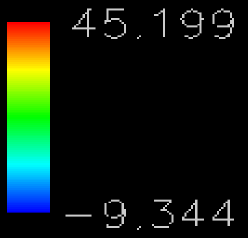
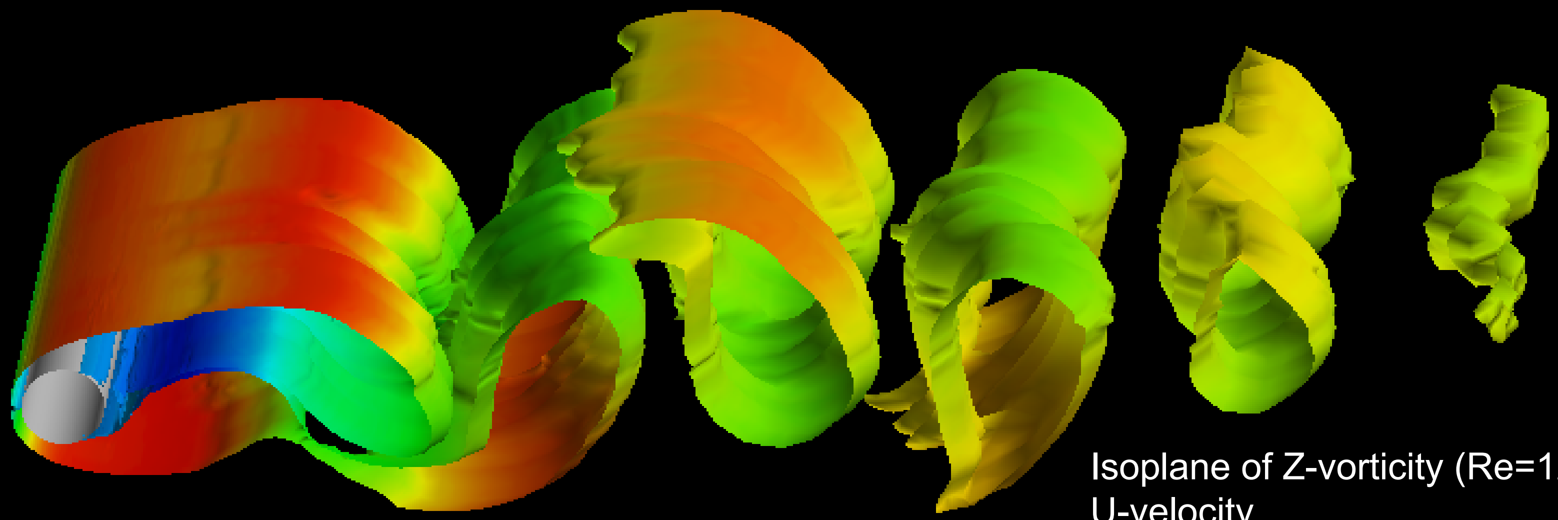
# Vortex shedding in the cylinder wake



Isoplane of Z-vorticity (Re=120) coloured by U-velocity

Comparison between 2d and 3d results

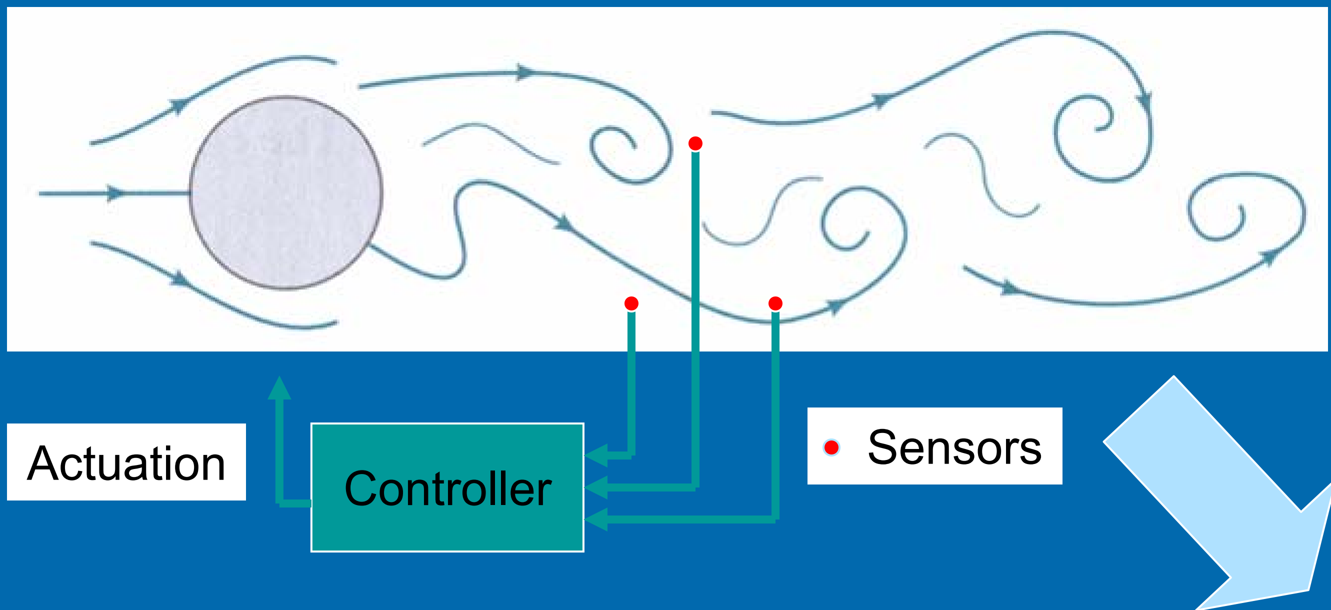
TU Delft
Delft University of Technology

# Acknowledgements

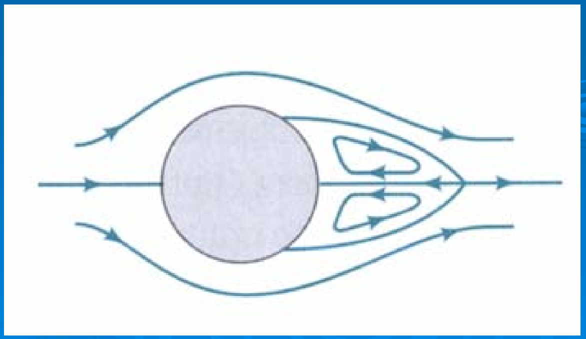
- Dr. Kelly Cohen
- Maj. Jim Forsythe
- Dr. Tom McLaughlin
- Maj. Scott Morton
- Dr. Stefan Siegel

Note the vortices ;-)

# Introduction




The BIG question: will this setup work in three dimensions?



