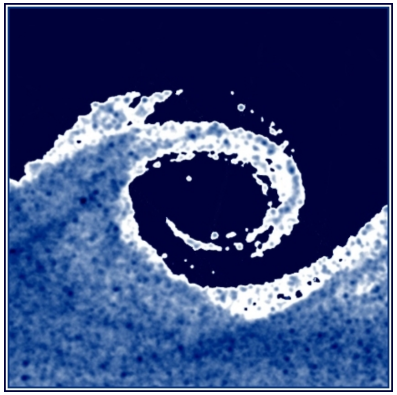


Quantifiying Coherent Structures in Large-Eddy Simulation

Máté Márton LOHÁSZ

László NAGY, Péter TÓTH, István KONDOR

Dept. of Fluid Mechanics @ Budapest University of Technology and Economics

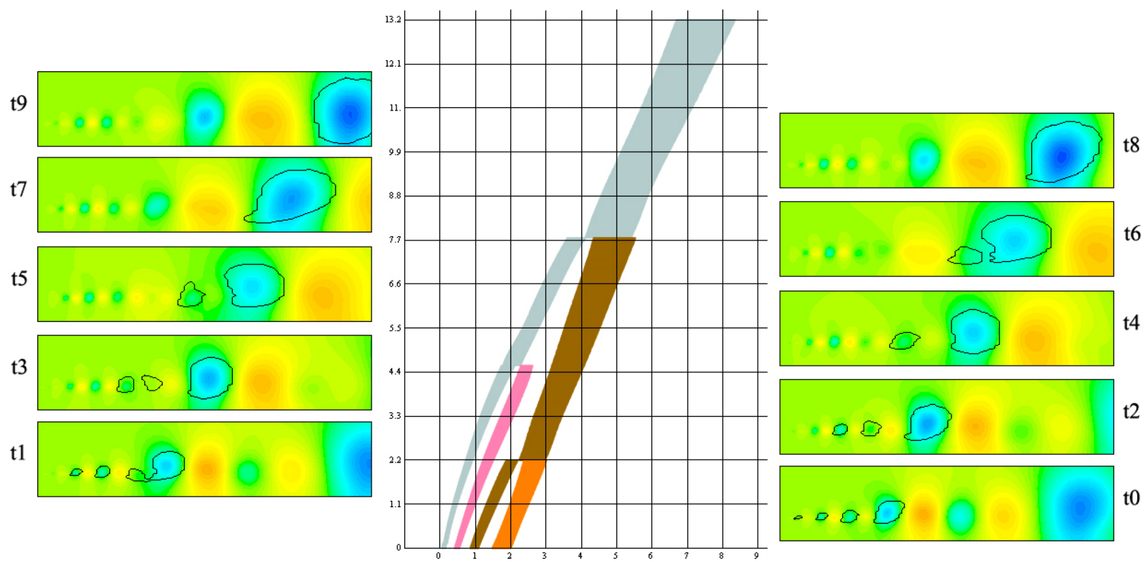


Table of contents

Coherent structure concept

Coherent structure (CS) concept:

Turbulent motion can be decomposed into three parts

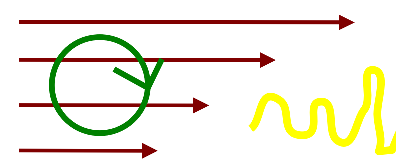
Reynolds decomposition

$$\varphi = \bar{\varphi} + \tilde{\varphi}$$

Triple decomposition

$$\varphi = \bar{\varphi} + \tilde{\varphi}_c + \tilde{\varphi}_b$$

$\bar{\varphi}$	Average
$\tilde{\varphi} = \tilde{\varphi}_c + \tilde{\varphi}_b$	Fluctuation
$\tilde{\varphi}_c$	Coherent motion
$\tilde{\varphi}_b$	Turbulent background



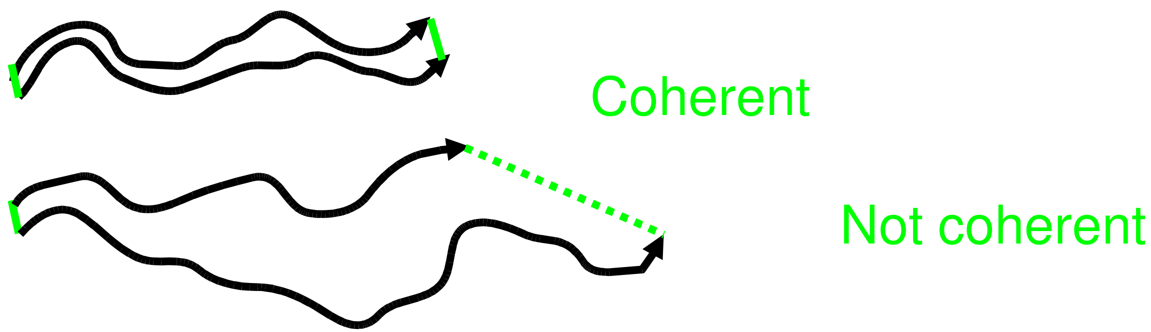
An important part of the fluctuation can be characterised by the motion of regular fluid structure so called coherent structures

Vortices are coherent coherent structures

- The vortices are the coherent (does not change much in space and time) structure in fluid motion

Chakraborty2005, Haller2005 gives the mathematical proof

Illustration:



- How to find vortices in 3D flowfields?

To select quantities which are related to rotating motion

Q vortex detection criteria

Q criteria: *(Hunt1988)*

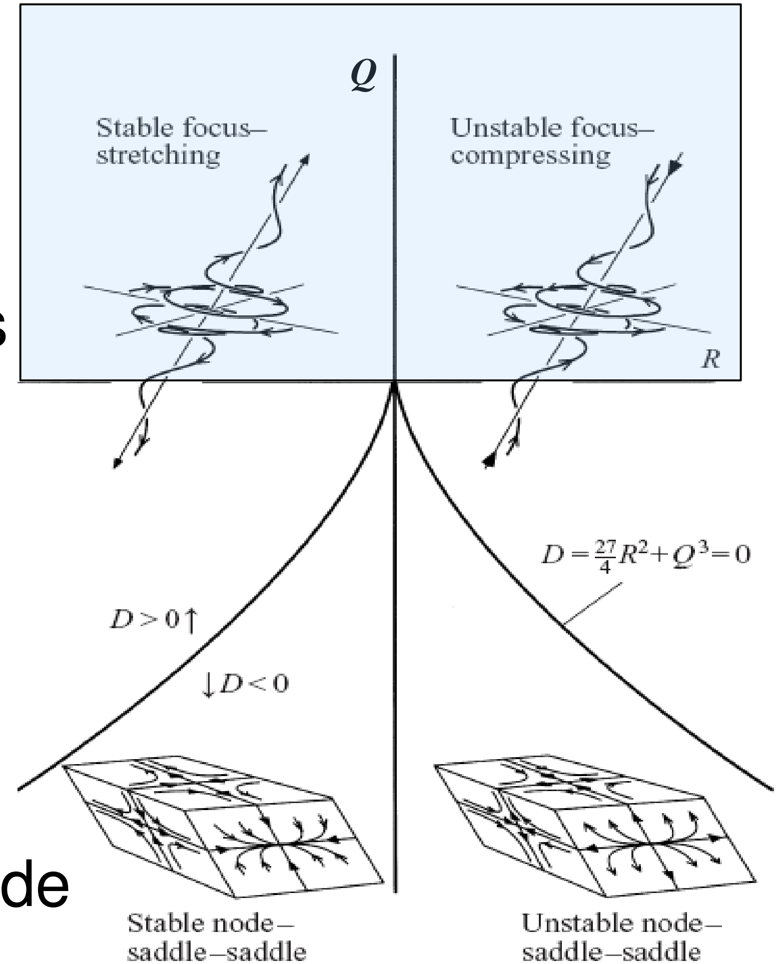
- Regions of $Q>Q_{th}>0$ with local pressure minima is defined as vortex
- Only a fraction of the rotating fluids is defined as a vortex

$$Q=-\frac{1}{2}A_{ij}A_{ji}=\frac{1}{2}\left(\Omega_{ij}\Omega_{ji}-S_{ij}S_{ji}\right)$$

Vorticity dominance

Q>0 means vorticity dominance

- *Charkaborty2005* showed that beside D>0, Q>0 is needed for coherence



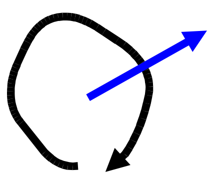
Q vortex detection criteria

Q is the source term in the Poisson equation for pressure

Pressure equation:

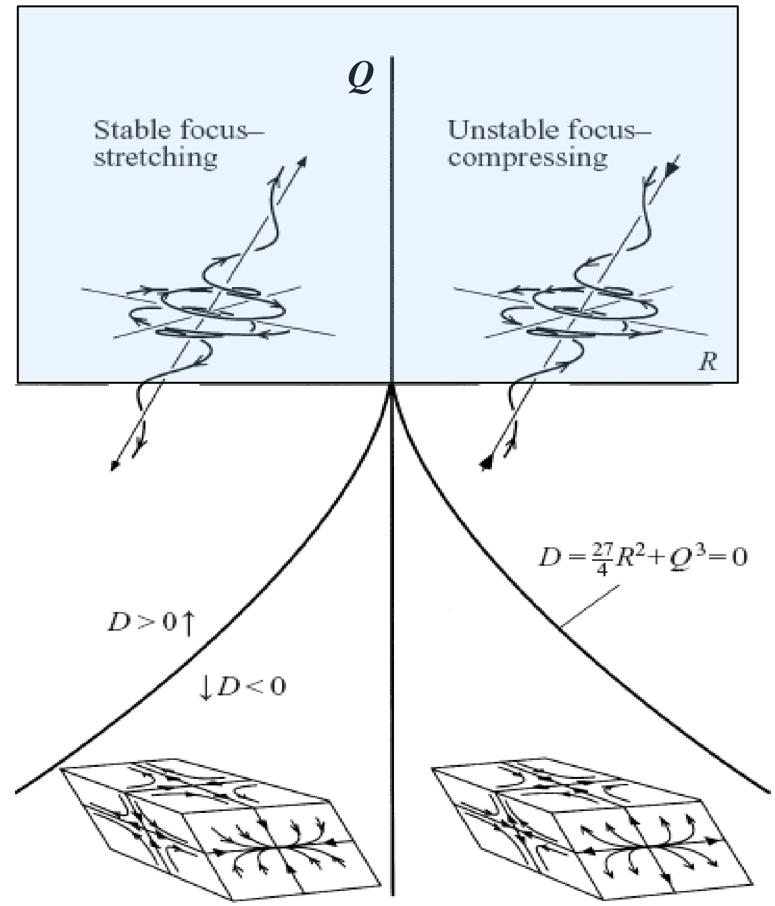
$$\Delta p = 2\rho Q$$

Source term



$$\frac{\partial p}{\partial n} < 0$$

Pressure is lower in the centre of the vortex



What to do with the coherent structures?

