ETC 11

11th EUROMECH European Turbulence Conference

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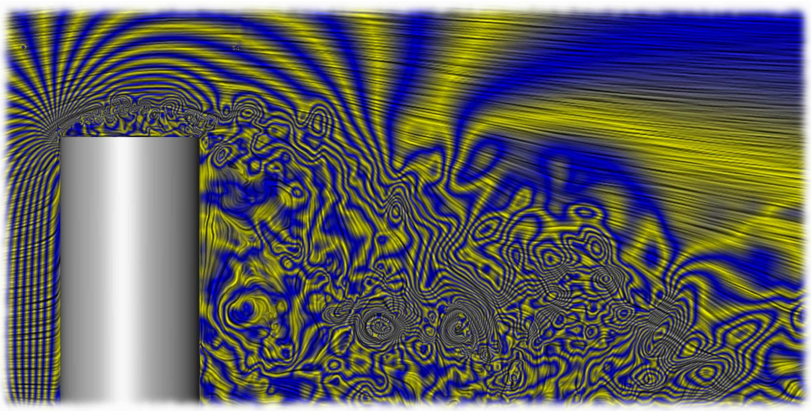
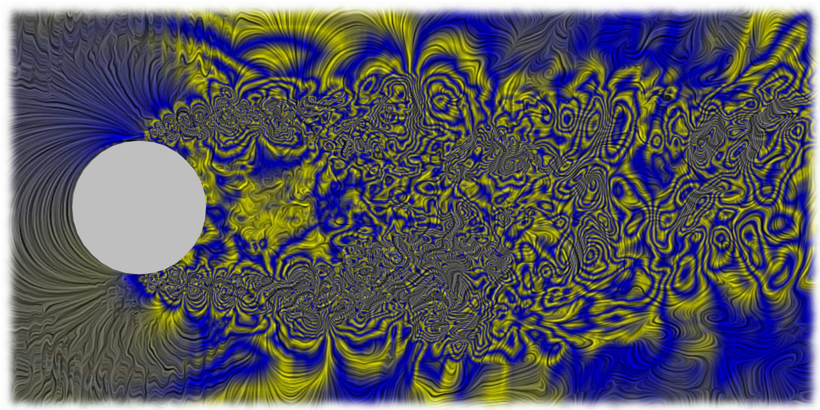
11th EUROMECH
European Turbulence Conference
June 25-28, 2007, Porto

Institute of Fluid Mechanics and Engineering Acoustics

Analysis of the Unsteady Flow around a Wall-Mounted Finite Cylinder at Re = 200 000





O. Frederich M. Luchtenburg E.Wassen F. Thiele

Institute of Fluid Mechanics and Engineering Acoustics
Berlin University of Technology

Outline

- Motivation
- Experimental and Numerical Configuration
- Numerical Method and Parameters
- Results
  - Time-averaged flow
  - Comparison to experiments
  - Unsteady flow
  - POD analysis of the unsteady flow pattern
- Conclusion
- Outlook

Motivation

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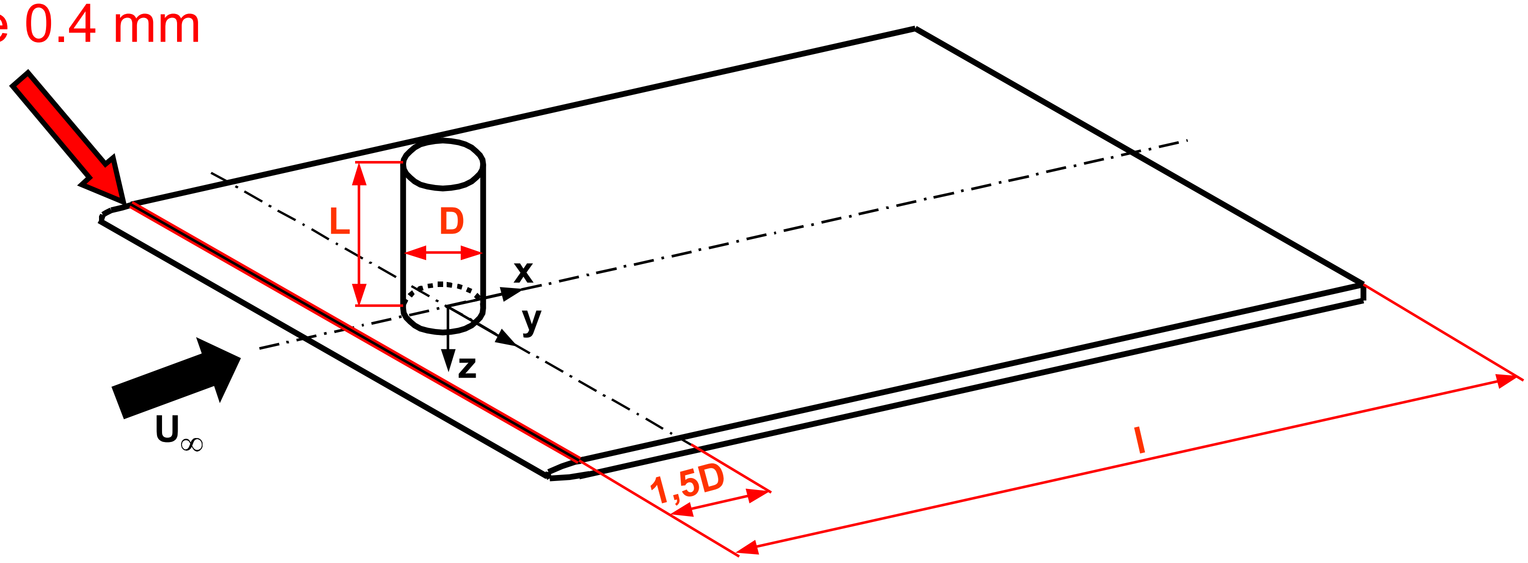
- Research project “Imaging Measuring Methods for Flow Analysis” funded by the DFG
- Analysis of complex 3D-(un)steady flows w.r.t. spatial and temporal resolution (similar to CFD ?)
  - Develop flow measuring and visualisation techniques and improve their performance
- Flow field around the wall-mounted cylinder chosen as reference for all method validations
- Provide database with correlated (un)steady quantities
- Comparison of different simulation approaches
- Establish combined test-case (experiment + CFD)

▪ Configuration of experimental setup

- Reynolds number Re_D = 200 000
- Inflow velocity U_∞ = 26.0 m/s
- Turbulence level Tu = 0.5%

- Cylinder diameter D = 120 mm
- Aspect ratio L/D = 2
- Plate length l = 1300 mm

- Trip wire 0.4 mm



Configuration II

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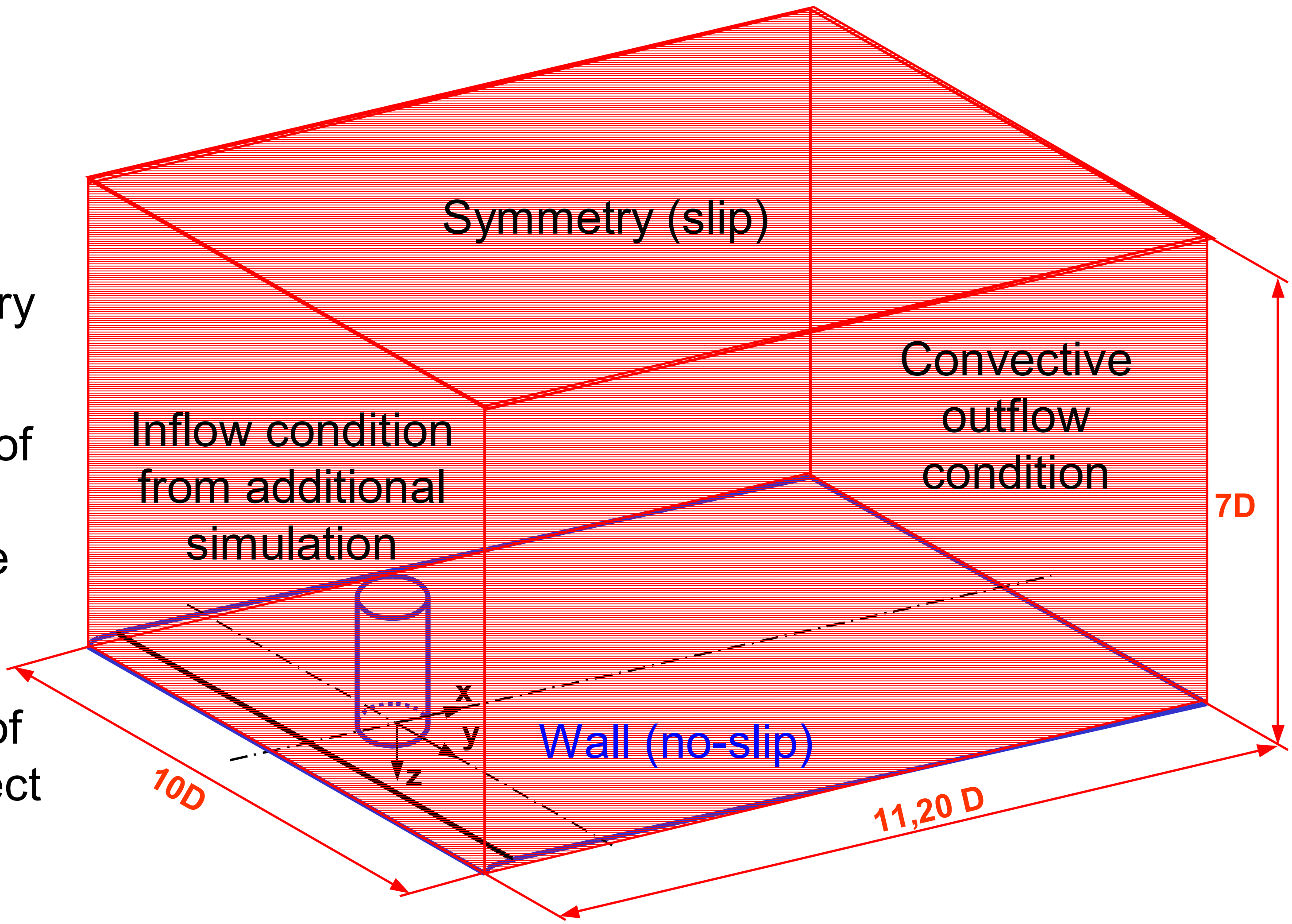
▪ Configuration of numerical setup