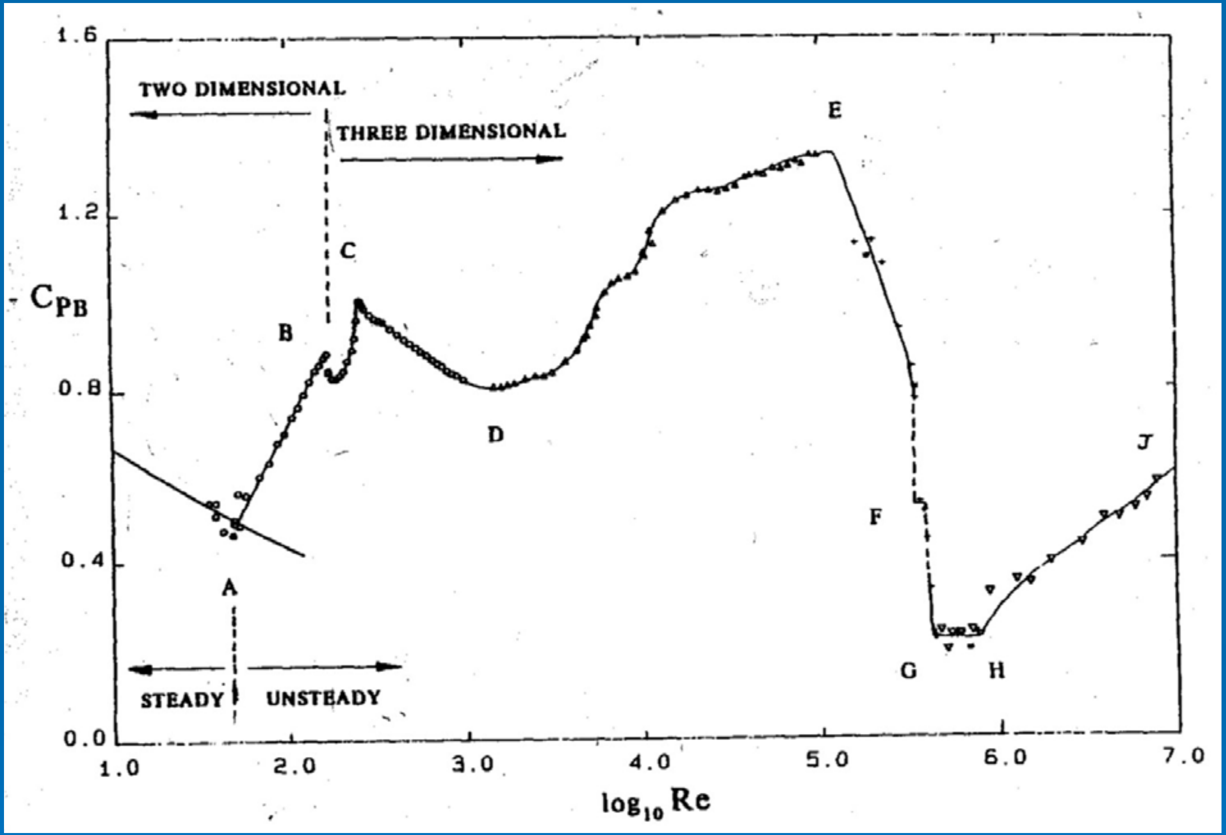
Sketches from: Munson, Young, Okiishi. *Fundamentals of Fluid Mechanics*. p 601.

# Outline

- Background
- Motivation
- Research objective
- Literature survey
- CFD Computations (Results)
- POD analysis (Results)
- Suggestions / Recommendations

# Background

## Vortex shedding regimes




**-A: laminar steady regime (Re<49)**

**A-B: laminar vortex shedding (49<Re<190)**

**B-C: wake transition regime (190<Re<260)**

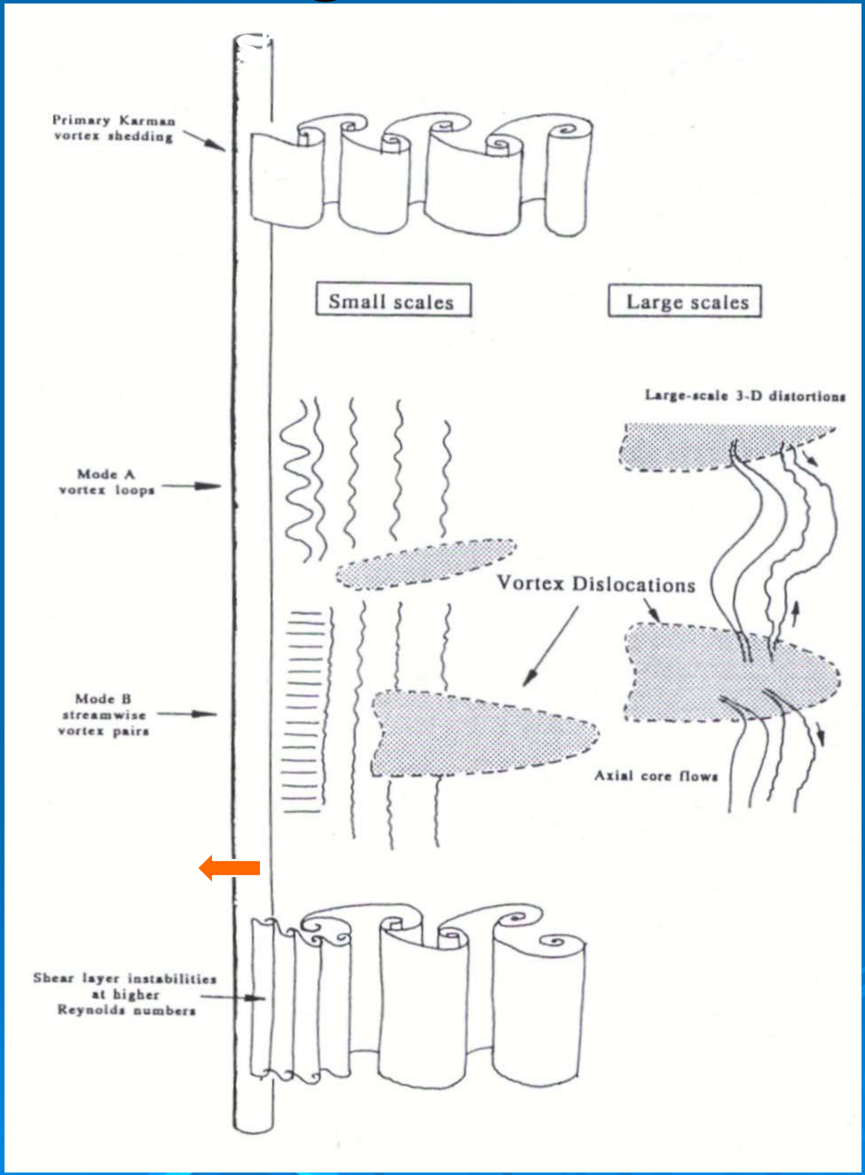
**C-D: fine scale regime (260<Re<1000)**

Pictures from Williamson, 1996

# Background

Vortex shedding regimes

(cont)



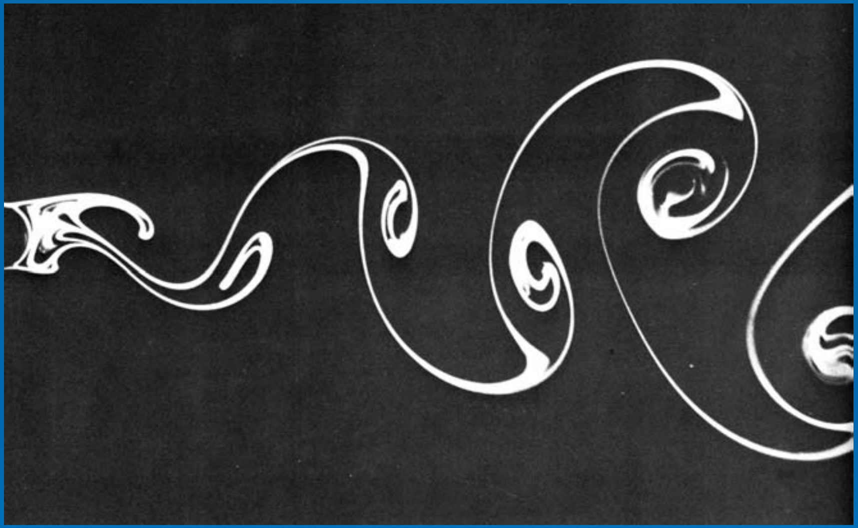

Pictures from Williamson, 1996

# Background (cont)

Laminar vortex shedding (Re=49-190)

- Flow behaves (almost) 2 dimensional in spanwise direction, if care is taken to manipulate the boundary conditions