Traditional technology: Image processing

1) Create movies of the temporal evolution of the vortices with different thresholds, and different viewpoints
2) Find “well known” features
3) Quantify what you can
4) Compare to possibly existing theory

“only” qualitative results

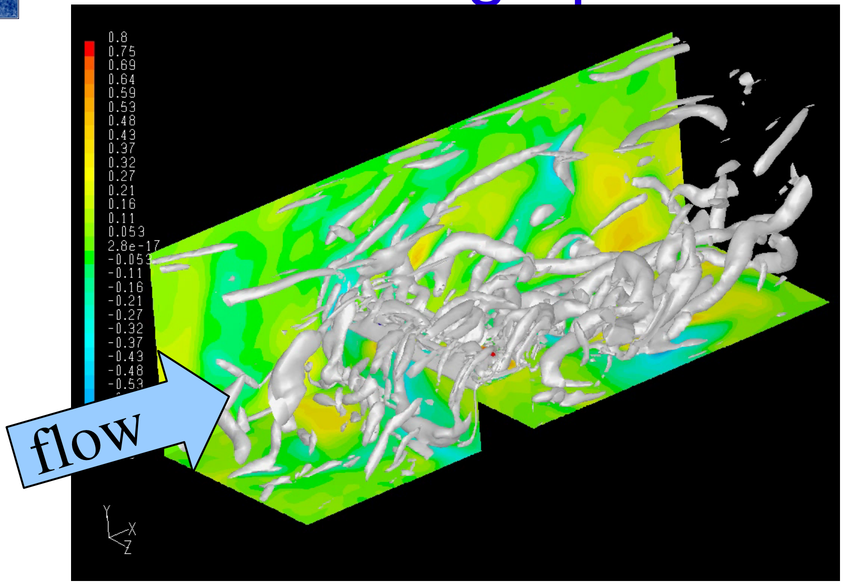
Drawback:

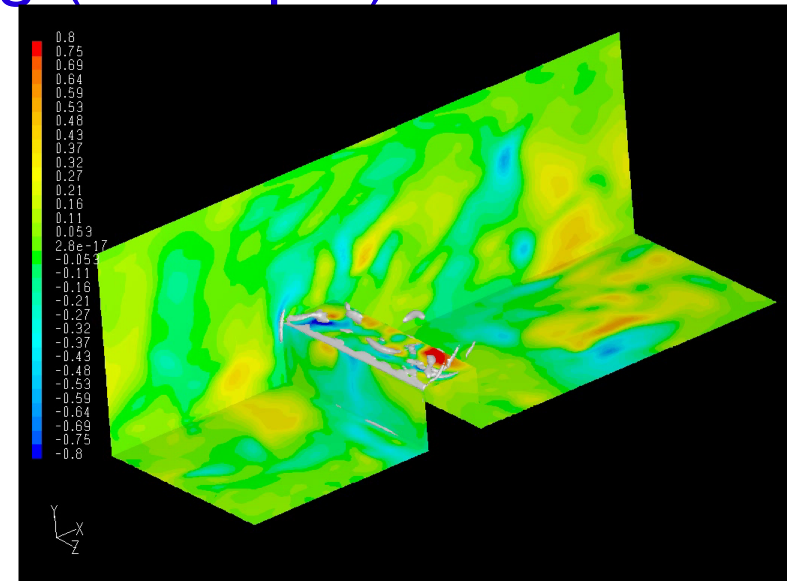
1) Result is user dependent
2) Evolution described in a poetic way e.g. :

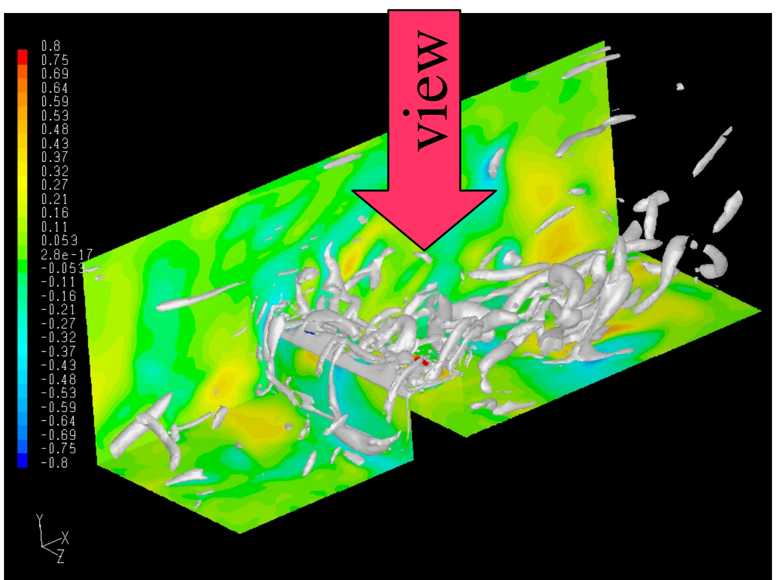
”One sees vortices passing by as a flight of big migratory birds” (Lesieur2003)

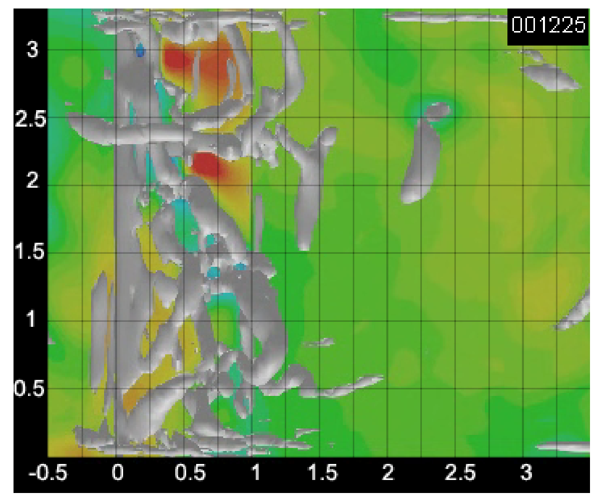
Methods are needed to quantify coherent structure evolution

Image processing (example)