- Definition of the domain and boundary conditions
- Generation of an adapted inflow profile
- Integration of trip wire effect



Numerical Method and Parameters

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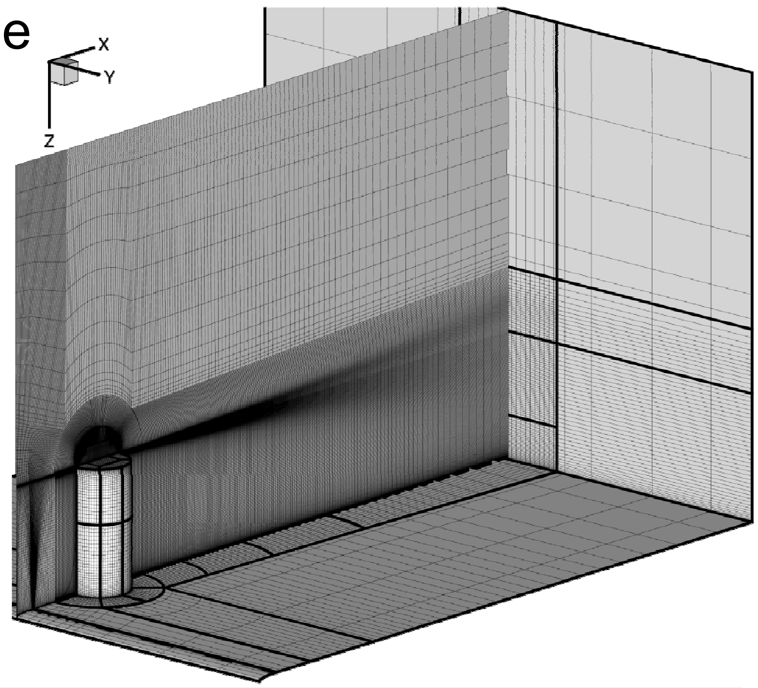
Numerical Method

- Flow Solver ELAN by *L.Xue*
- Incompressible 3D Finite-Volume approximation
- Formulation in curvilinear coordinates
- 2nd order accuracy in space and time
- Gradient-based central differencing scheme 4th order for convective terms
- Semi-structured grid (hanging nodes)

- 12.3 Mio grid points
- 9.9 Mio points in focus-region
- hanging nodes
- All boundary layers resolved
- Geometrical wire model
- 63 structured blocks
- $\Delta t = 0.005\, D/U_\infty = 0.0000231$ s



Subgrid-scale modelling

- Standard Smagorinsky model with C_s=0.1
- Detached-Eddy Simulation with LLR k-ω
- LES w/o SGS model („coarse“ DNS)
- Wall-modelled LES

Time-averaged flow

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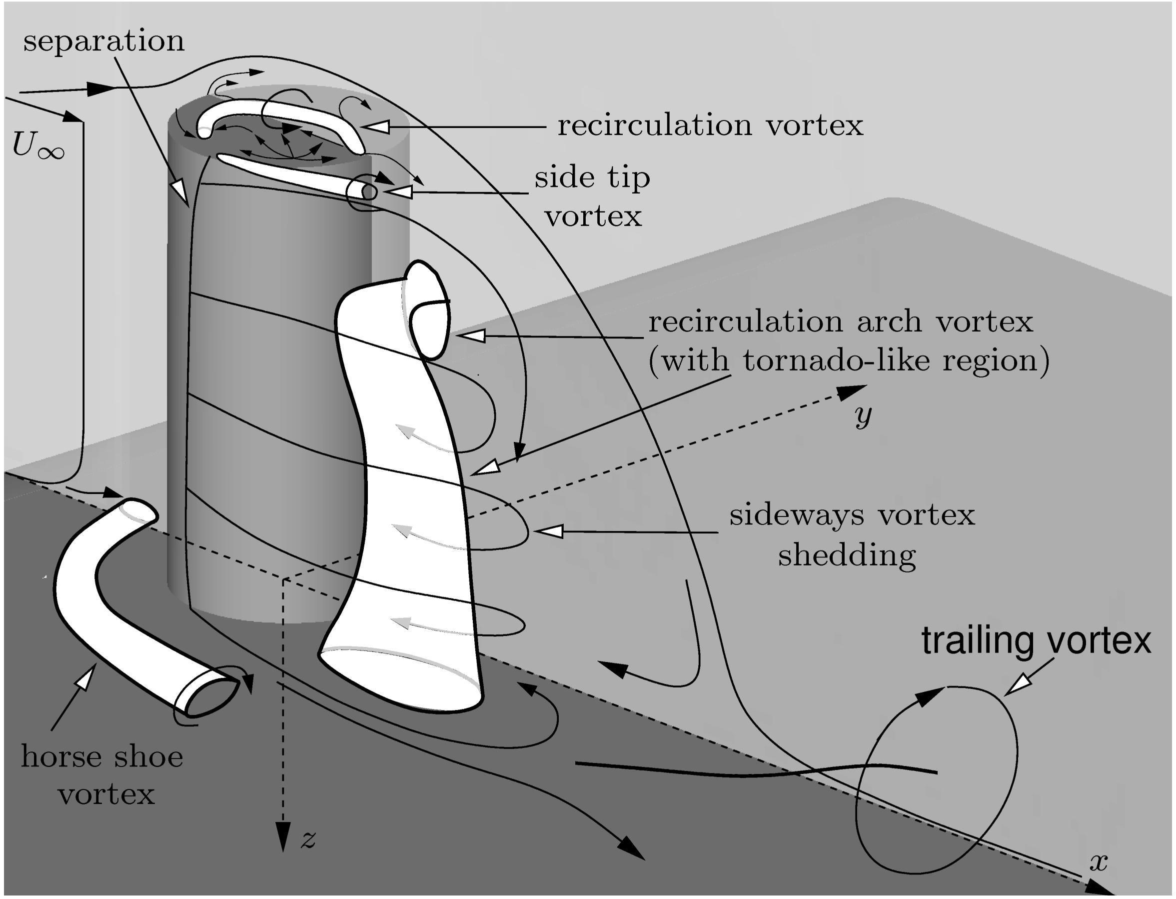
▪ Time-averaged vortex structures

- Superposition of the detected vortical flow details represents the mean flow
- Base for understanding the unsteady flow pattern
- Vortex shedding regime is completely 3D
- Vortex axes seems to be orthogonal to each other