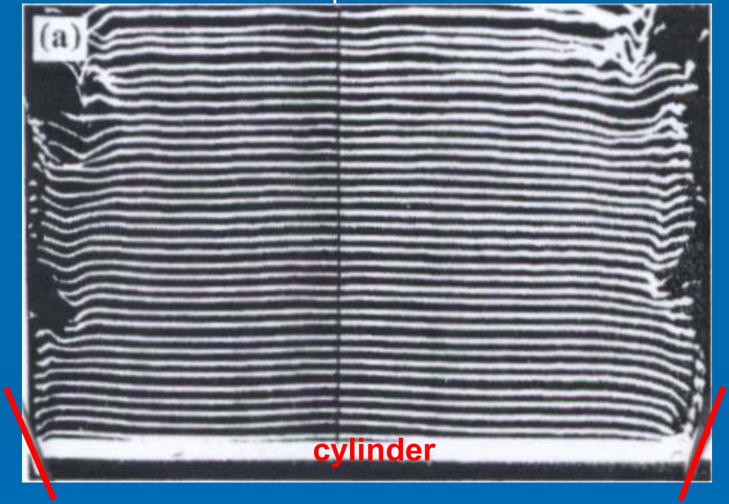
Side view



Von Karman vortex street; Re=140

Van Dyke, 1982

Top view




Parallel vortex shedding, using angled endplates

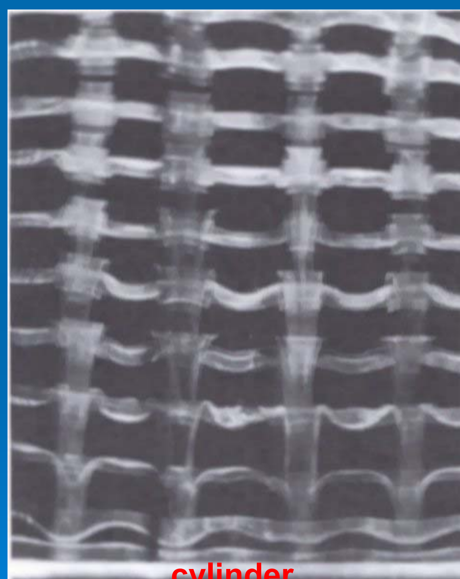
Williamson, 1988

# Background (cont)

Wake transition (Re=190-260)

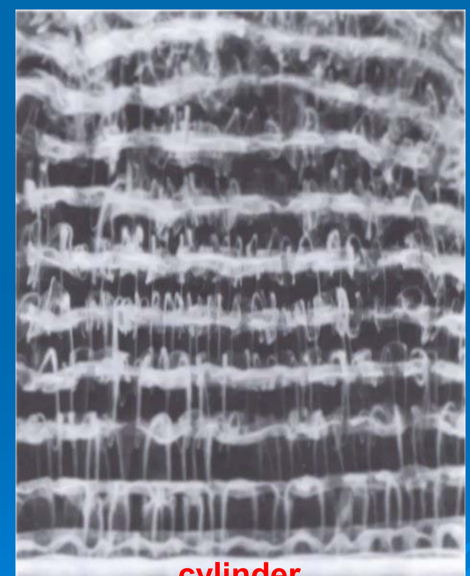
- Above Re=190 the wake becomes (really) 3 dimensional (the von Karman vortex street still persists)
- Large (mode A) and fine (mode B) scales due to shift in phase or frequency difference in spanwise direction

Top view




Mode A; Re=180 and above

Top view




Mode B; Re=230 and above

Pictures from Williamson, 1992

# Motivation

- Compare 3D with 2D cylinder simulations in order to see if the the control strategy to suppress the 2D flow, will also work in three dimensions.

# Research objective

- The control strategy is based upon controlling the POD modes of the flow. So the main focus is on the comparison of the 2D and 3D POD modes.

# Literature survey

- Wake flow of a cylinder at Re=100 and above exhibits self-excited oscillations, which are sustained by the flow itself → absolute instability

- The period of oscillations is determined by the St number, which is a continuous function of the Re number

  (good check case for numerical results)

Sources: Gillies, 1995/97; Blevins, 1990; Williamson 1996

# Literature survey

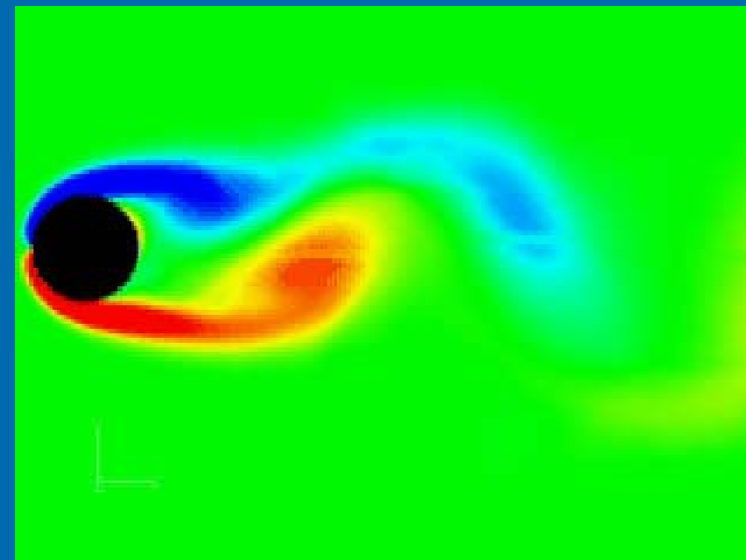
Forced flow is characterized by two different regimes:

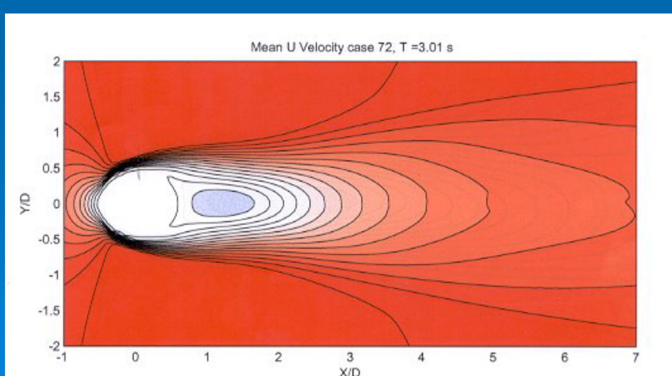
- non lock-in: Flow (structure + temporal behavior) is indepent of fn and fa (natural, applied freq.)
- lock-in: Flow is dependent of relationship between fa and fn. Lock in depends on fa/fn and amplitude of forcing

Sources: Gillies, 1995/97; Blevins, 1990; Williamson 1996

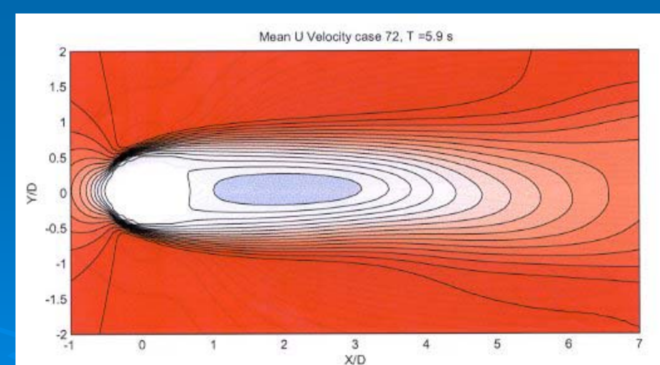
# Literature survey

- The formation length gives an indication of the drag (def.: length from reference point till maximum velocity fluctuation)