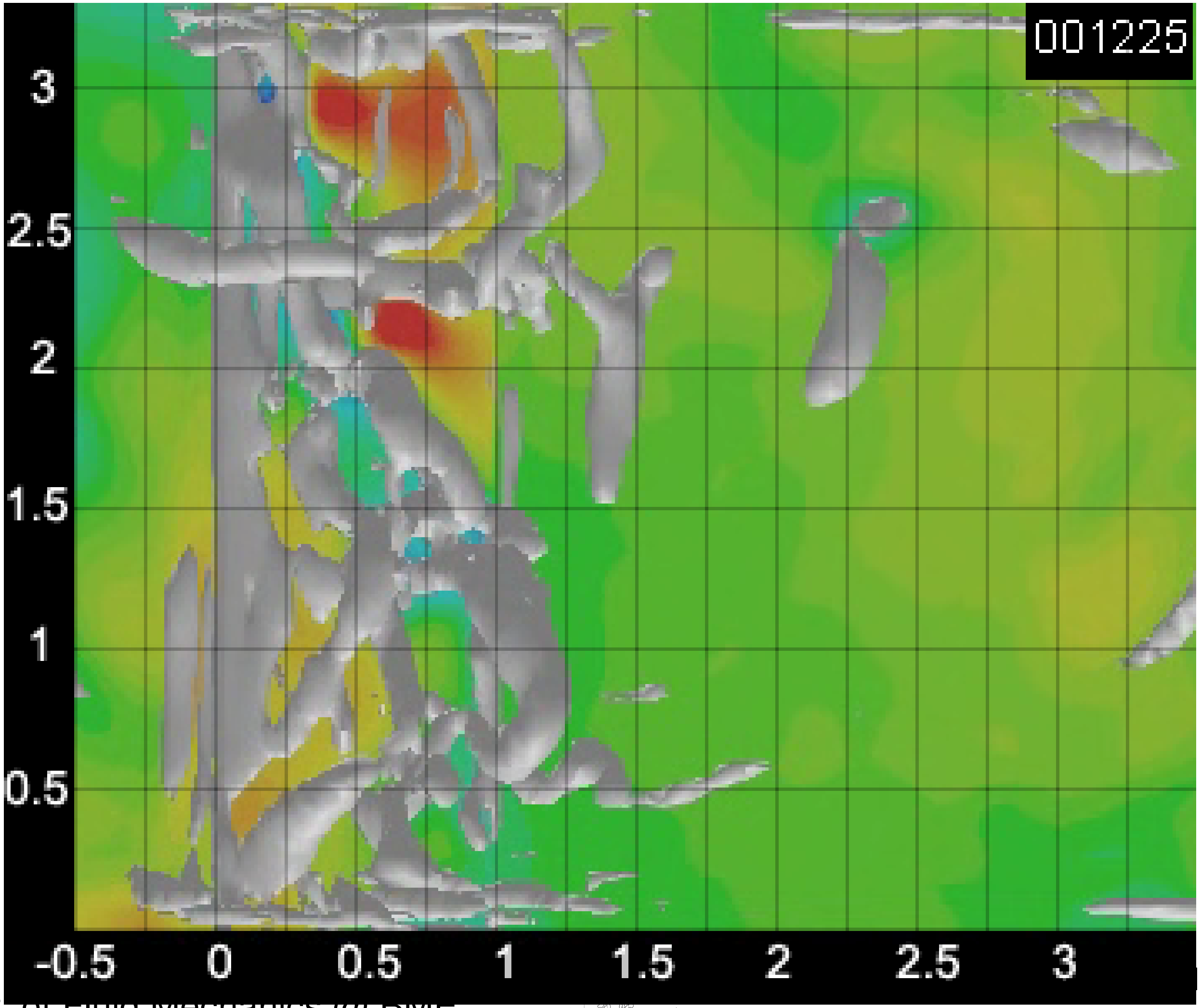




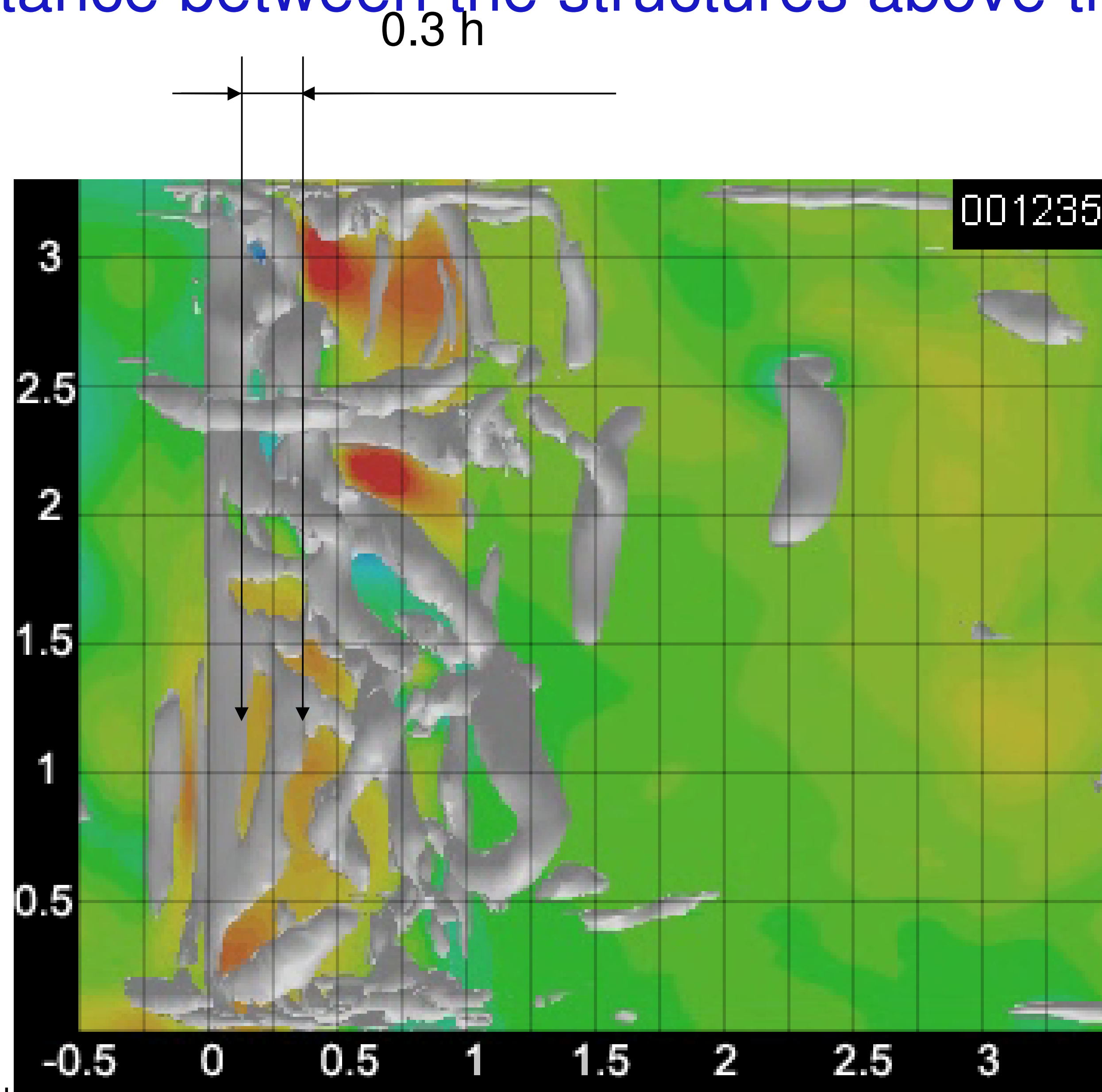
(Lohász2006)

Distance between the structures above the rib

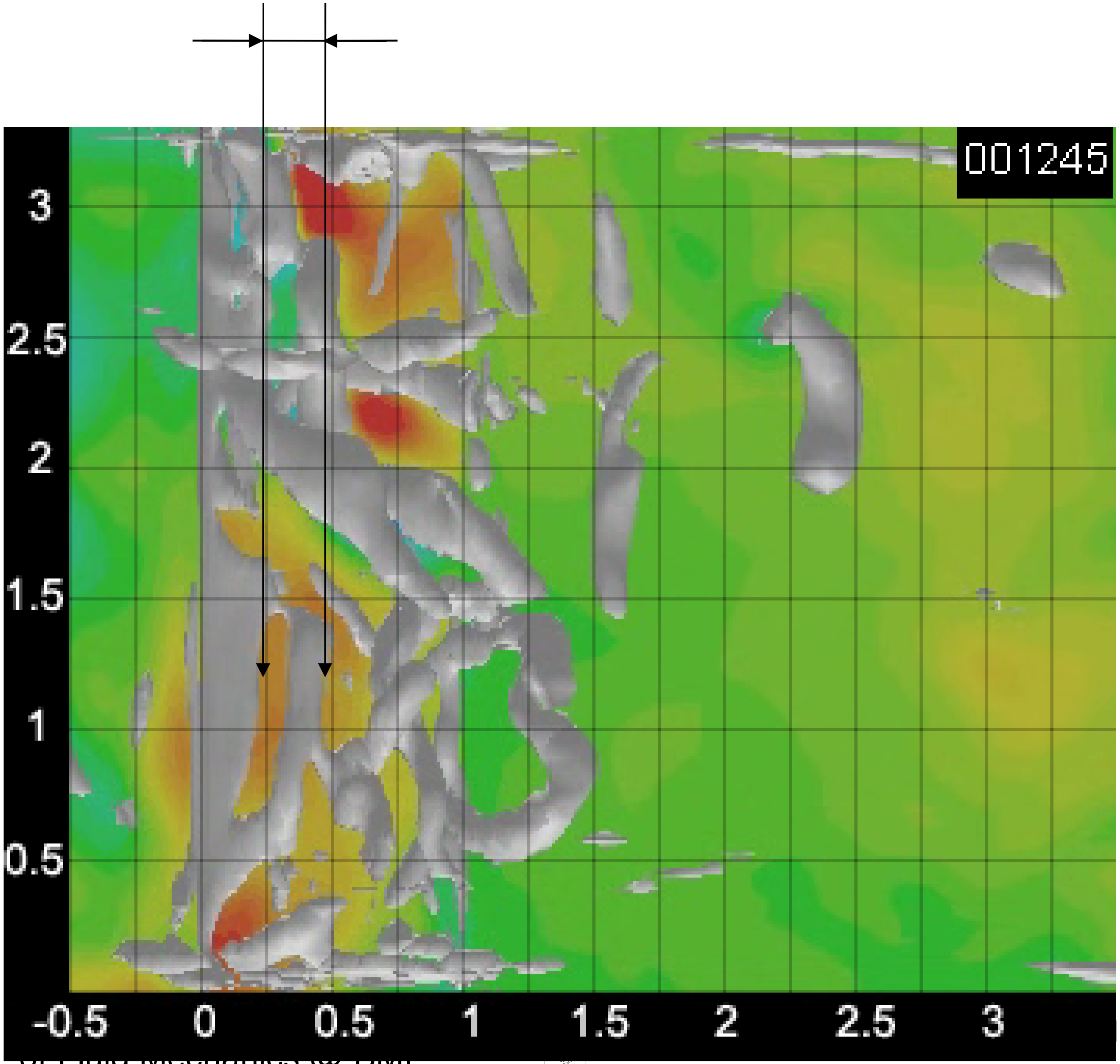
Changes between 0.2-0.3h



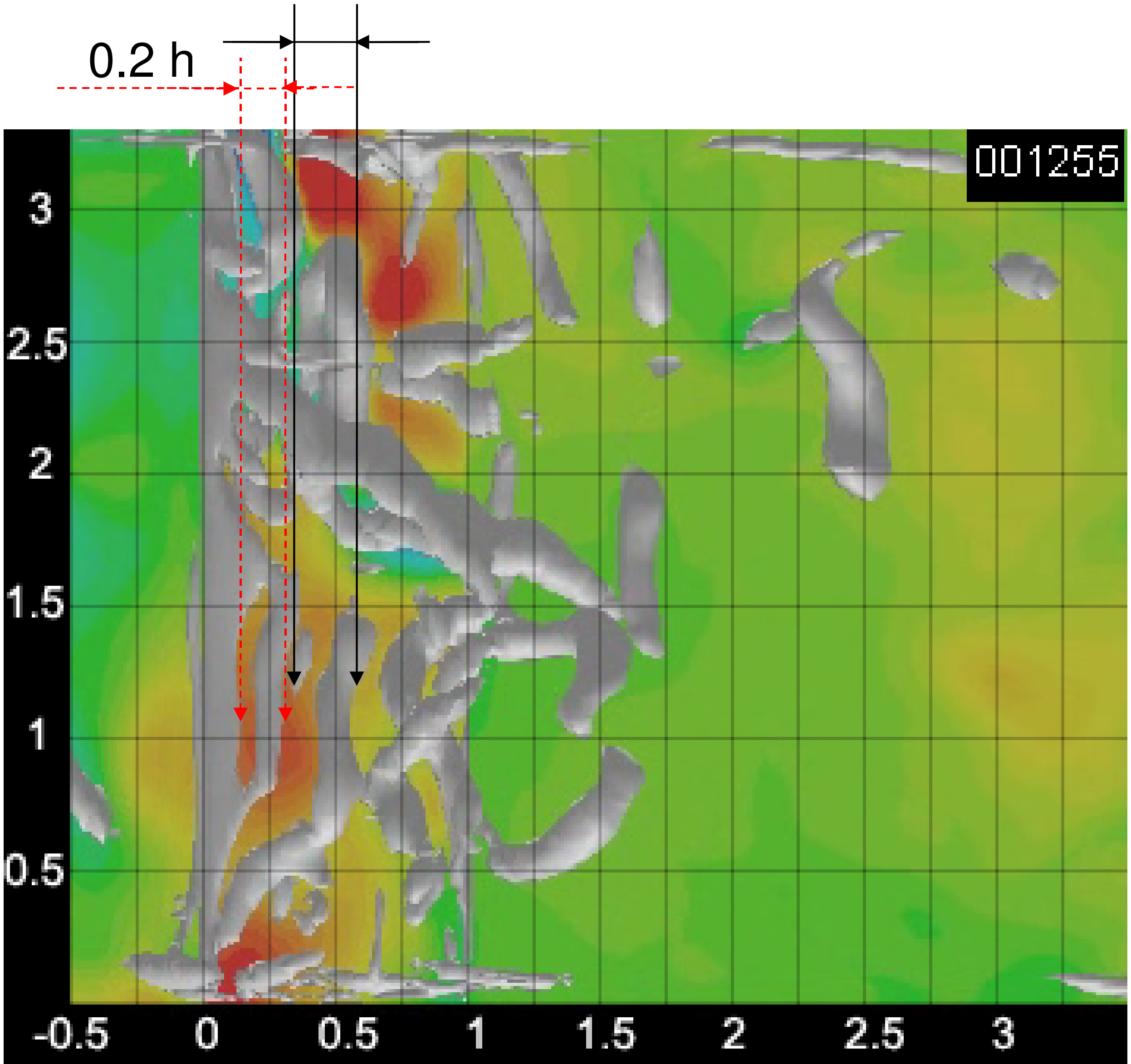
Distance between the structures above the rib