Comparison to experiments I

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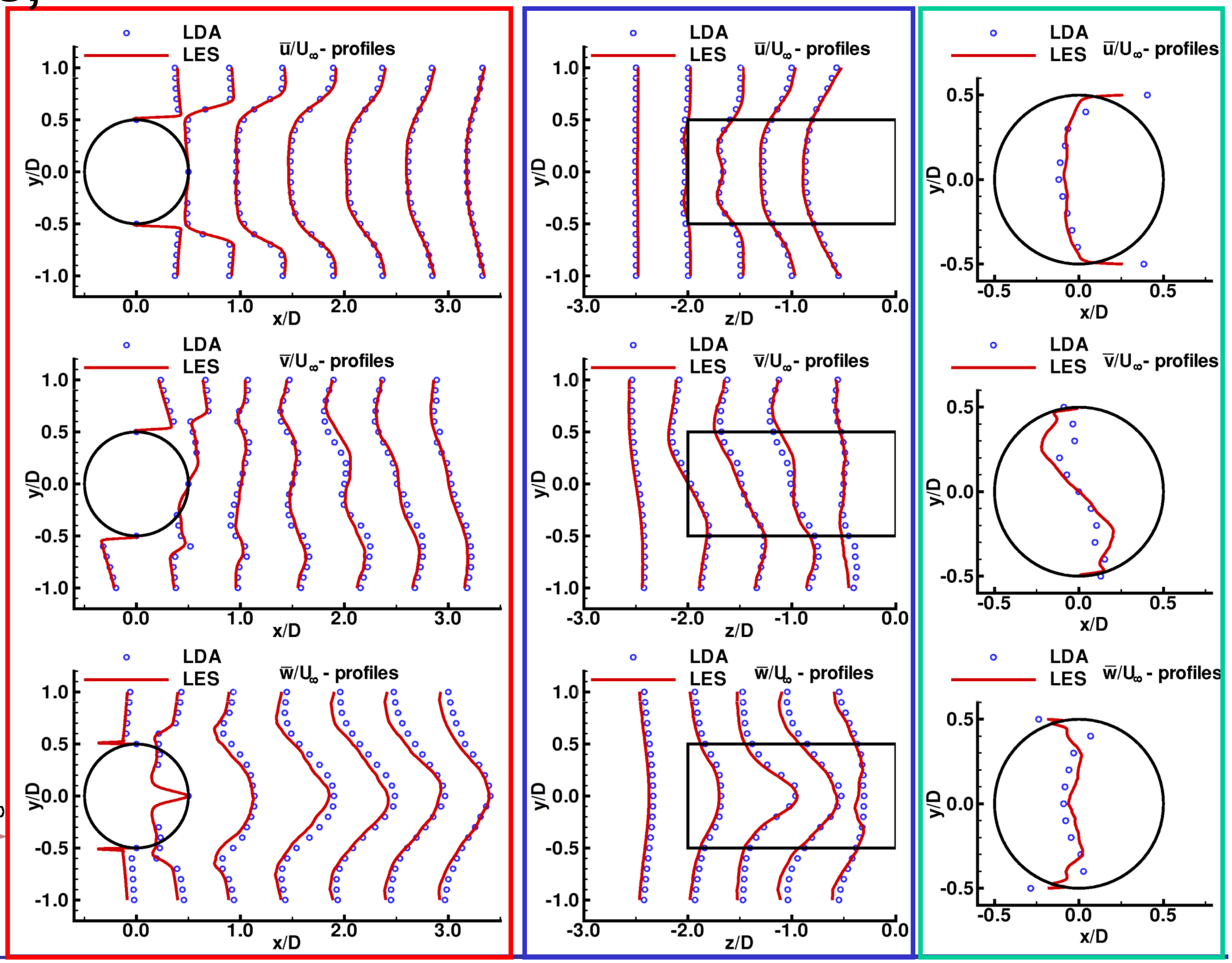
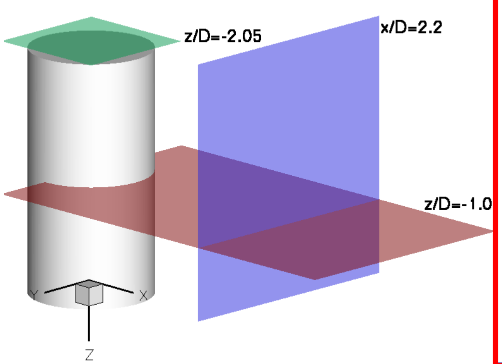
- **UVW-Profiles, qualitative**

Very good agreement of the velocity profiles in the wake

Small discrepancies on cylinder top

z/D = -1.0   x/D = 2.2   z/D = -2.05





Comparison to experiments II

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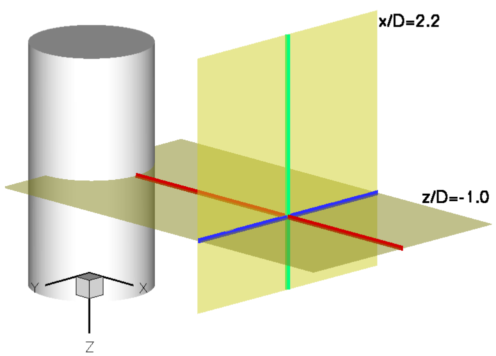
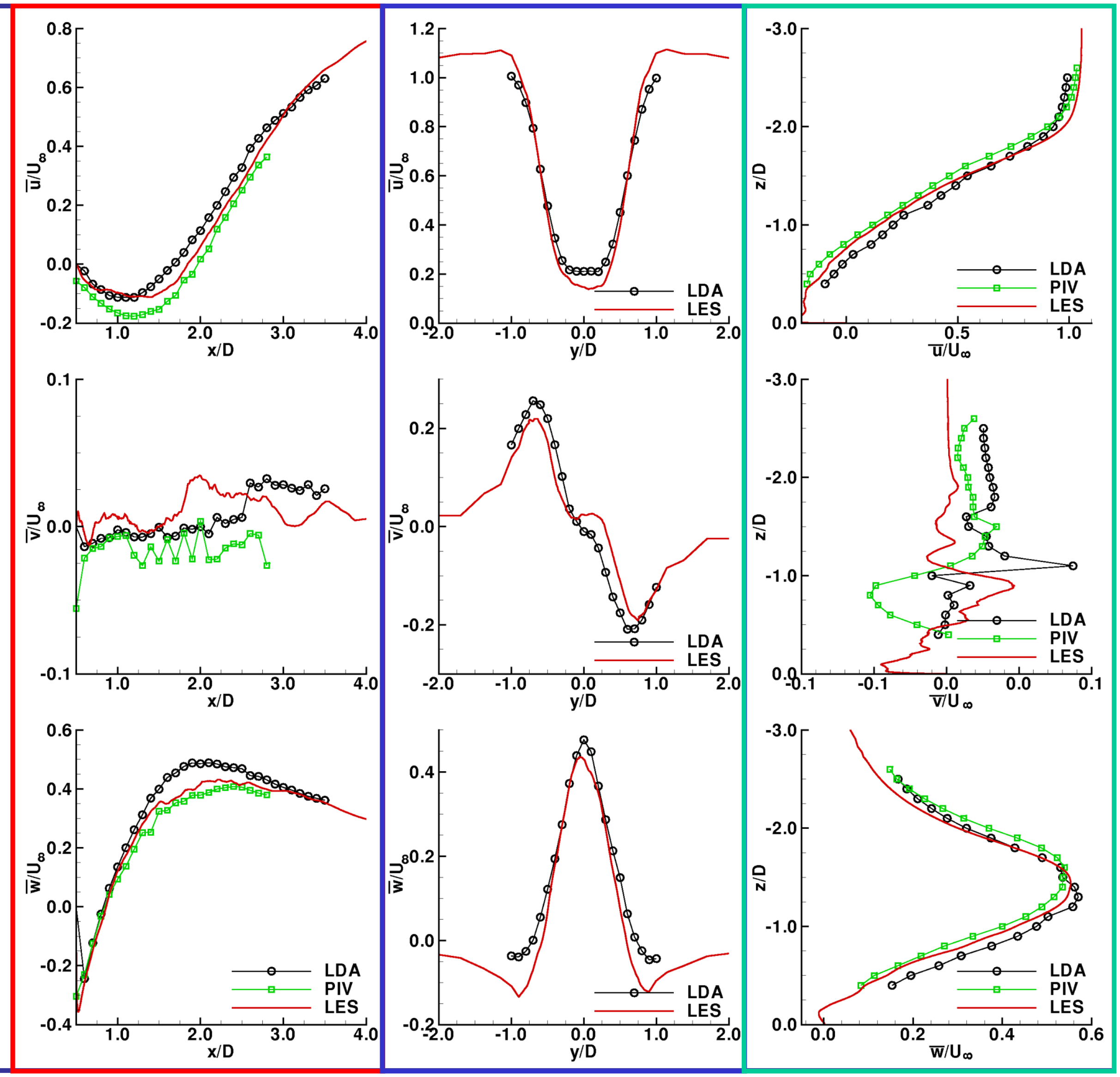
- **UVW-Profiles, quantitative**

Good agreement also quantitatively

Lateral velocity in the symmetry plane 3-4% U_∞ (not full statistically converged)





Comparison to experiments III

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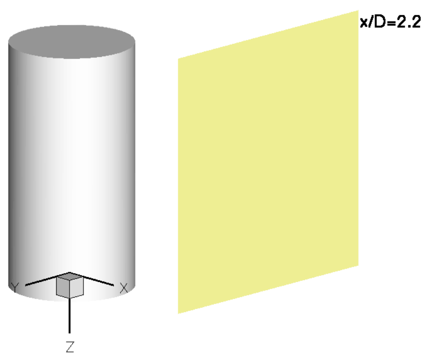
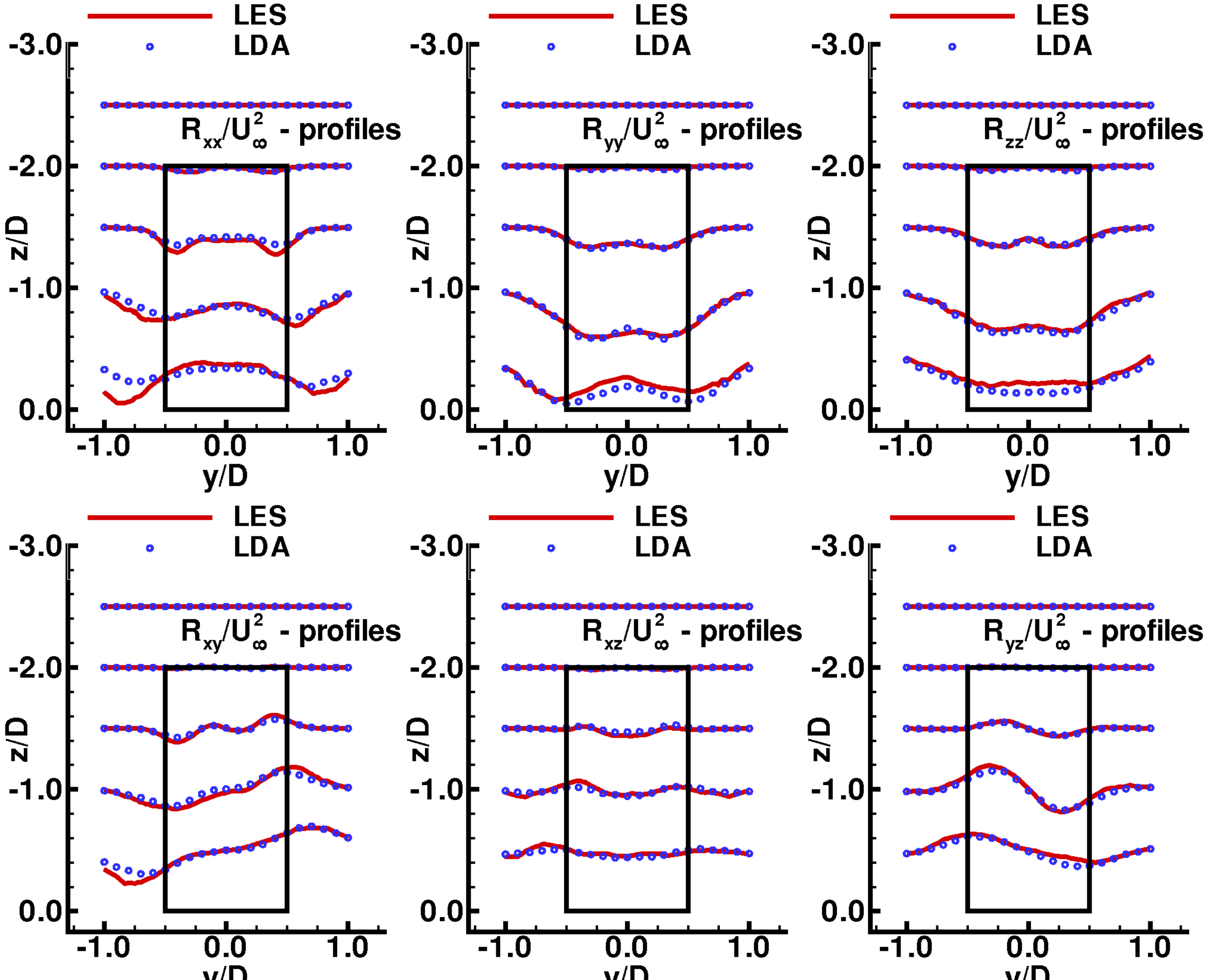
- **Reynolds-stresses, qualitative**