→




Courtesy: dr. S. Siegel

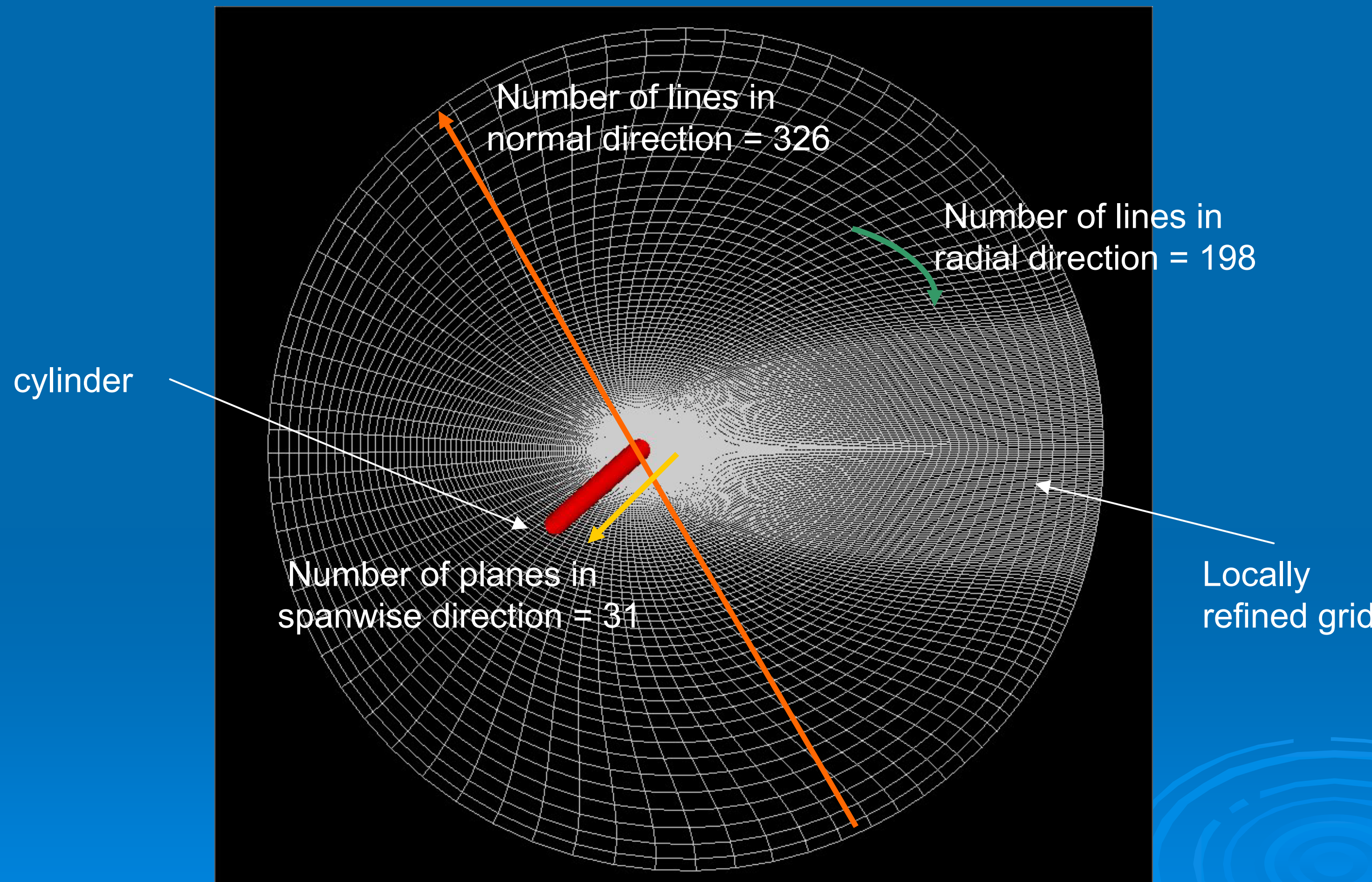
# CFD Computations

## Method CFD

- Cobalt as flow solver
  - Finite Volume, cell-centered, 2nd order spatial and temporal (5 Newton subiter.)
- Structured grid (number of Nodes=990388; 952560 cells)
- Computational domain
  - $-17d<x<21d$; $-19d<y<19d$; $0<z<96d$
- Computational time step: $\Delta t\ U_\infty / d = 0.05$
- About 130 time steps per shedding cycle

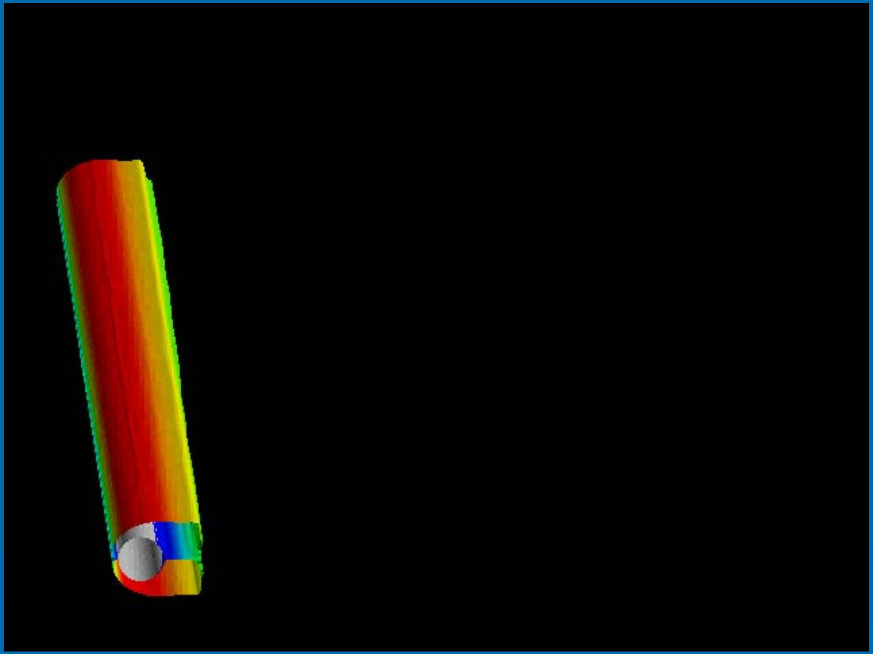
# CFD Computations

## Computational grid (3D)



# !But first a cool movie!

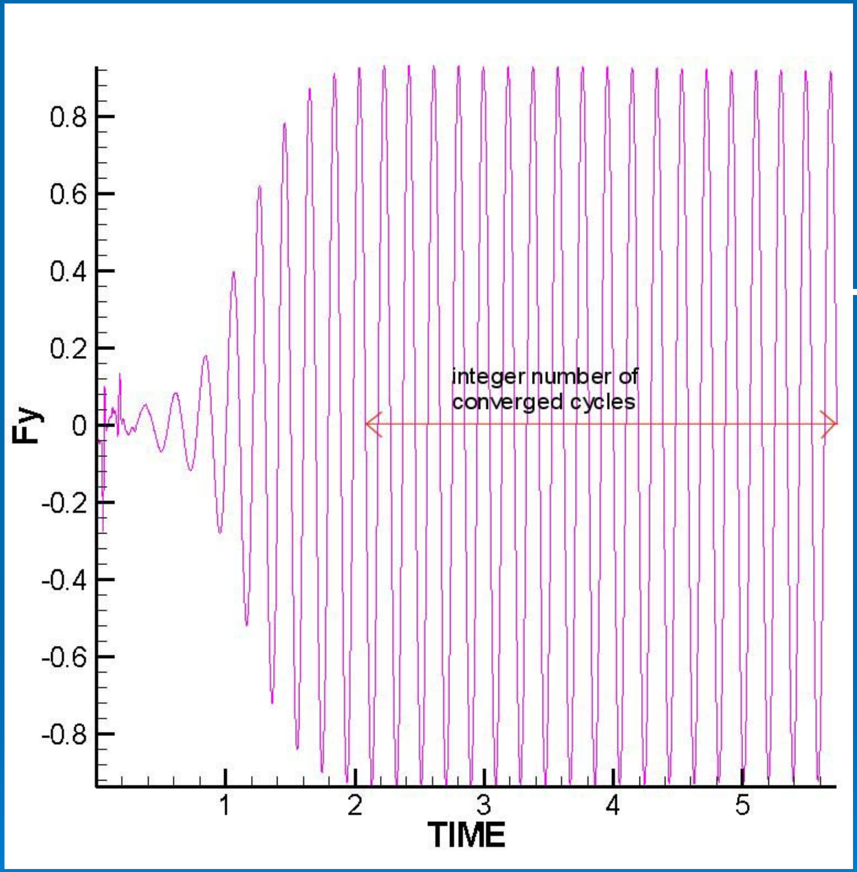
Isoplanes of Z-vorticity colored by U-Velocity