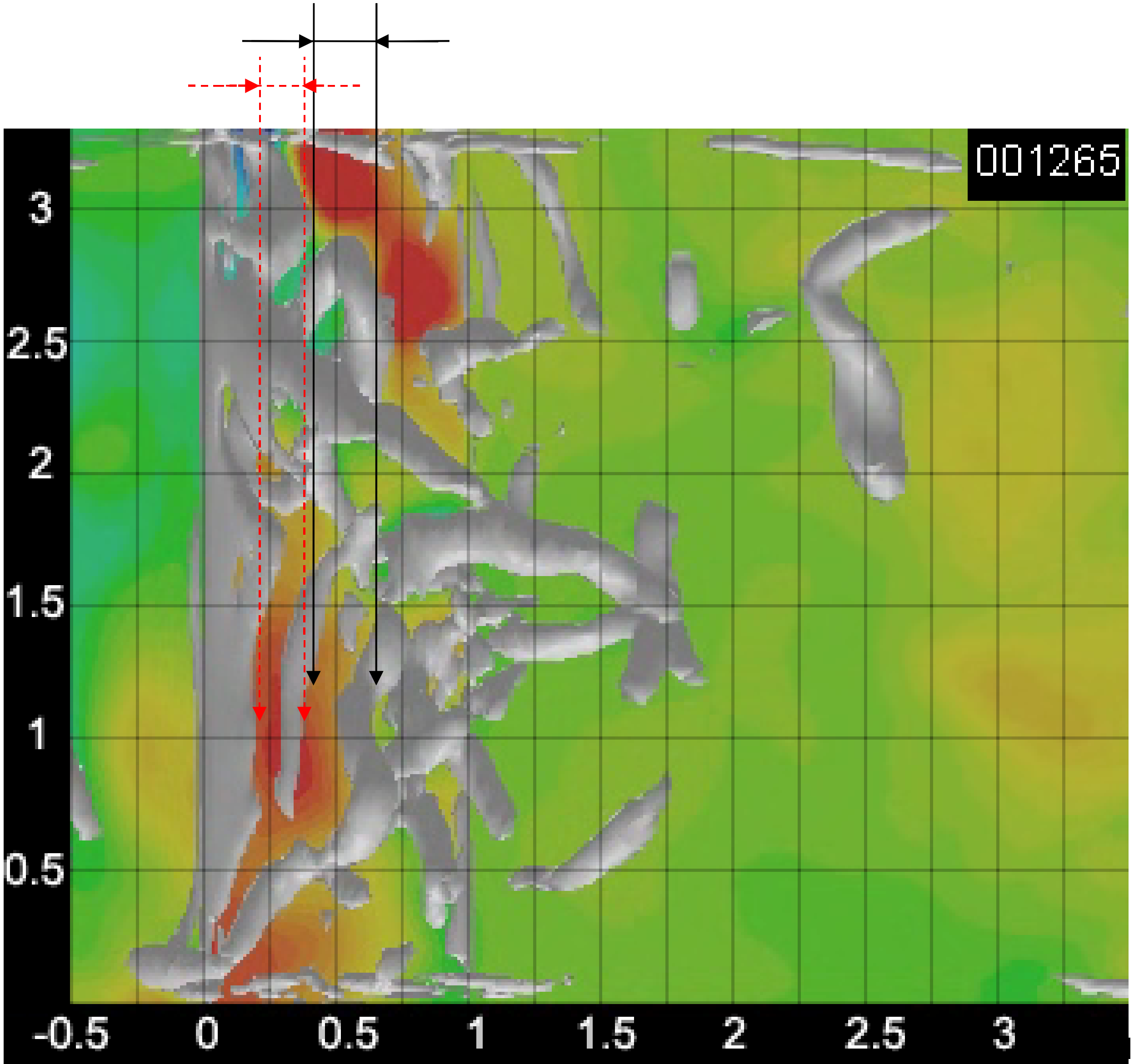
Distance between the structures above the rib



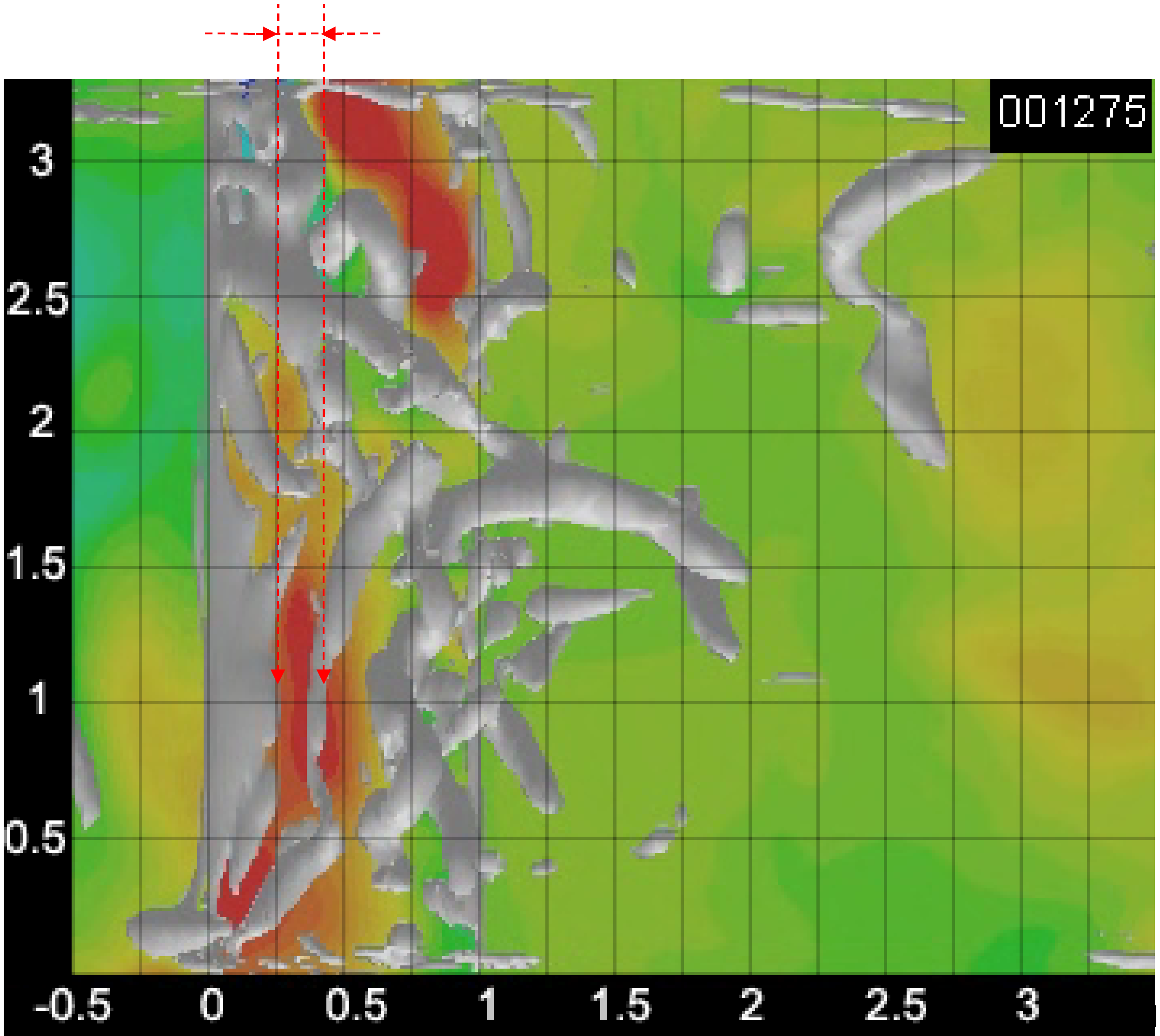
Distance between the structures above the rib



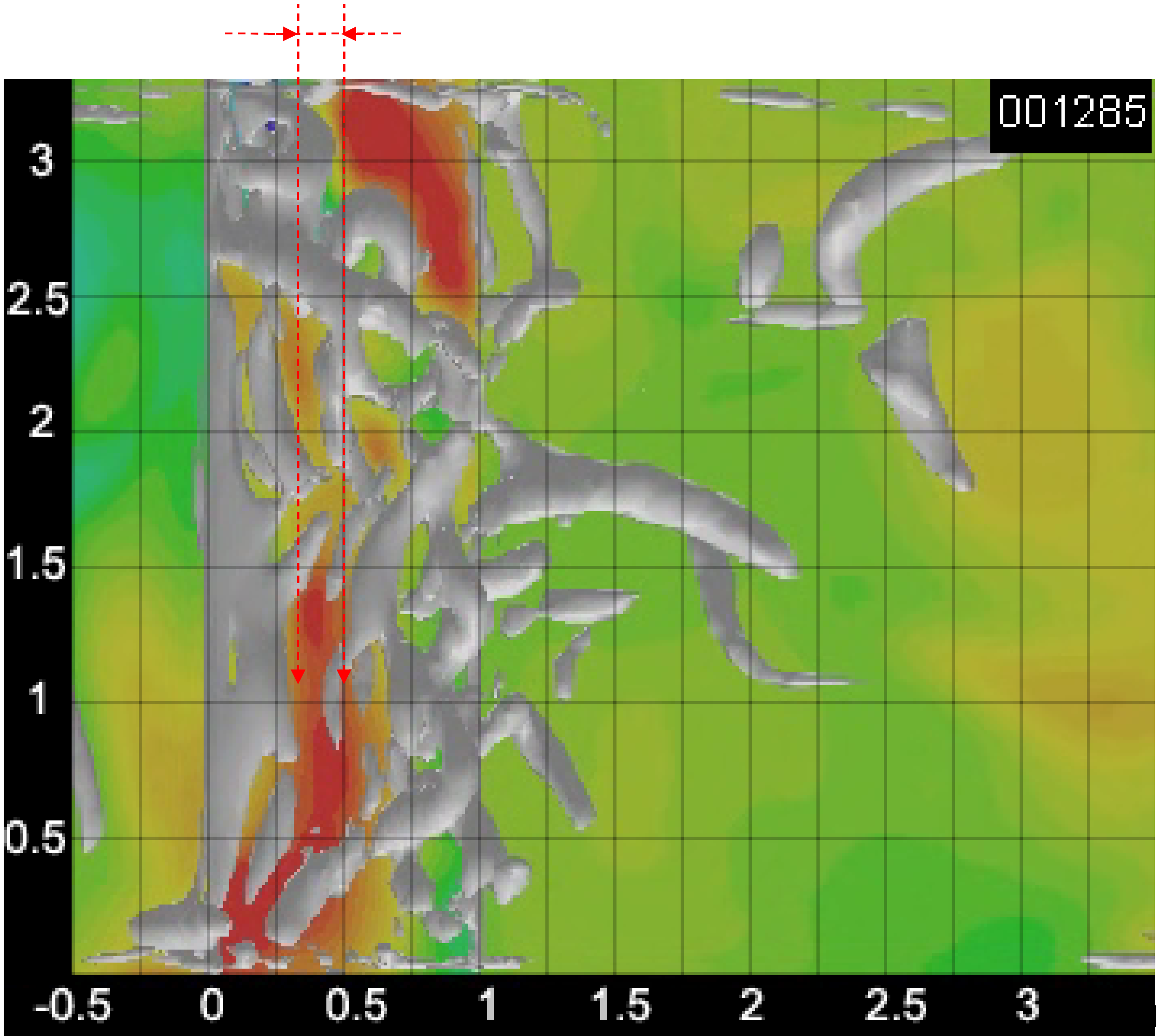
Distance between the structures above the rib