Overall good agreement in second order statistics

Small differences near plate due to different spatial resolution (and inflow profiles)





Comparison to experiments IV

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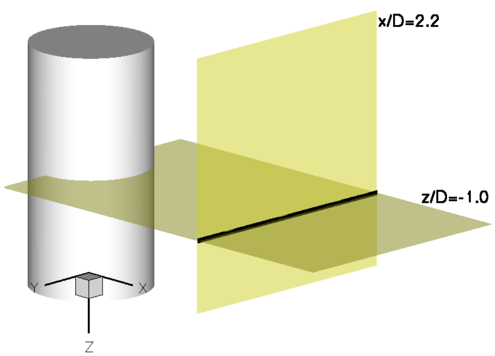
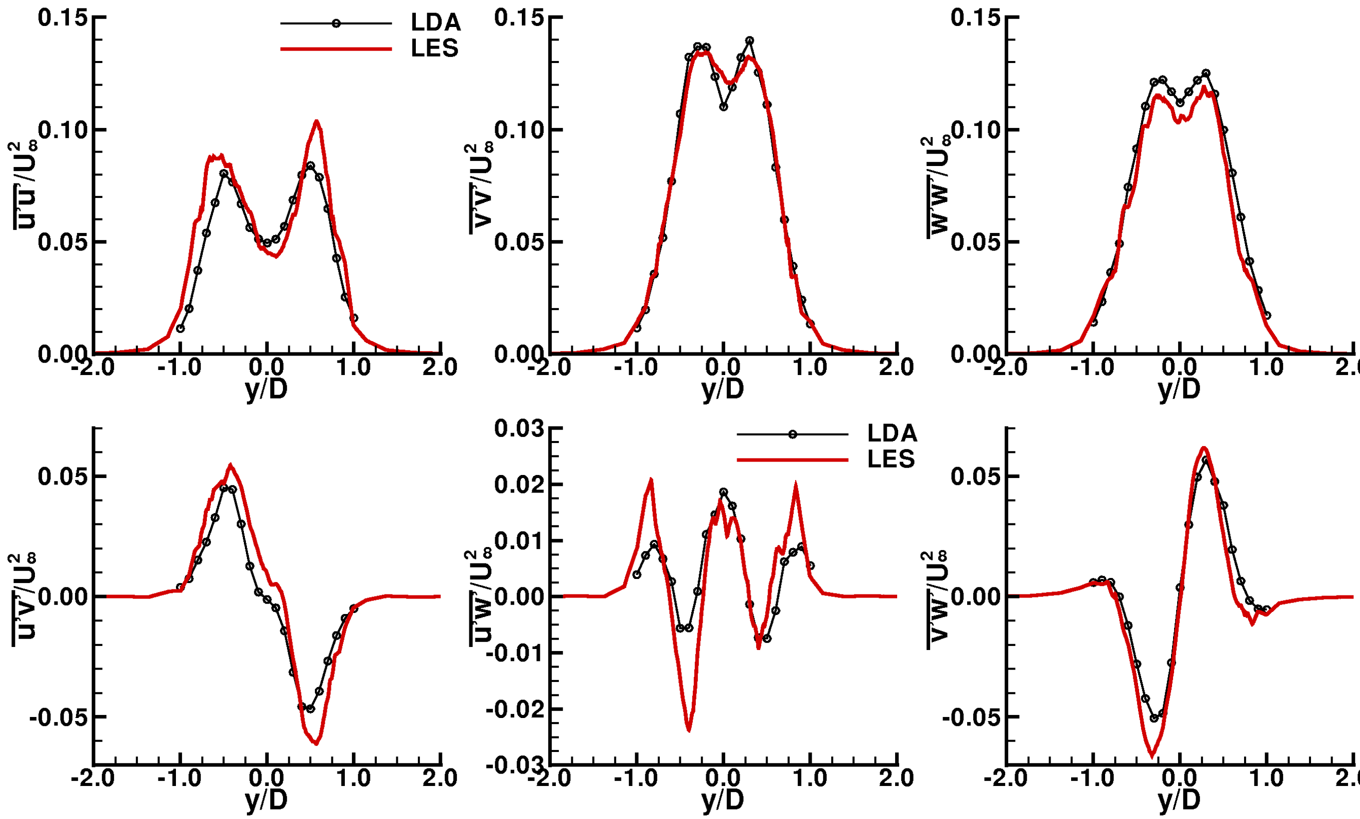
▪ Reynolds-stresses, quantitative

Good agreement also quantitatively with small variations due to statistics and spatial resolution.

PIV data
not available
for this line





Unsteady Flow I

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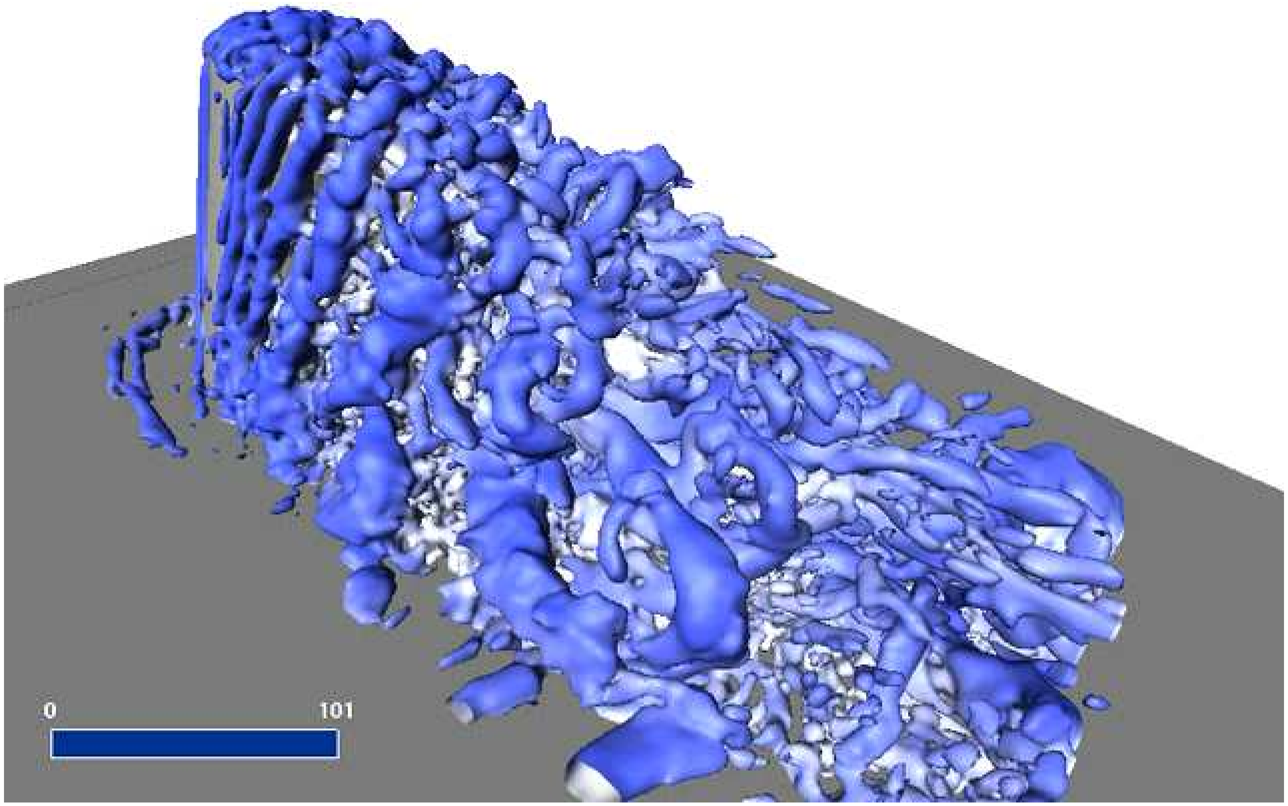
- **Unsteady flow pattern**