Unforced flow field, Re=100

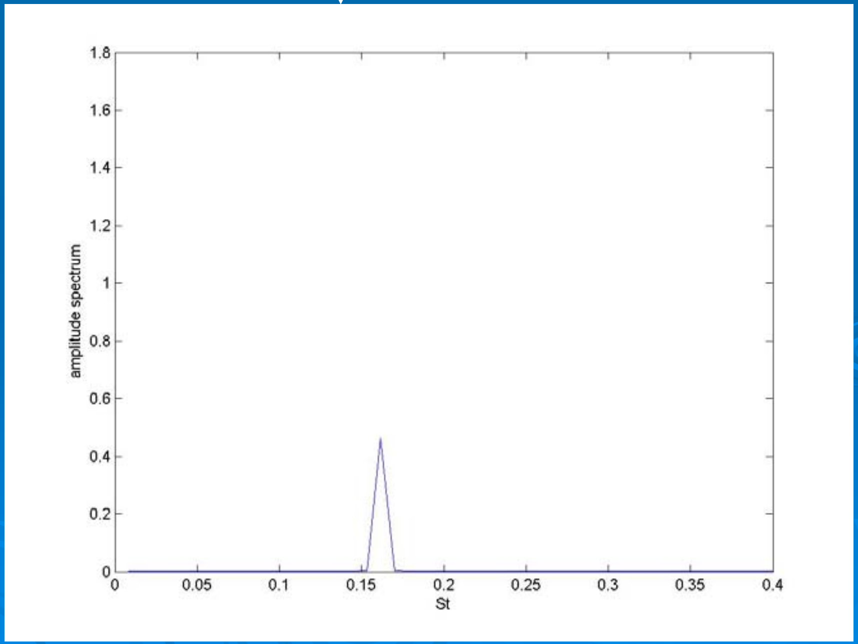
# CFD Computations (cont)

Method for determining the Strouhal number




This method is not accurate to this specific case

FFT analysis




M=0.1; Re=100

# CFD Computations (cont)

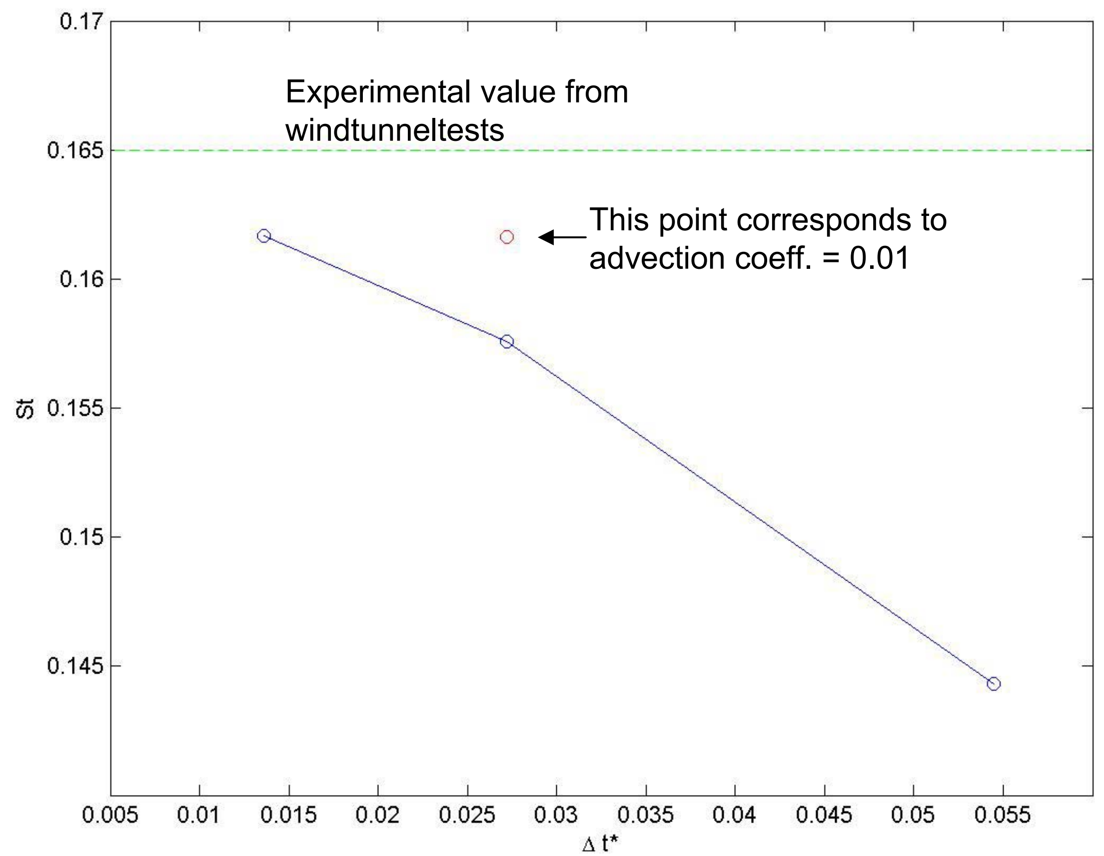
## Method for determining the Strouhal number (cont)

- FFT is not accurate here because it is very sensitive to small changes in the amount of data

- A simple approach works better: Count number of cycles based on the peaks of the normal force and divide by time to estimate the shedding freq.