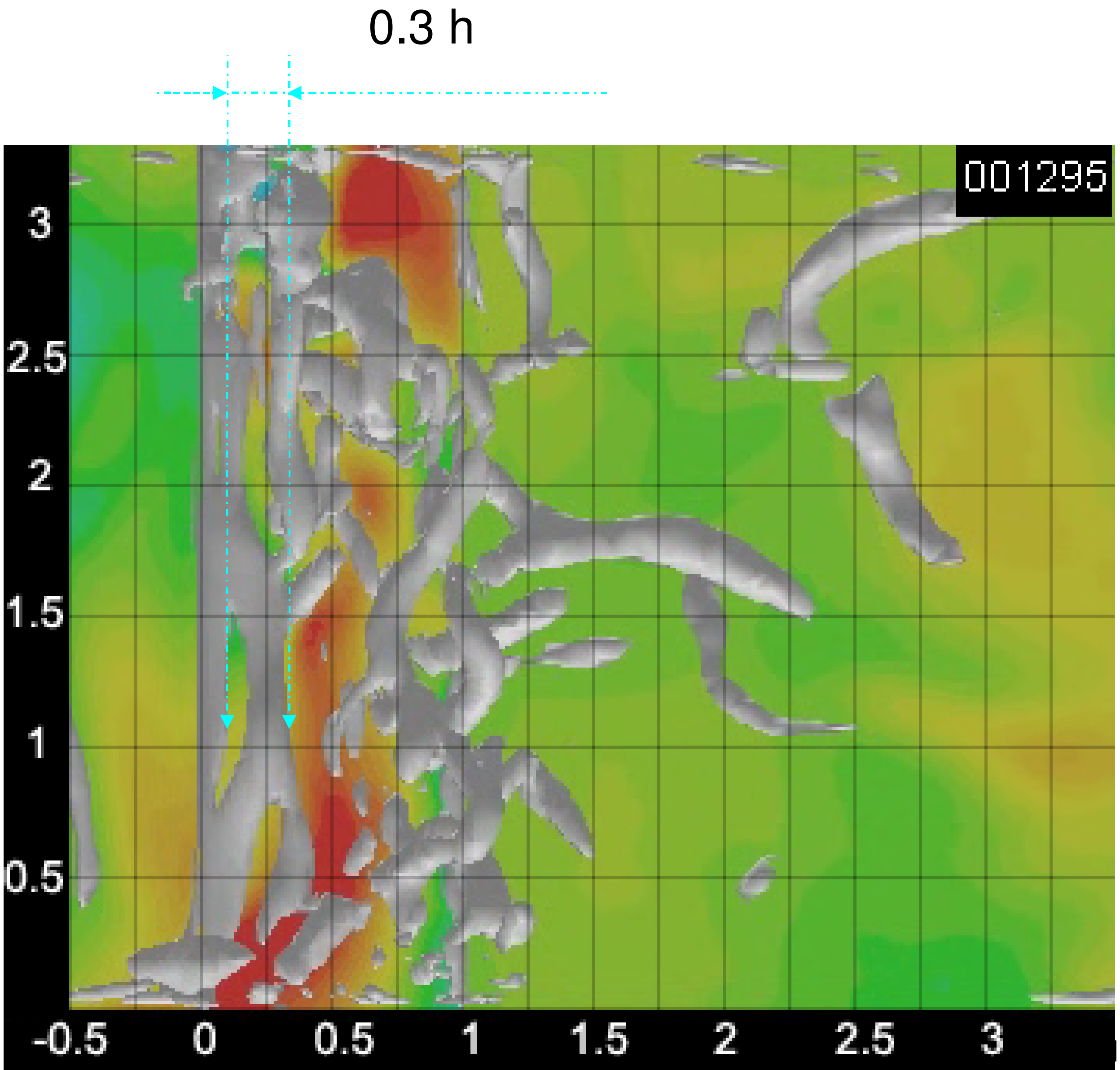
Distance between the structures above the rib



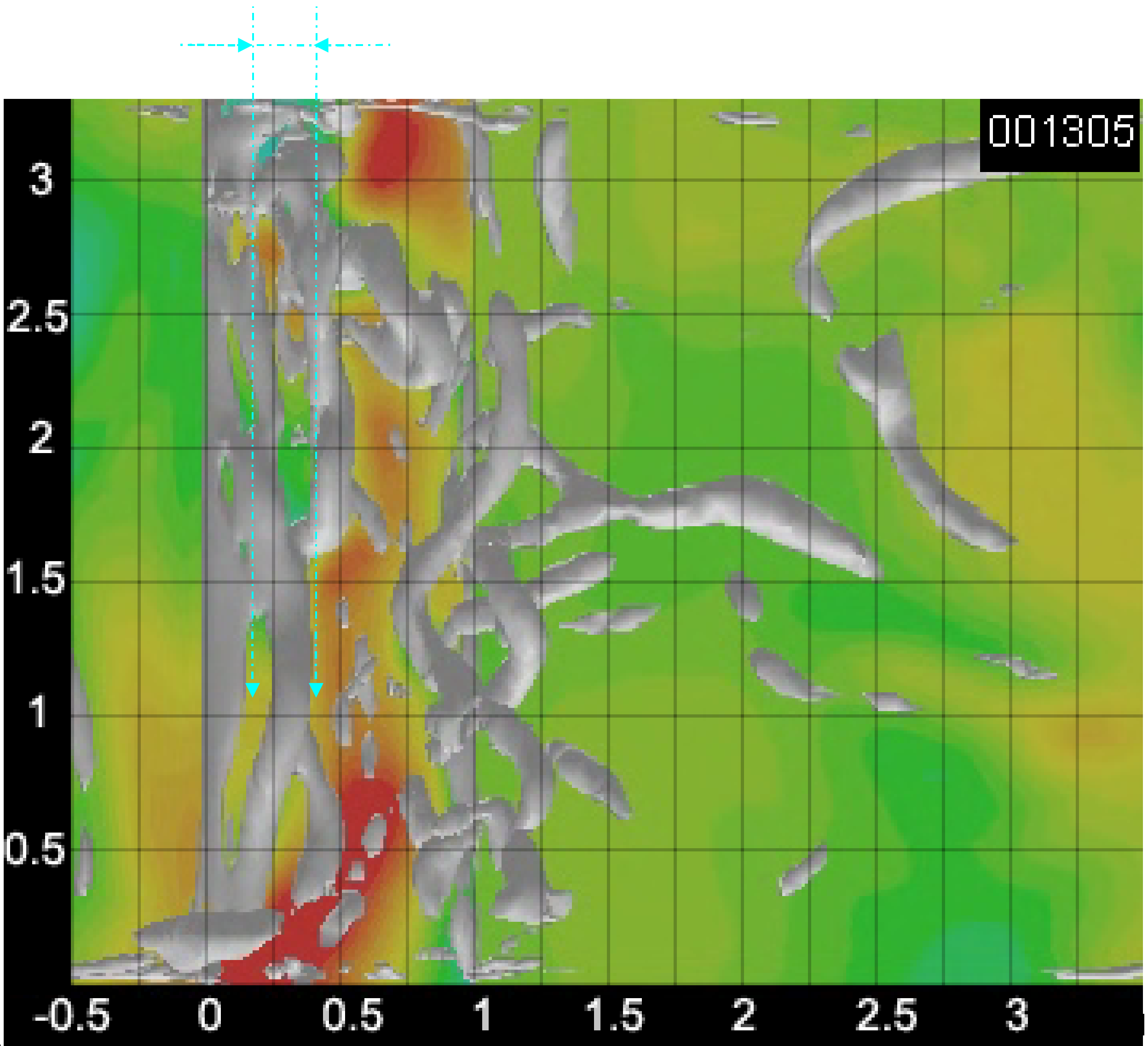
Distance between the structures above the rib



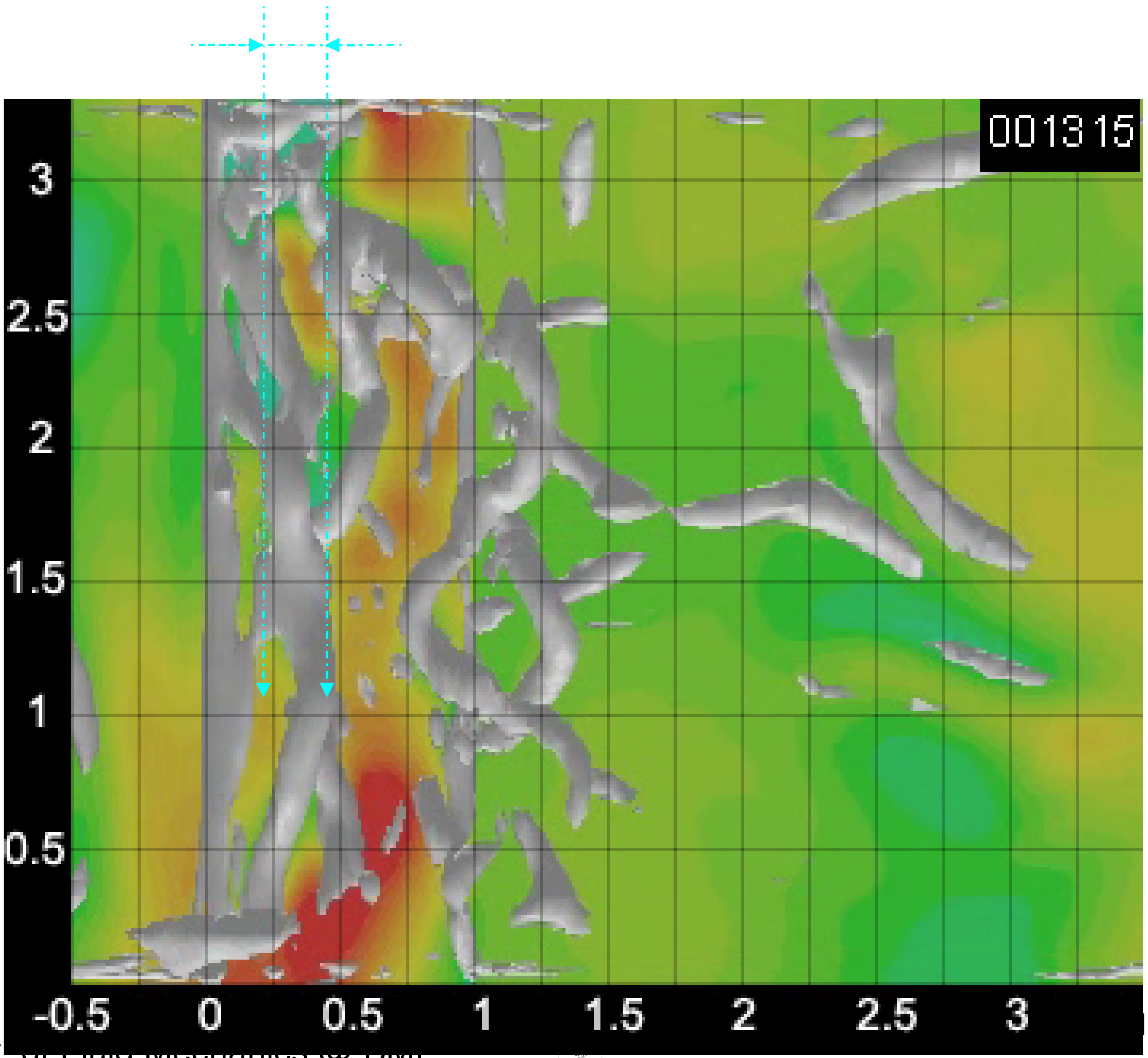
Distance between the structures above the rib



Distance between the structures above the rib



Distance between the structures above the rib



Conditional averaging

Indicator function:

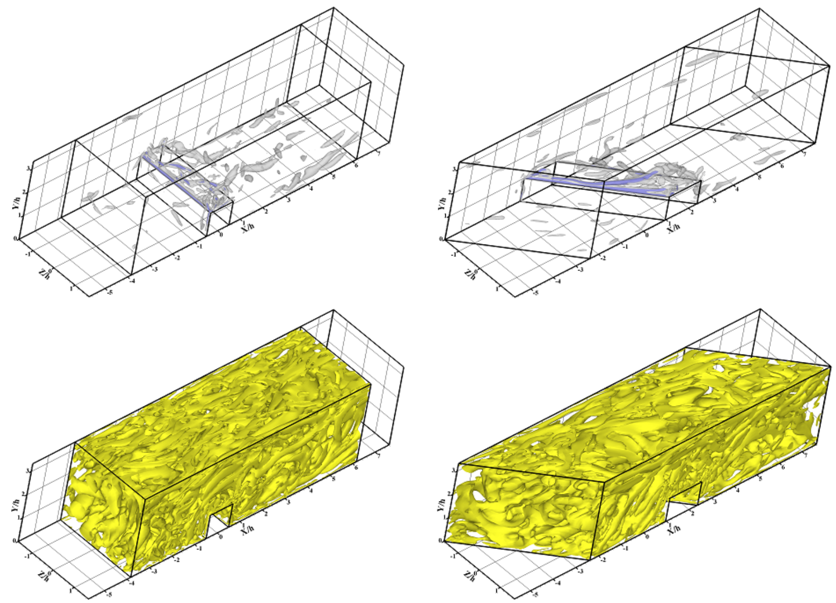
$$I_\alpha \doteq \begin{cases} 1 & Q(\mathbf{x},t) \in Q_\alpha \\ 0 & Q(\mathbf{x},t) \notin Q_\alpha \end{cases}$$

The classes:

$$\begin{aligned}
Q_{I.} &\doteq \{x : x \in \mathbb{R} \wedge \quad x < 0\} \\
Q_{II.} &\doteq \{x : x \in \mathbb{R} \wedge \quad 0 < x < 200\} \\
Q_{III.} &\doteq \{x : x \in \mathbb{R} \wedge \quad 200 < x < 1500\} \\
Q_{IV.} &\doteq \{x : x \in \mathbb{R} \wedge \quad 1500 < x \quad \}
\end{aligned}$$

Conditional averaged variable:

$$\langle \varphi \rangle^\alpha \doteq \frac{\langle \varphi I_\alpha \rangle}{\langle I_\alpha \rangle}$$



Deviation:

$$\Delta^\alpha \varphi = \left(\langle \varphi \rangle^\alpha - \langle \varphi \rangle \right)$$

(Lohász2005)

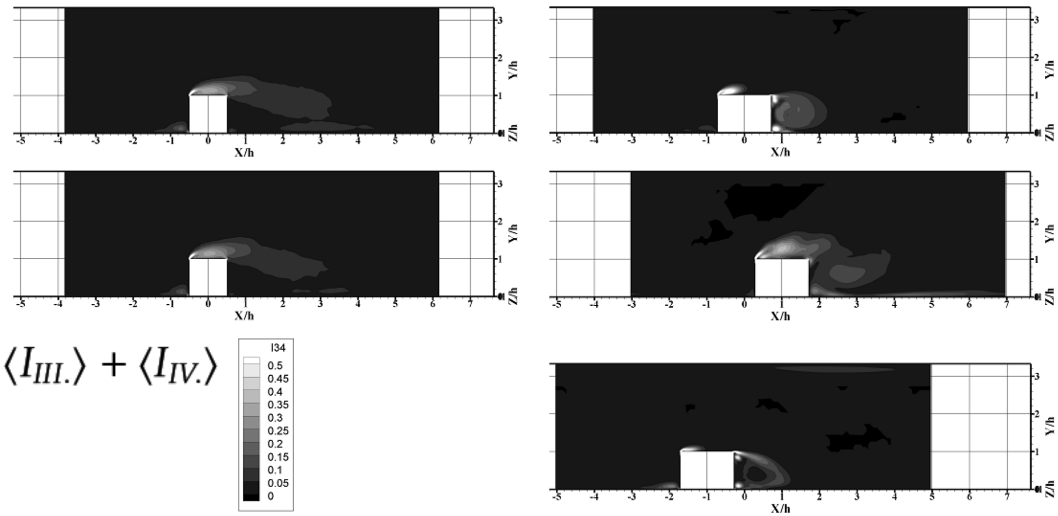
Probability of the classes

Class	Definition	90° Case	45° Case
I.	$Q < 0$	0.6	0.597
II.	$0 < Q < 200U_b^2/D_h^2$	0.376	0.388
III.	$200U_b^2/D_h^2 < Q < 1500U_b^2/D_h^2$	0.019	0.014
IV.	$Q > 1500U_b^2/D_h^2$	0.0008	0.0009
III.+IV.	$Q > 200U_b^2/D_h^2$	0.02	0.015

More background than vortex for both cases

Intense vortices are more probable for perpendicular rib

Location of the intense vortices



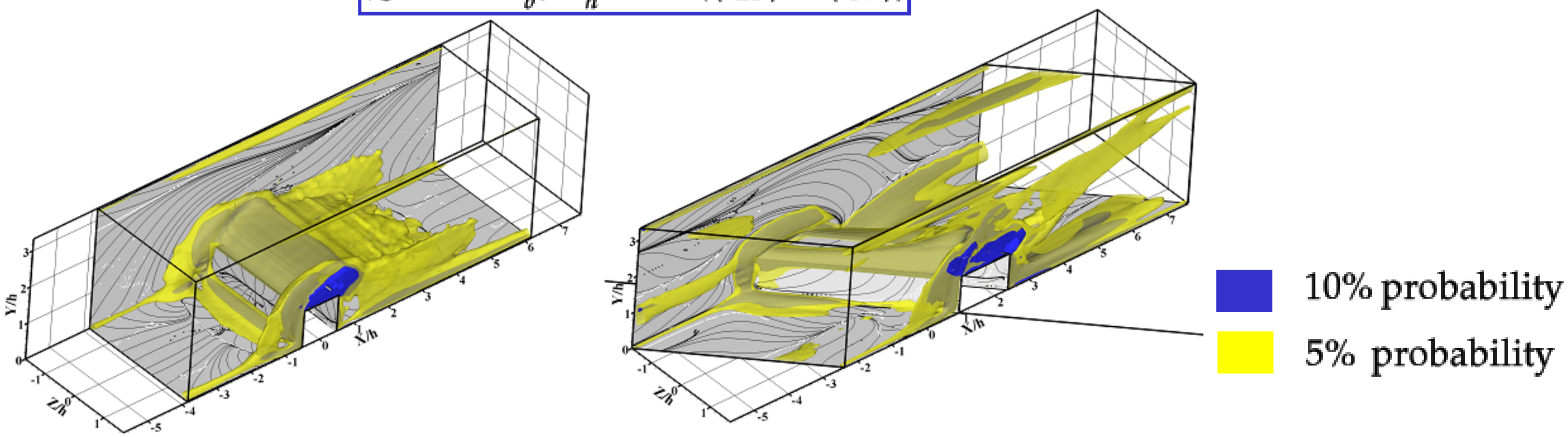
$Z/h = 0$

$Z/h = 1$

$Z/h = -1$

- Leading edge of the rib
- Shear layer of 90° rib
- Wake of the 45° rib

$Q > 200 U_b^2 / D_h^2$ class $(\langle I_{III.} \rangle + \langle I_{IV.} \rangle)$



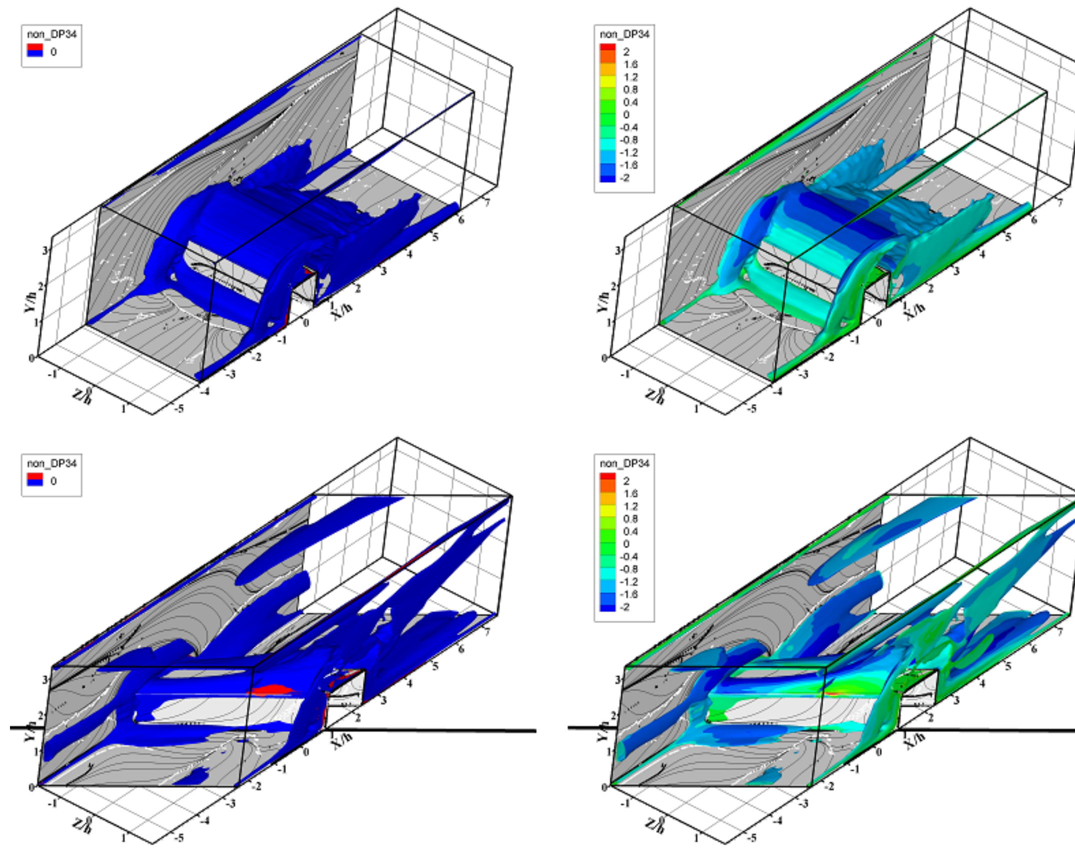
The pressure deviation

Volume average of the pressure deviation for each class for the higher than 5% probability regions

Class	$\Delta^{\alpha} P$ 90°	$\Delta^{\alpha} P$ 45°	90°	45°
I.	0.208	0.302	1	1
II.	−0.254	−0.391	0.999	0.996
III.	−1.083	−1.435	0.084	0.063
IV.	−1.376	−1.201	0.003	0.003
III.+IV.	−1.134	−1.189	0.085	0.064

Size of the higher than 5% probability regions

Isosurface of $\langle I_{34} \rangle = 0.05$ coloured by $\langle \Delta^{34} P \rangle / \sqrt{\langle p'^2 \rangle}$