Visualisation of every 25th time-step out of 2500

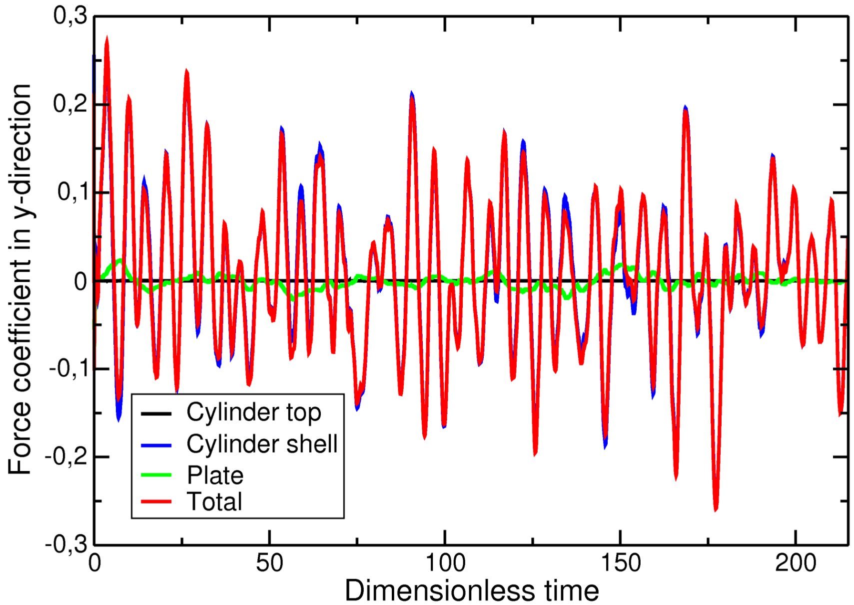
λ_2-iso-surfaces colorized with velocity magnitude

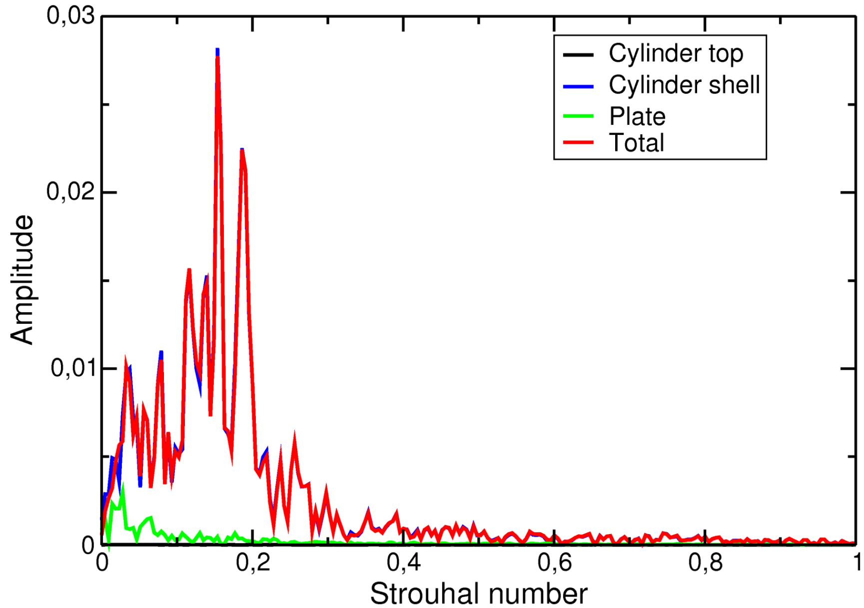


▪ Frequency analysis

- Strouhal number of the dominant frequency St = 0.16
- Existence of a 2nd frequency with St = 0.20, particularly with reduced distance to plate
- Evaluation of global force coefficients and local (pressure-) signals coincides

	St	f_1 [Hz]	f_2 [Hz]
LES	0,16	34,66	42,9
LDA	0,16	35,00	43,0
TR-PIV	0,16	35,16	k.A.





Proper Orthogonal Decomposition I

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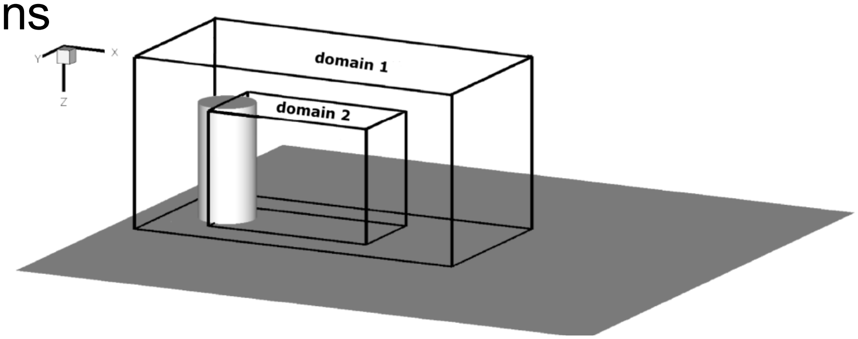
▪ Database and eigenvalues

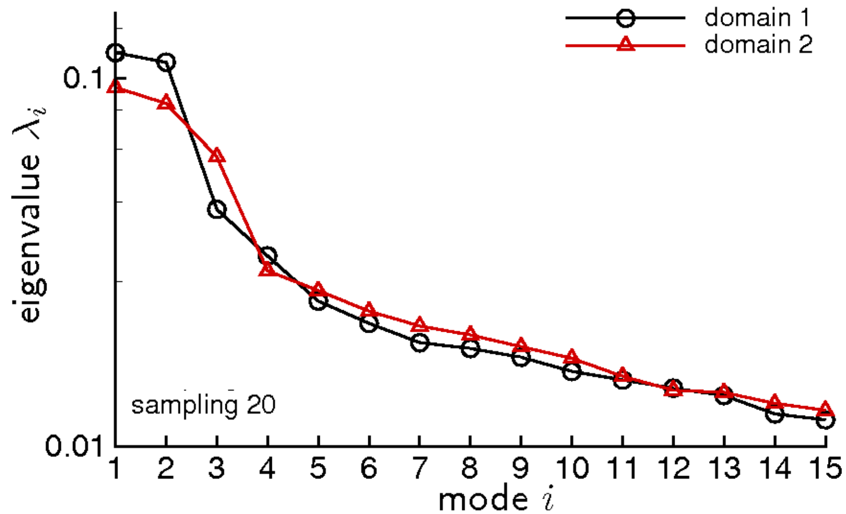
- 2300 snapshots (every 5th timestep) representing 60 convective units D/U_∞
- Spatial re-sampling and usage of sub-domains
- Varying sampling rate (5 ... 100)

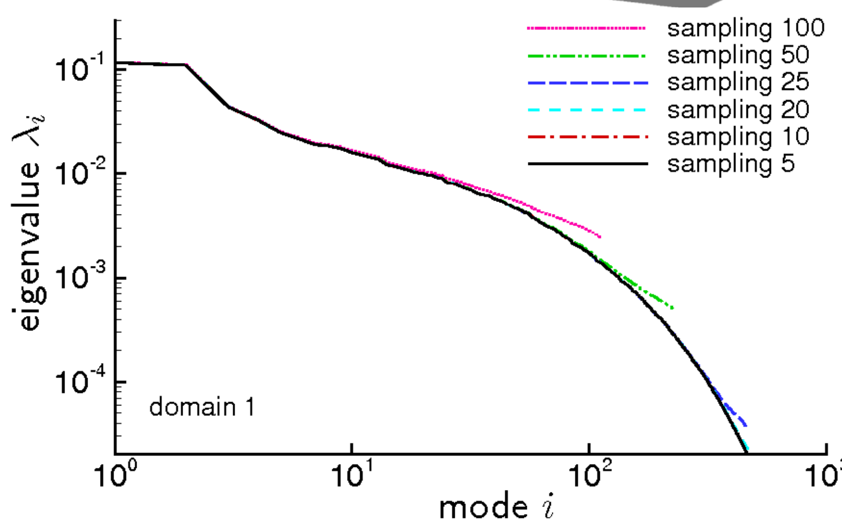
➢ Spatial domain as large as possible

➢ Moderate sampling rate of 50 sufficient

	domain 1		domain 2	
x/D	-1 ... 5	256	0 ... 3	128
y/D	-1.5 ... 1.5	128	-0.75 ... 0.75	64
z/D	-3 ... 0	128	-2 ... 0	86