# CFD computations

## Time step study ! 2D !



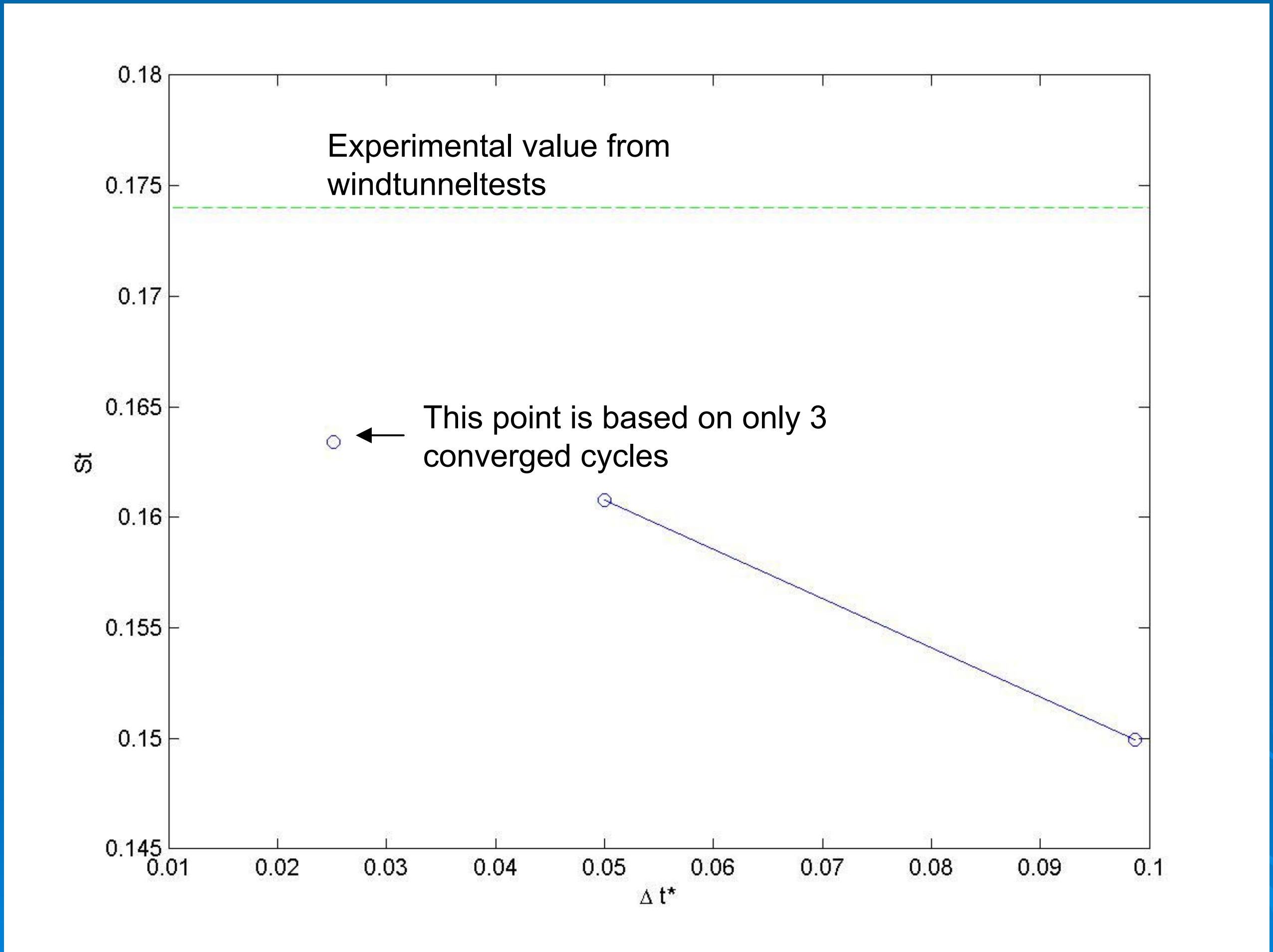

Advection coeff. = 0.02

Diffusion coeff. = 0.01

M=0.1; Re=100

# CFD Computations (cont)

Time step study 3D



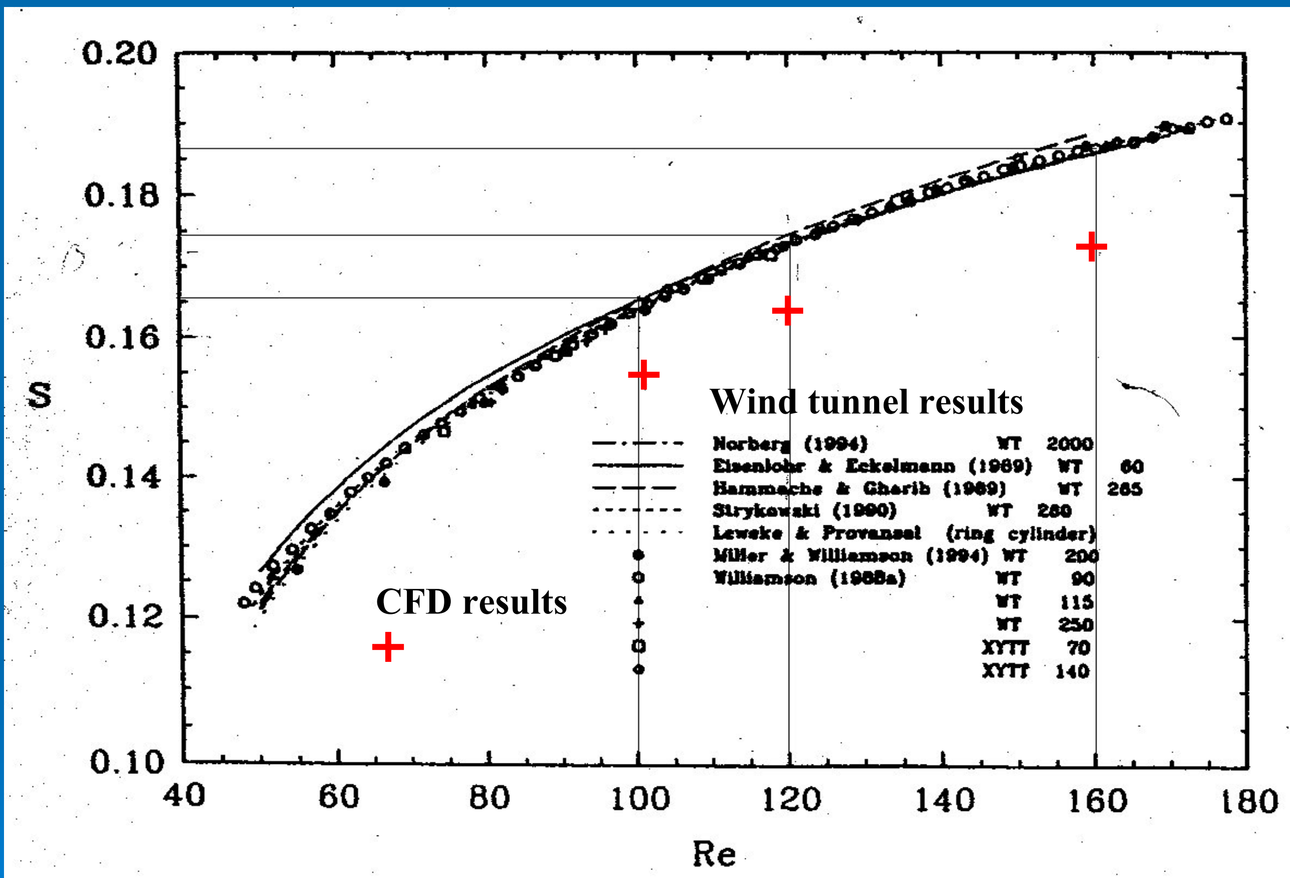

Advection coeff. = 0.02

Diffusion coeff. = 0.01

M=0.1; Re=120

# CFD Computations (cont)

## Comparison with experiments (3D)




Williamson, 1996

Results obtained by counting cycles of normal force

CFD Data

| M | Re | St | Error |
|---|---|---|---|
| 0.1 | 100 | 0.15 | 9.1 % |
| 0.1 | 120 | 0.16 | 8.6 % |
| 0.1 | 160 | 0.17 | 8.1 % |

# CFD Computations (cont)

Comparison with experiments (3D), Some Remarks

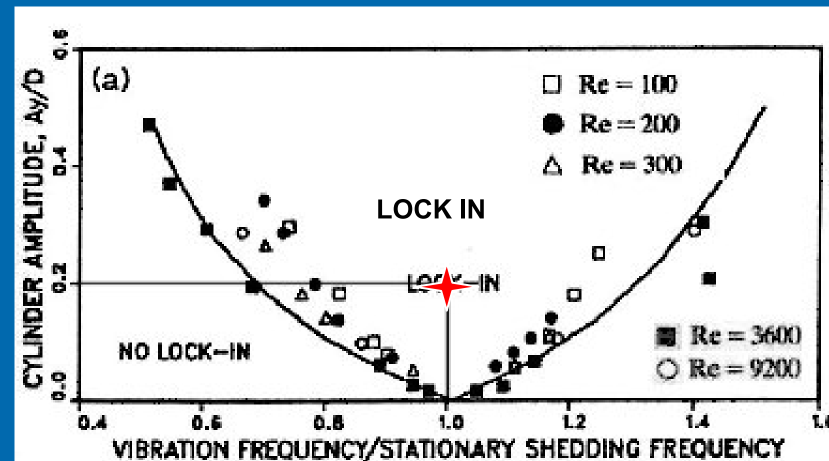
- Most probably the 3D results will improve when a smaller time step is used (this can be seen from the 2D time step study)
- The cheapest solution is to adjust the advection, diffusion coefficients which can also improve the results
- The Strouhal number generally increases as the cylinder aspect ratio L/d increases (Friehe 1989) → maybe the resolution in spanwise direction is not sufficient