Channel flow

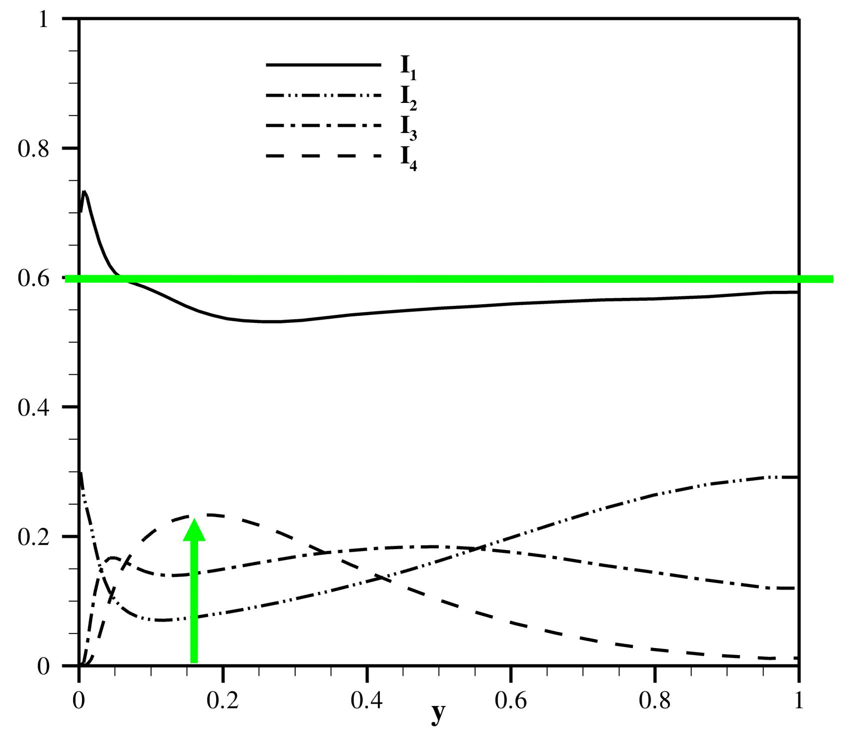
Re_τ=180

LES with Dyn. Smag.
72^3 cells
sec. ord. scheme

Q class borders:
0, 0.1, 0.01 U_b^2/δ^2

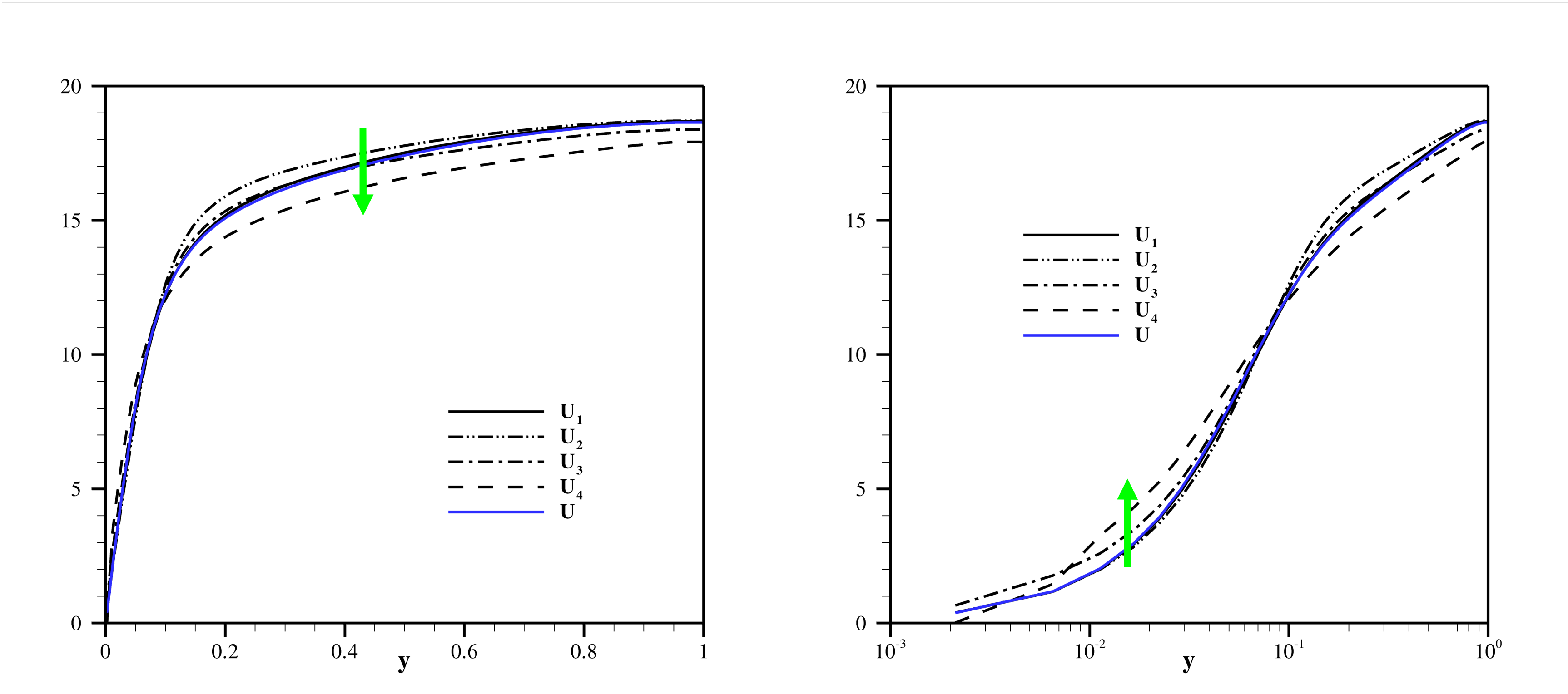
- Q<0 is appr. 60%, i.e vortices are rare
- Intense vortices have high probability in buffer zone

Vortex probability



Channel flow

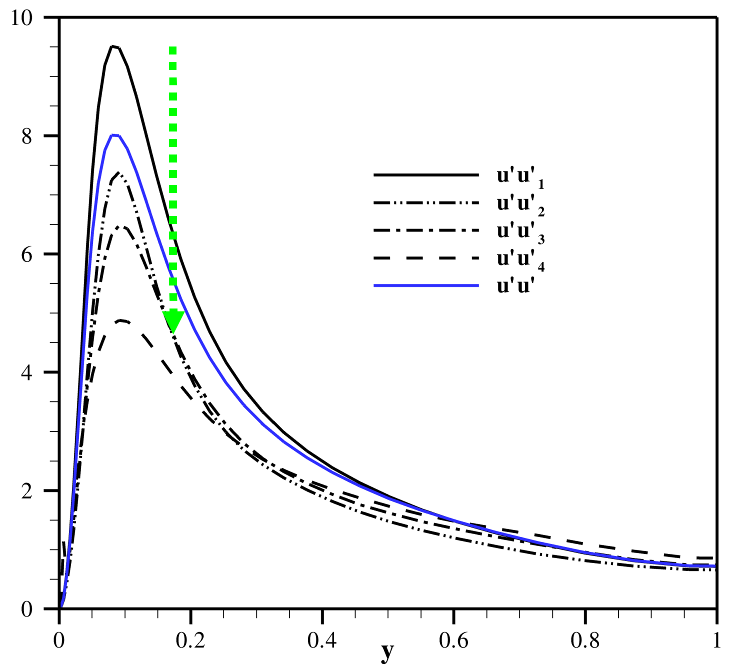
Streamwise velocity



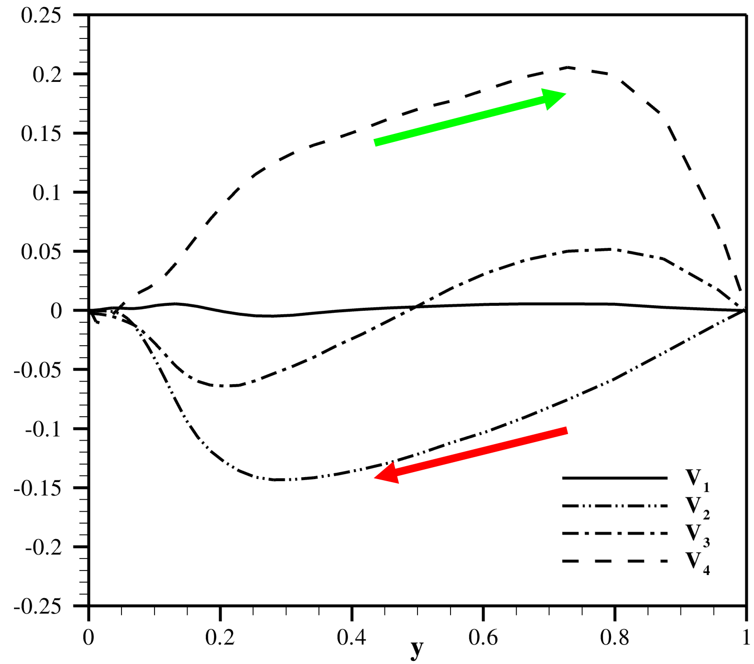
Intense vortices (or vortex cores) move slower at the channel center, and faster close to the wall

Channel flow

Streamwise velocity fluctuation



Wall-normal velocity



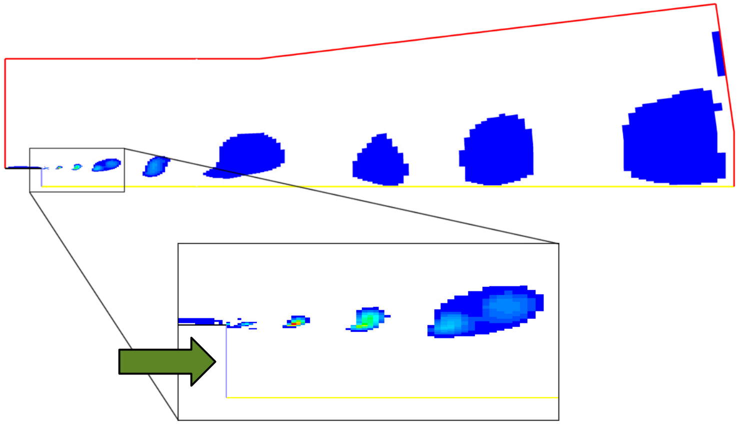
Q strength inversely prop. to streamwise fluctuation

Vortex core tends to the center perimeter to the wall

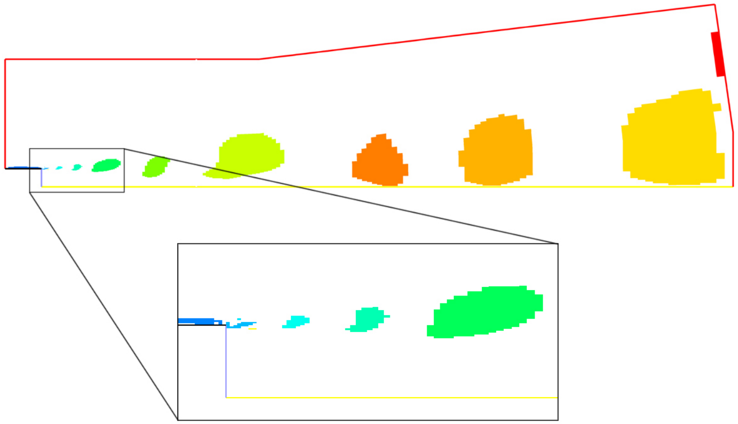
Vortex tracking

- Vortices need to be identified separatly
  - The educted region needs to be divided into disjunct sets
- Needed for the quantitative investigation of the interactions