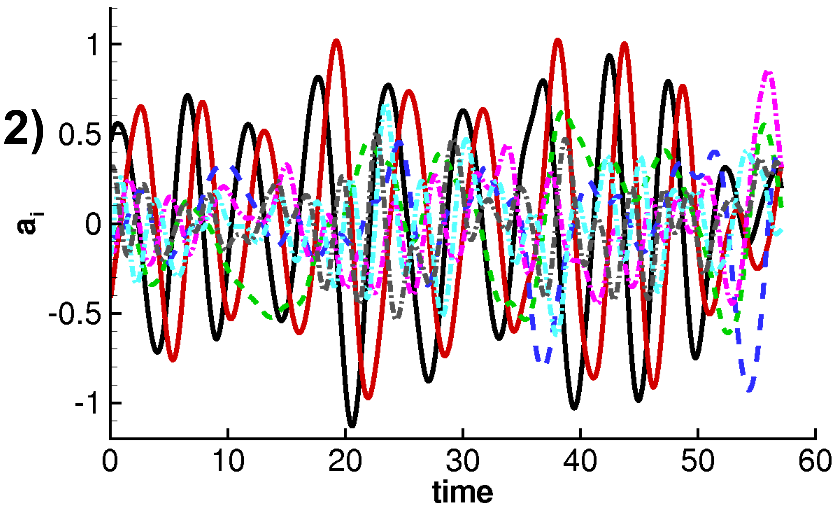


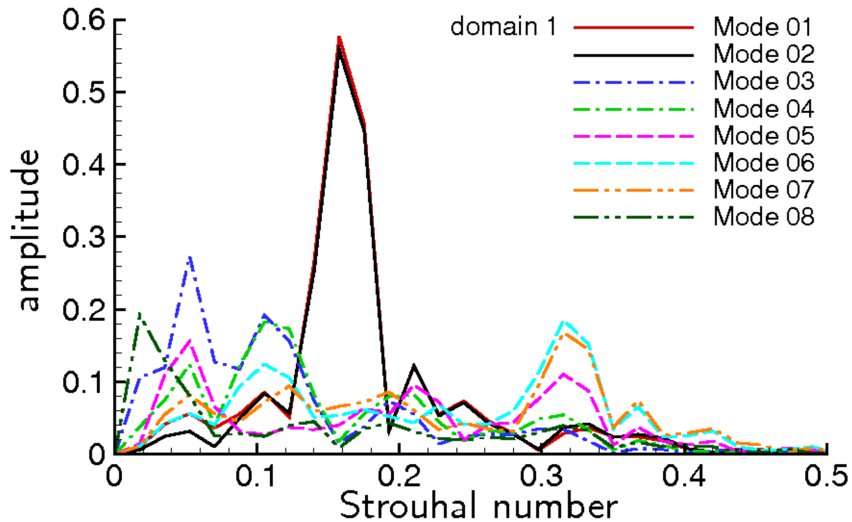


Proper Orthogonal Decomposition II

▪ Time coefficients and spectral properties I

- Clearly **dominant harmonic mode pair (1,2)** with Strouhal number of **0.158**
- Strict decomposition of different frequencies only found for mode pair (1,2)
- Mode **pair (3,4)** represent **sub-harmonic**
- **Modes (5,6,7)** describe **2nd harmonic**
- Modes (1,2) capture 23% and modes (1-7) capture 37% of the kinetic energy





Proper Orthogonal Decomposition III

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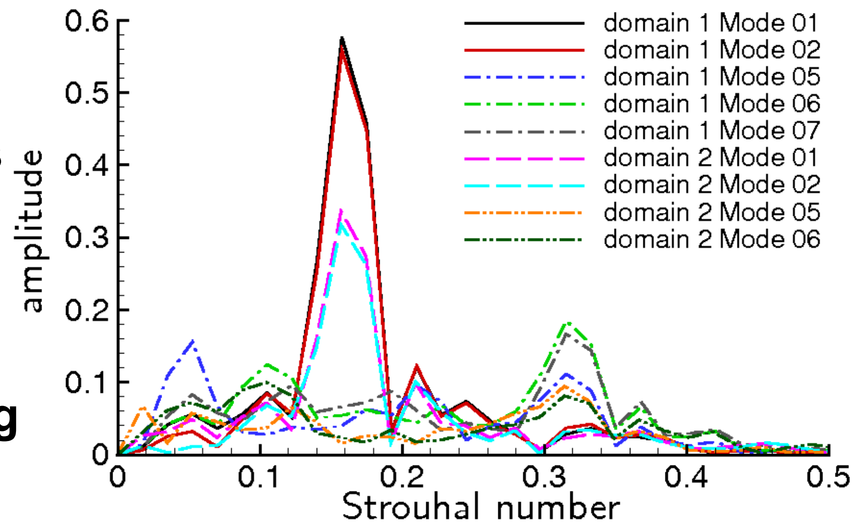
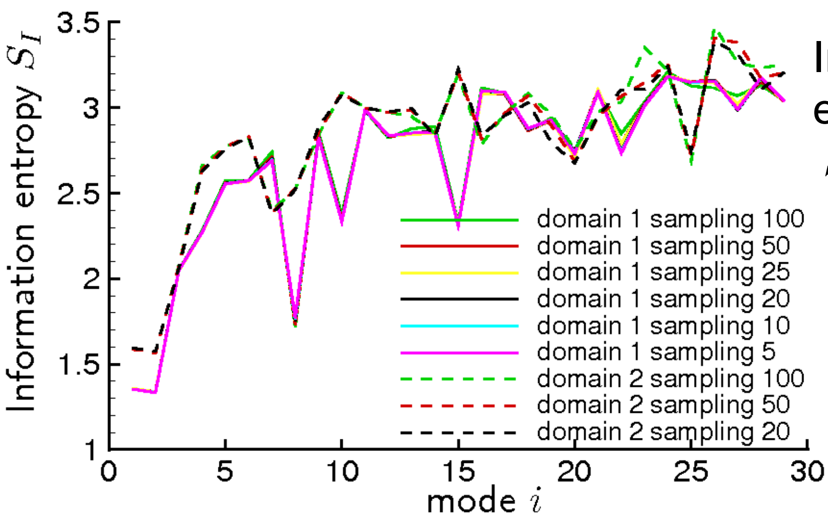
▪ Modes and their correlation

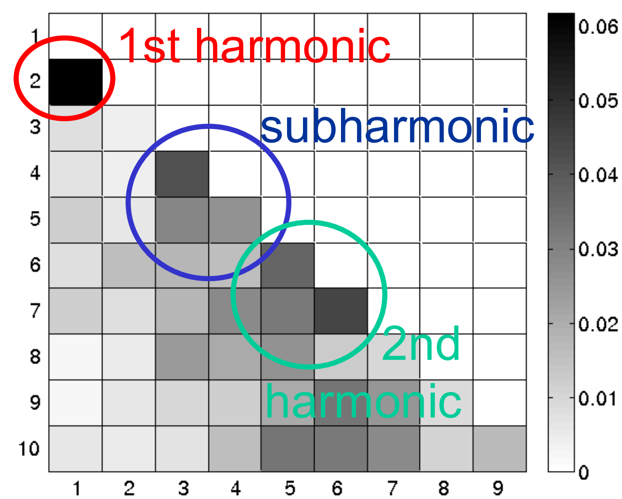
- **Correlations** of the modes **reveal** the **interactions** to produce relevant harmonics
- Frequency content tends to mix at smaller wavelengths (**entropy increases moving to higher modes**)
- **Domain size reduction** leads to **increasing entropy** and correlation reduction





Information entropy:

$S_I = -\Sigma p_i \log p_i$



Correlations of the POD time coefficients

Proper Orthogonal Decomposition IV

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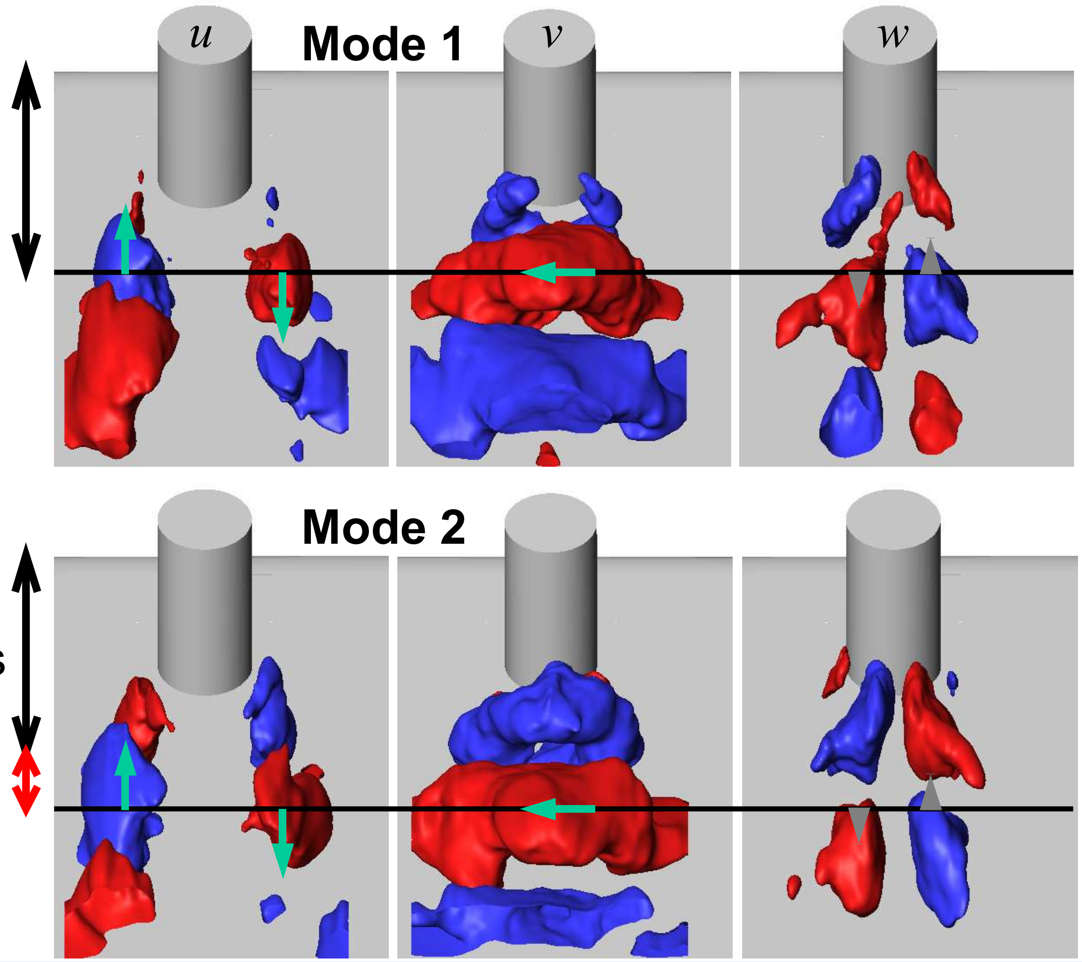
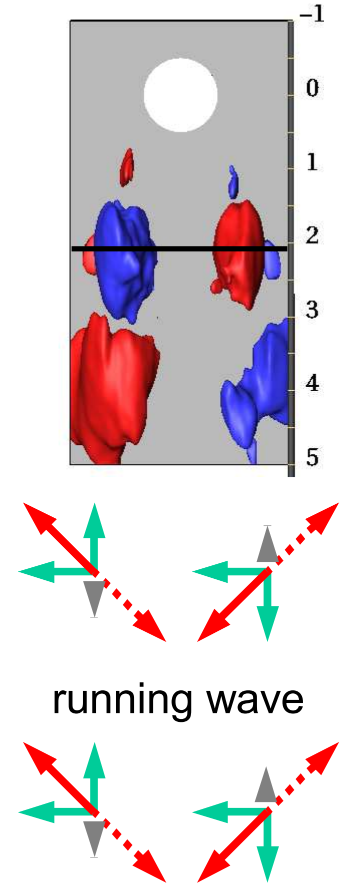
▪ Dominant mode pair (1,2)

- Representing sideways vortex shedding
- Harmonic very similar to those of an infinite cylinder
- Differences due to end effects
- Recirculation region increases the streamwise depth of the bluff body

iso-surfaces
$u_i = \pm 0.18\ U_\infty$





Proper Orthogonal Decomposition V

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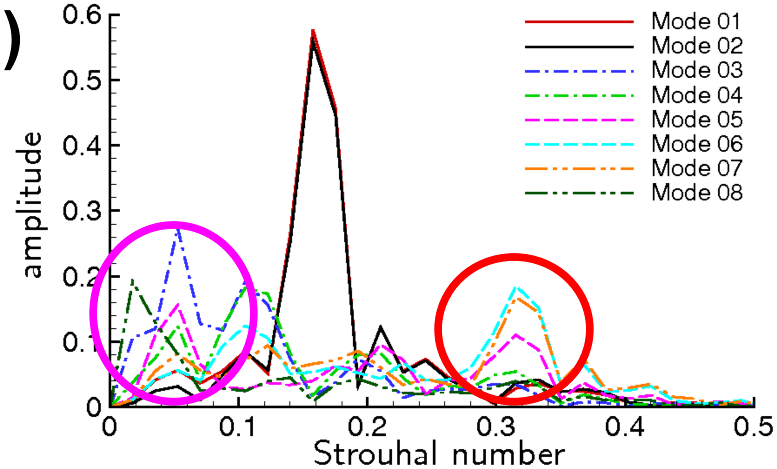
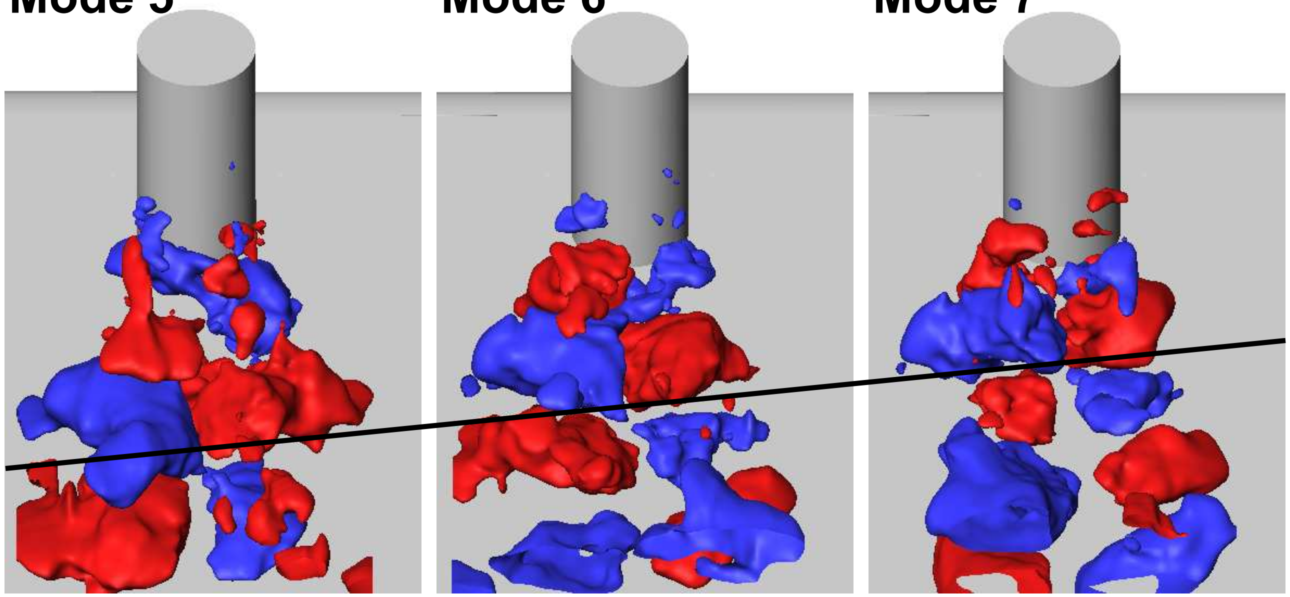
▪ Second harmonic - modes (5,6,7)



- Three modes involved
- Insufficient number of samples (or energy transfer between harmonic and sub-harmonic)
- POD is not able to separate frequencies due to its energetic approach
- u- and w-component do not represent this clear harmonic



iso-surfaces
$v = \pm 0.18\ U_\infty$

Proper Orthogonal Decomposition VI

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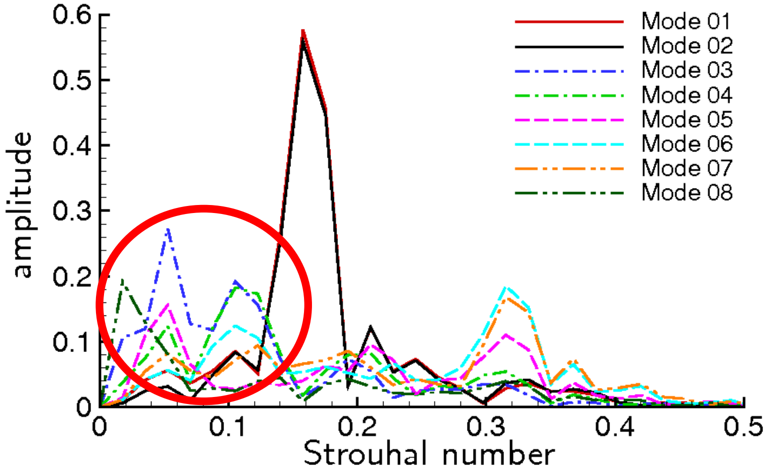
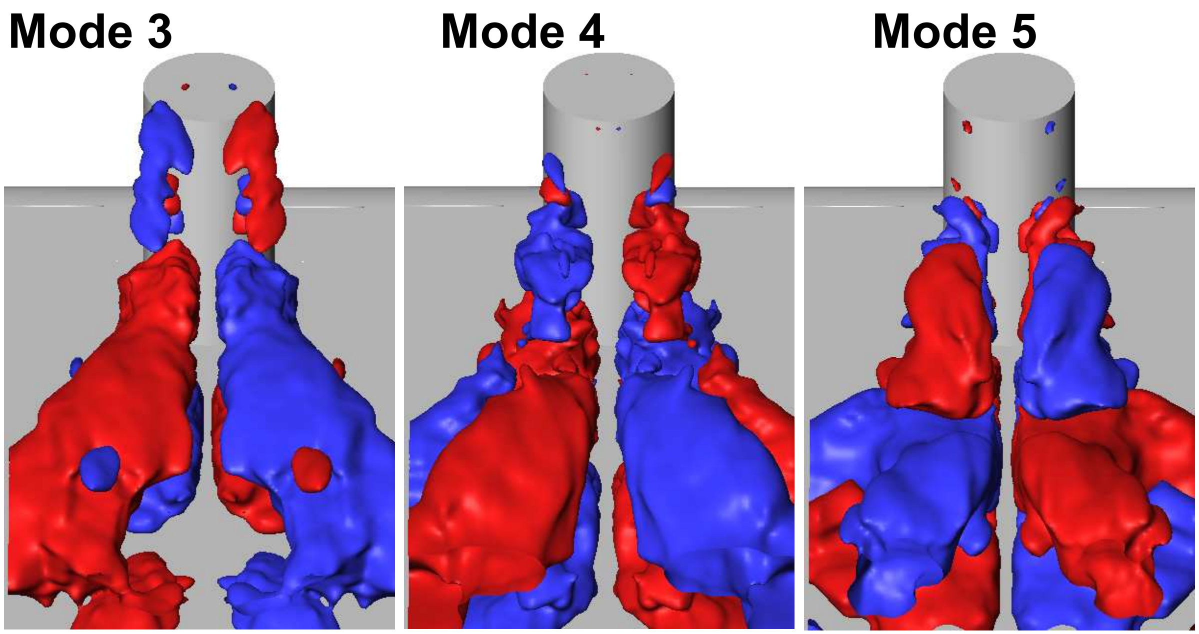
▪ Sub-harmonic - modes (3,4) (5)