# CFD Computations (cont)

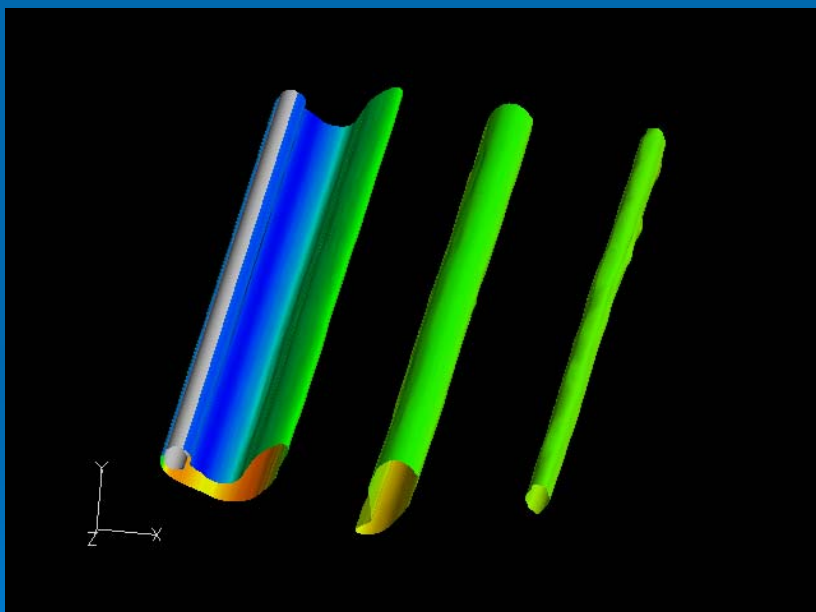
## Comparison with experiments (cont)

- Phase lock in:

Forced cylinder motion with freq. at the vortex shedding freq. (20% amplitude)

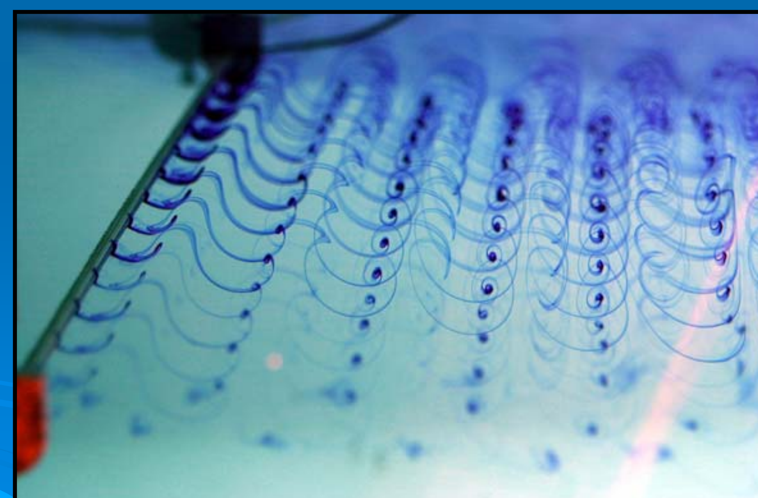



Blevins, 1990



Sinosoidal forcing

CFD Result, Re=100



Water tunnel; courtesy dr. Siegel

# CFD Computations (cont)

Discussion results

- Time step study shows that the St-number converges to the right value
- Results of CFD runs are a bit lower compared to experimental data from windtunnel tests
- There is an trade off between perfect results and computation time, i.e. the model must be good enough for the control model and give results in reasonable time

- From the lock in run it can be seen that CFD captures the lock in phenomenon

# POD analysis

## Description of POD

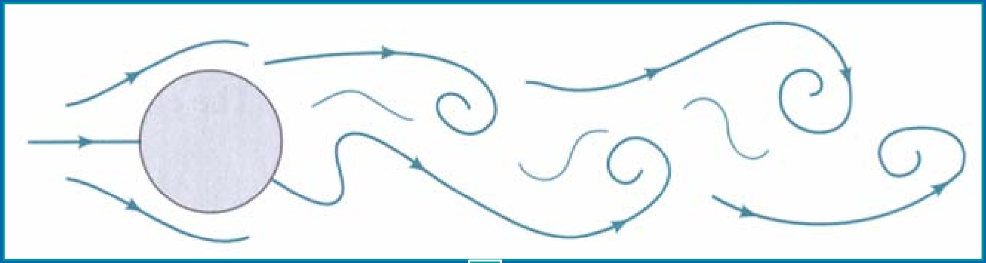
- Experimentally, wake flows look to be dominated by a few large spatial structures → this motivates to describe the flow by its most dominant PO modes
- POD reveals coherent spatial structures within the data, the decomposition is optimal in the sense that it sorts the spatial modes with respect to their energy content
- The fluid velocity field is represented by a superposition of the empirical spatial (PO) modes multiplied by time-dependent coefficients:

$$u(x,t) \approx \sum_{k=1}^{N} a_k(t) \cdot \phi_k(x)$$

- It should be noted that in the present configuration only the POD modes of the U-Velocity are considered. (modes 1&2 of the U-Velocity are controlled in the present setup)

# POD analysis (cont)

Description of POD (cont)



POD
(Proper
Orthogonal
Decomposition)