The complete educed region



Vortices with indices



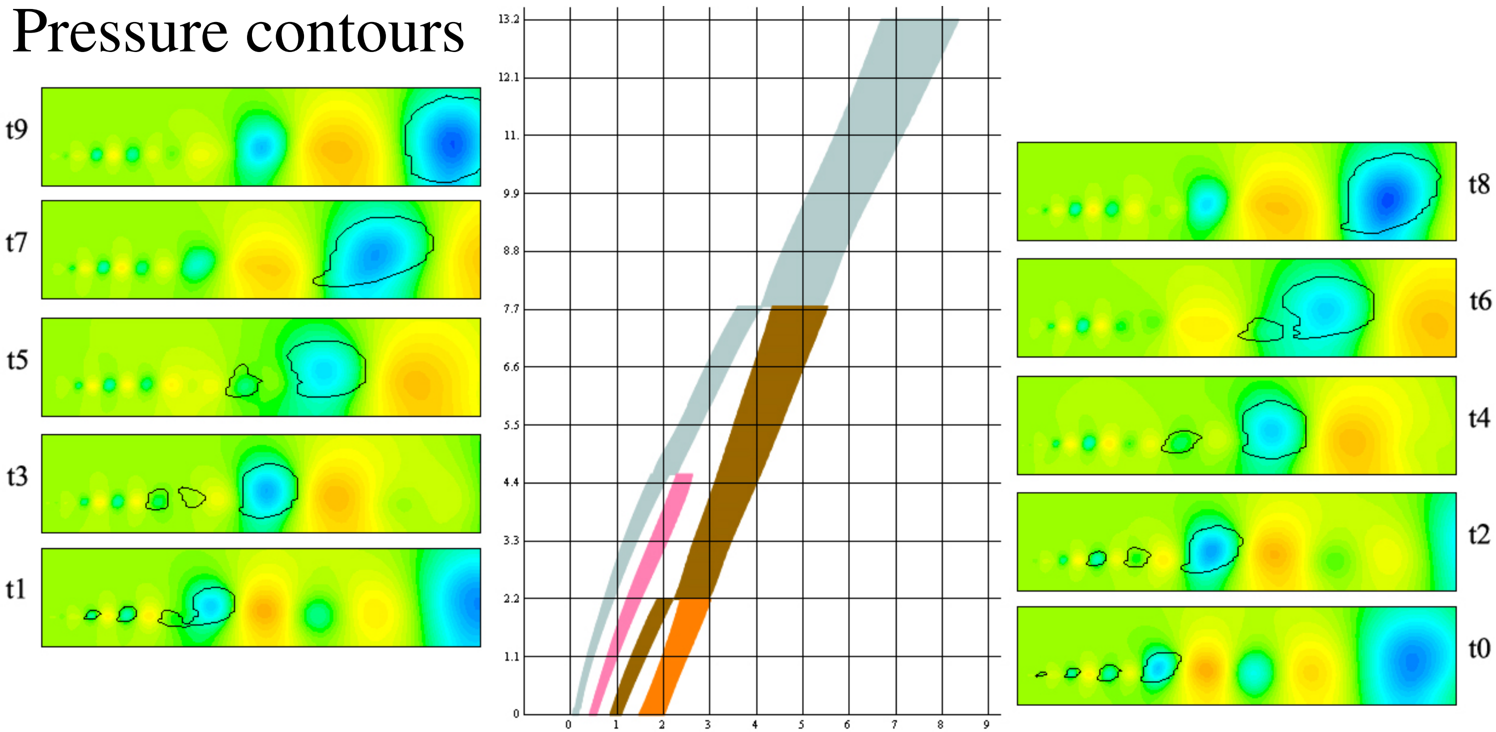
Example of an axisymmetric jet

(Nyers2008)

Vortex tracking

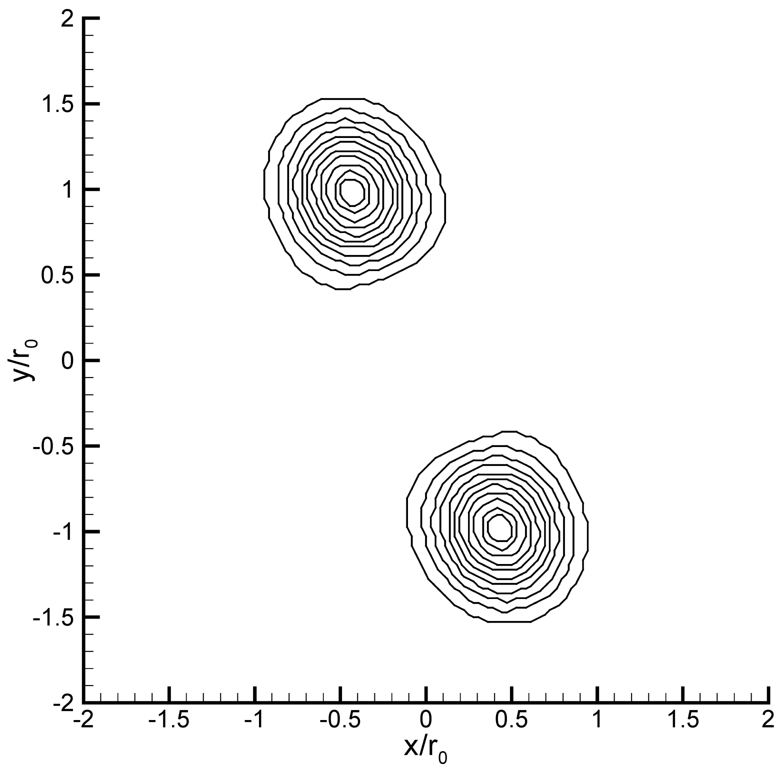
Application example:

Position and size of the vortices

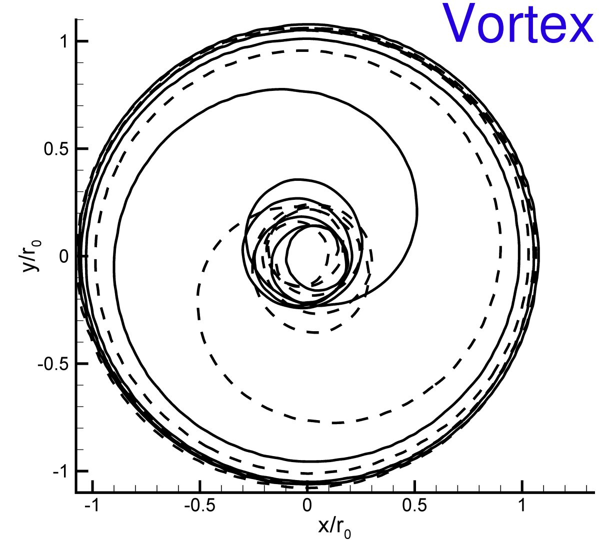


Spinning, merging vortices

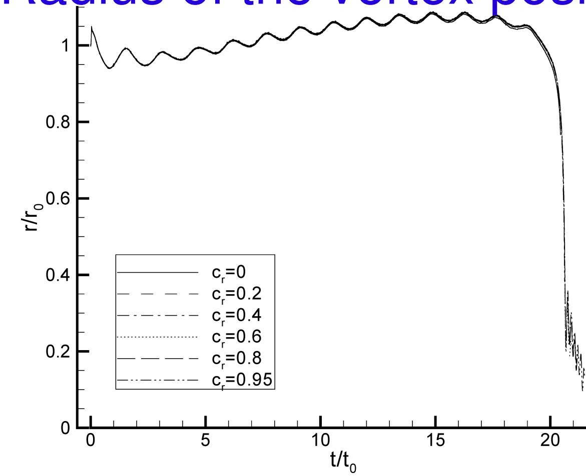
Spinning vortex pair, different threshold



Vortex path

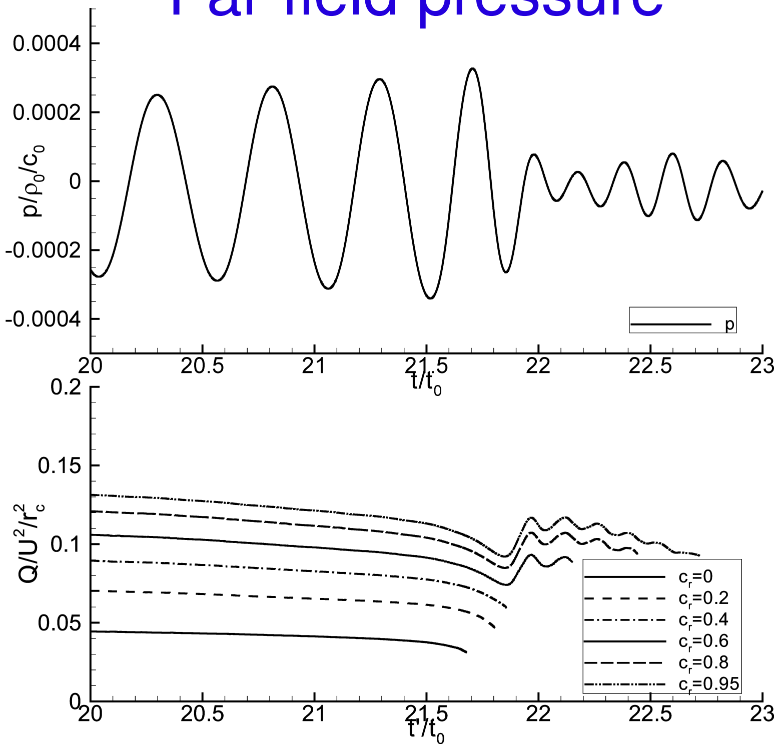


Radius of the vortex position

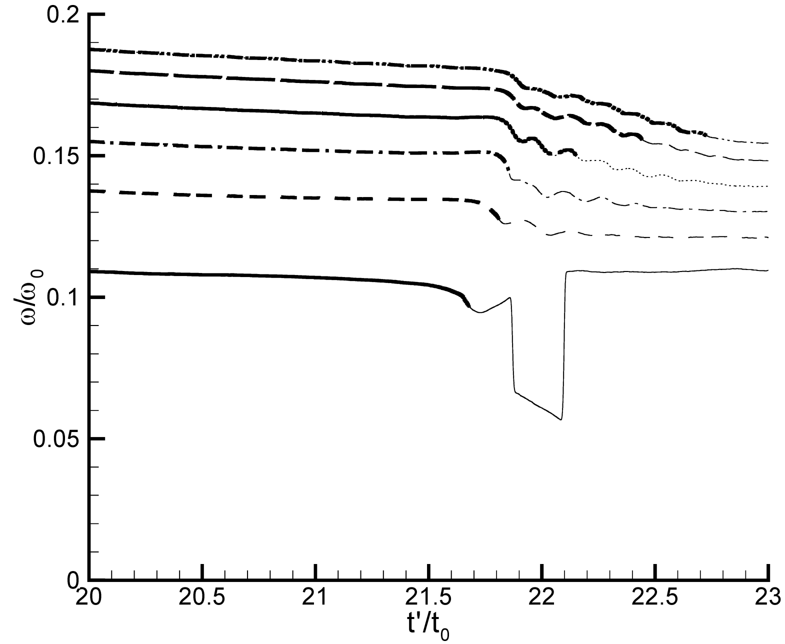


Correlation between noise and vortices

Far field pressure



Average vorticity evolution



Goal: Prediction of far field sound using vortex position and strength evolution

Conclusion

The combination of the two methods:

A tracking based averaging could provide the best understanding of the vortex evolution

Thank you for your attention!