- Three modes involved (again).
- Includes the rotational components in the trailing vortices and side tip vortices
- Describes the interaction between the end effects and the harmonics
- Contains two main frequencies





iso-surfaces
$v = \pm 0.18\ U_\infty$
antimetric

Proper Orthogonal Decomposition VII

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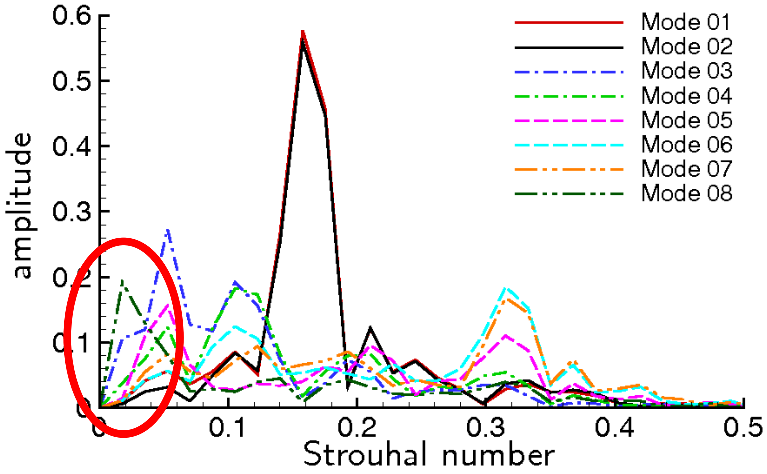
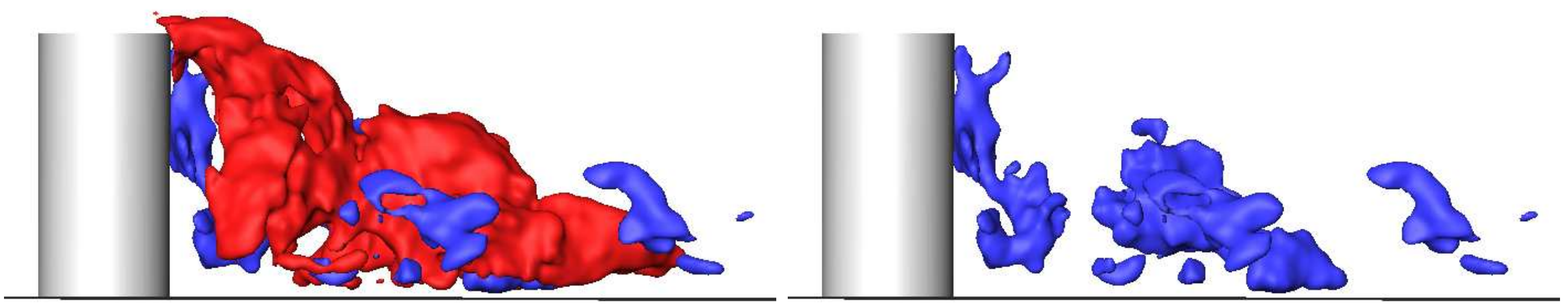
▪ Mode 8



- Dominant at a single frequency (range)
- Mode 3 includes also content of this frequency.
- Describes mainly the „rolling“ structures close to the symmetry plane (time-averaged: recirculation)
- Results from the flow over the free end

iso-surfaces
$w = \pm 0.18\ U_\infty$



Proper Orthogonal Decomposition VIII

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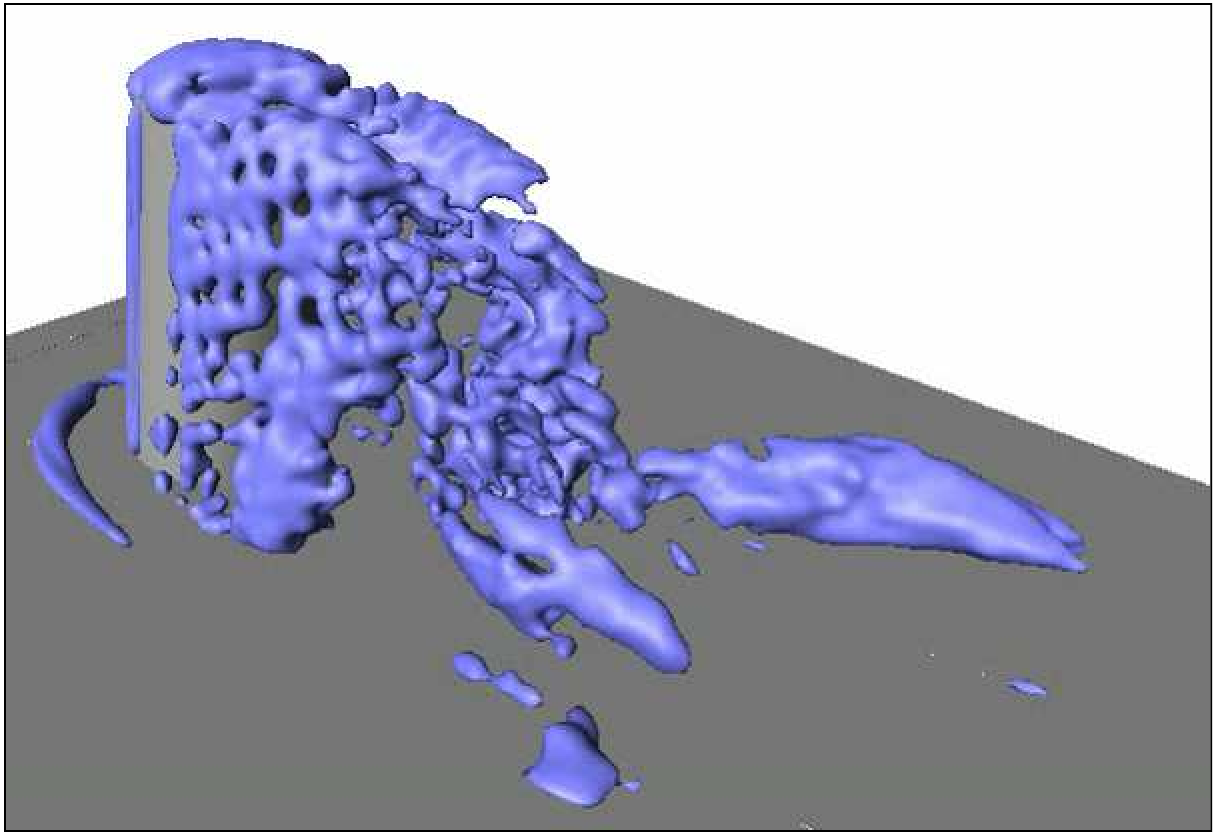
▪ Reconstruction of modes 0,1,2

- Mean Flow and dominant harmonic mode



iso-surfaces
$\lambda_2 = -0.1$

Conclusion

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- **Very good agreement** of experiments and simulation with respect to the **time-averaged flow** proved.
- Topological decomposition of the time-averaged flow valid for simulation and experiments.
- Detected frequencies (Strouhal numbers) from recorded signals, double correlations, etc. reveal that **also good agreement** will be achieved **w.r.t. the unsteady flow** (only statistical variations expected).
- **POD analysis** has been performed **for a large database in 3D**.
- Several **modes** could be **associated with physical phenomena**.
- Strict decomposition of frequencies only achieved for the dominant mode pair.
- Requirements identified for the enhancement of the database (sampling rate and domain size).
- **Database of flow field variables is available** to a lot of co-operations and can be provided to new ones.

ETC 11

Outlook

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- **Continuation of POD**:
  - Comparing **POD of 2D slices** for simulation and experiment.
  - **Frequency separation** in POD time coefficients and POD of reconstructed snapshots for each frequency (MOD).
  - **POD of full computational domain** (1- resampled, 2 - original grid, adaptation for curvilinear grids and multiblock)
  - Enhancement of the database (additional snapshots).
- **Particle Tracking** and S**tructure tracing algorithm** to analysis the unsteady flow.
- **Conditional sampling** instead of phase-averaging to extract coherent structures.
- **Quantitative comparison** of experiment and numerical results based on further double and triple correlations.
- **Combined database** for validation of existing and modelling of new simulation methods and SGS-models for LES (comparison of LES and “coarse” DNS)

Acknowledgements

- Special thanks go to

  - ETC11 committee for *Inviting our work*
  - German Research Foundation (DFG) for *Funding*
  - North German Cooperation of High-Performance Computing for *Computational resources*
  - LSM, University Rostock for the *Experimental field data*
  - ILR, TU Berlin for the *Experimental wall data*

  - All other supporters

You for *your attention* !