Mode shapes are obtained from converged cycles

N Temporal Mode Amplitudes
$a_1(t)$
$a_2(t)$
…
$a_N(t)$

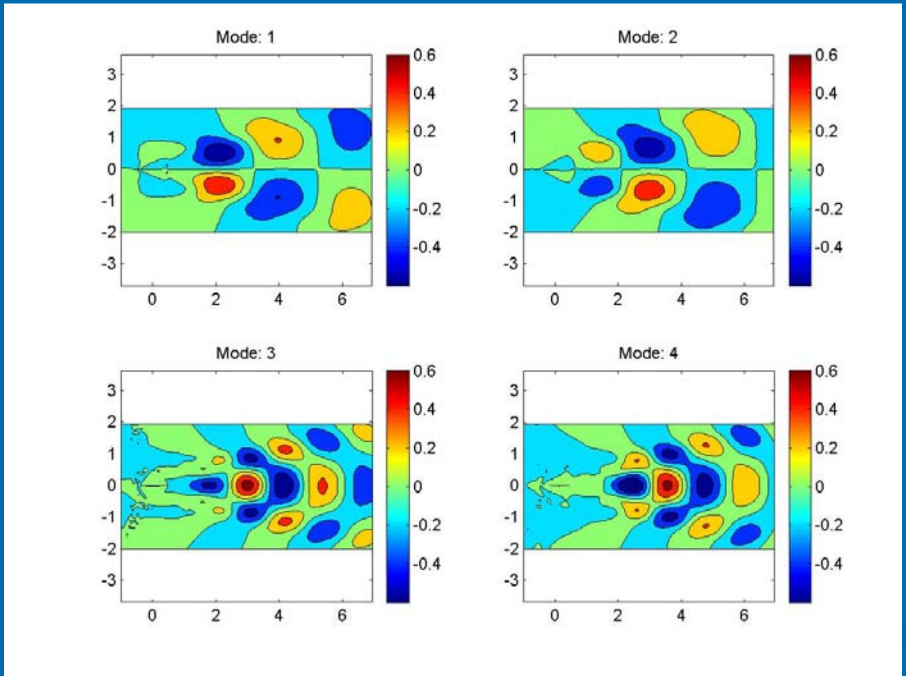
Representation of U-Velocity

$$u(x,t) \approx \sum_{k=1}^{N} a_k(t) \cdot \phi_k(x)$$

N Mode Shapes
$\varphi_1(x,y)$
$\varphi_2(x,y)$
....
$\varphi_N(x,y)$

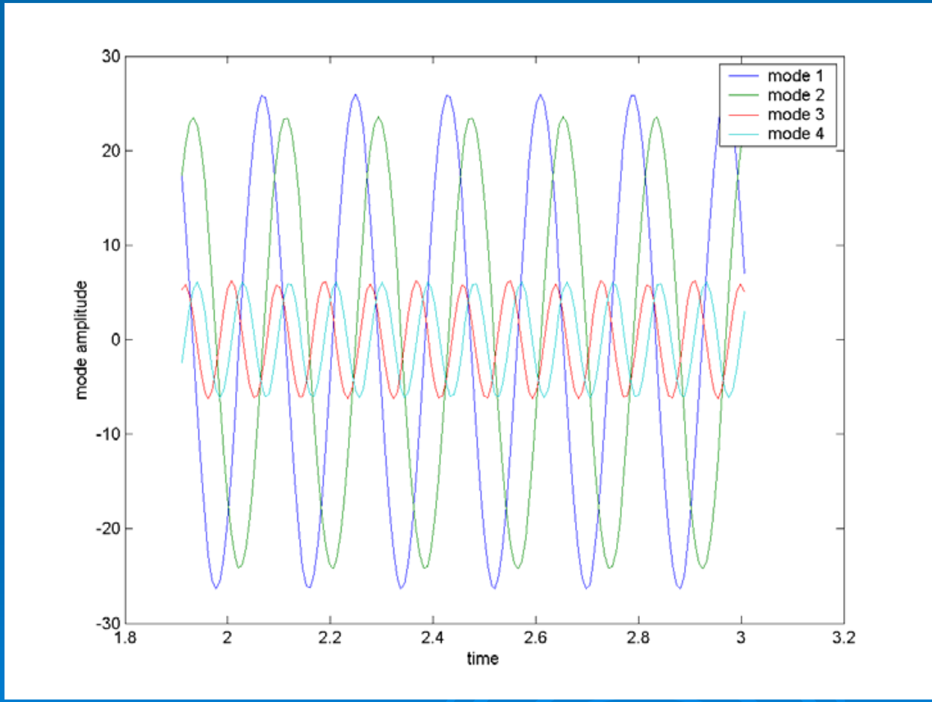
# POD analysis (cont)

2D Results




Mode Shapes

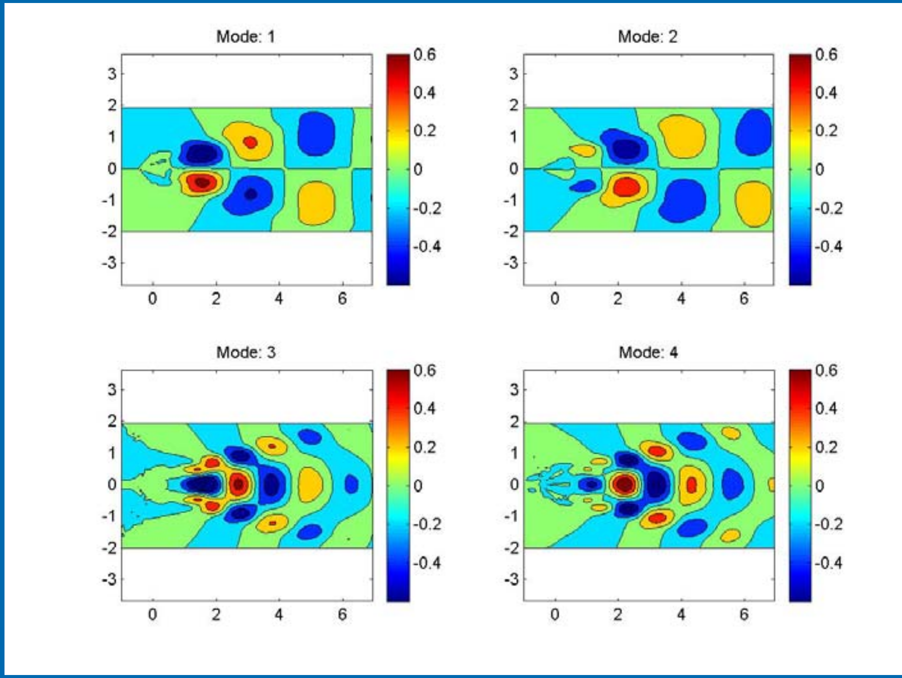
Mode Amplitudes




POD analyis of U-Velocity; **Re=100**

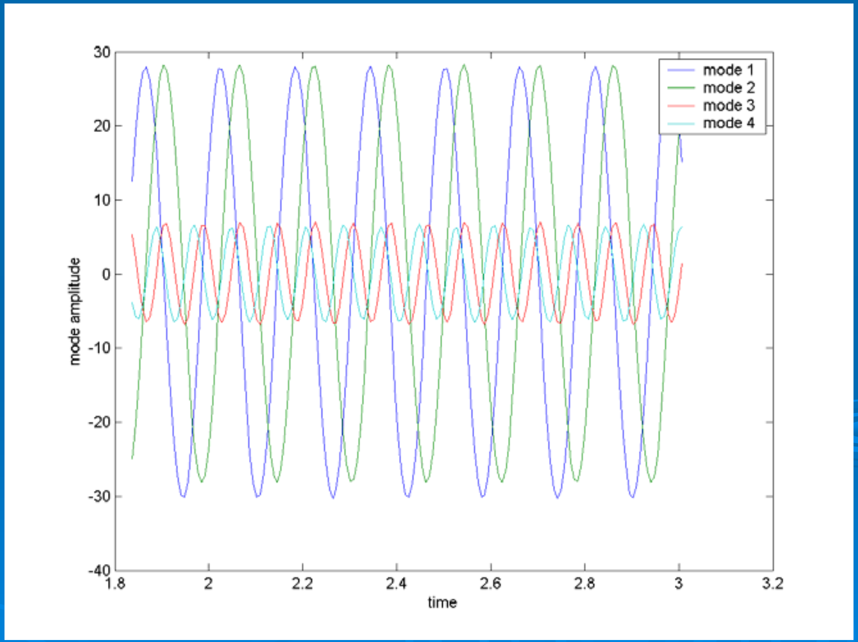
# POD analysis (cont)

2D Results




Mode Shapes

Mode Amplitudes



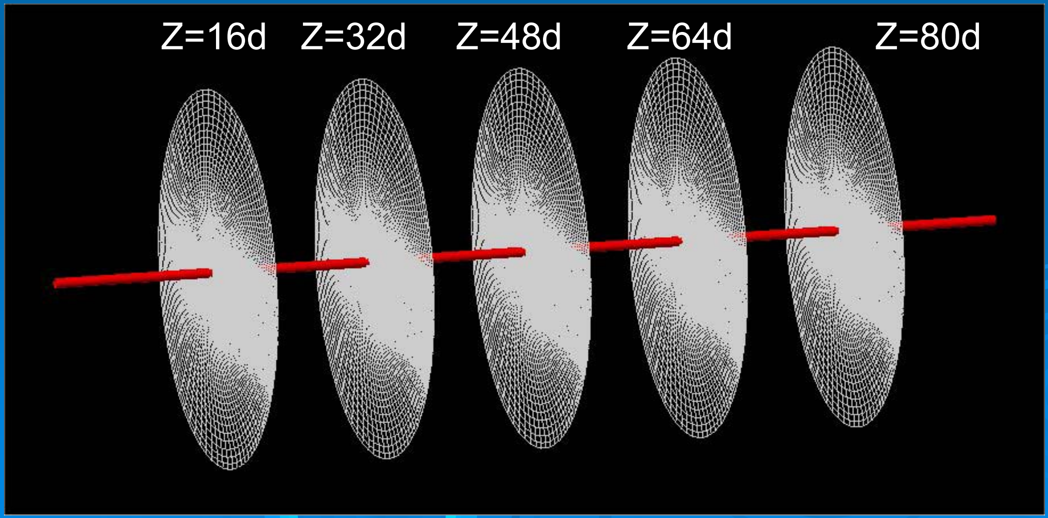

POD analyis of U-Velocity; **Re=160**

# POD analysis (cont)

3D Results

- POD is performed on five planes in spanwise direction of the cylinder (multiples of 16d)
- The decomposition is based upon 159 snapshots for the 2D- and, 61 snapshots for the 3D case
- By sweeping in spanwise direction the difference between the several stations can be seen

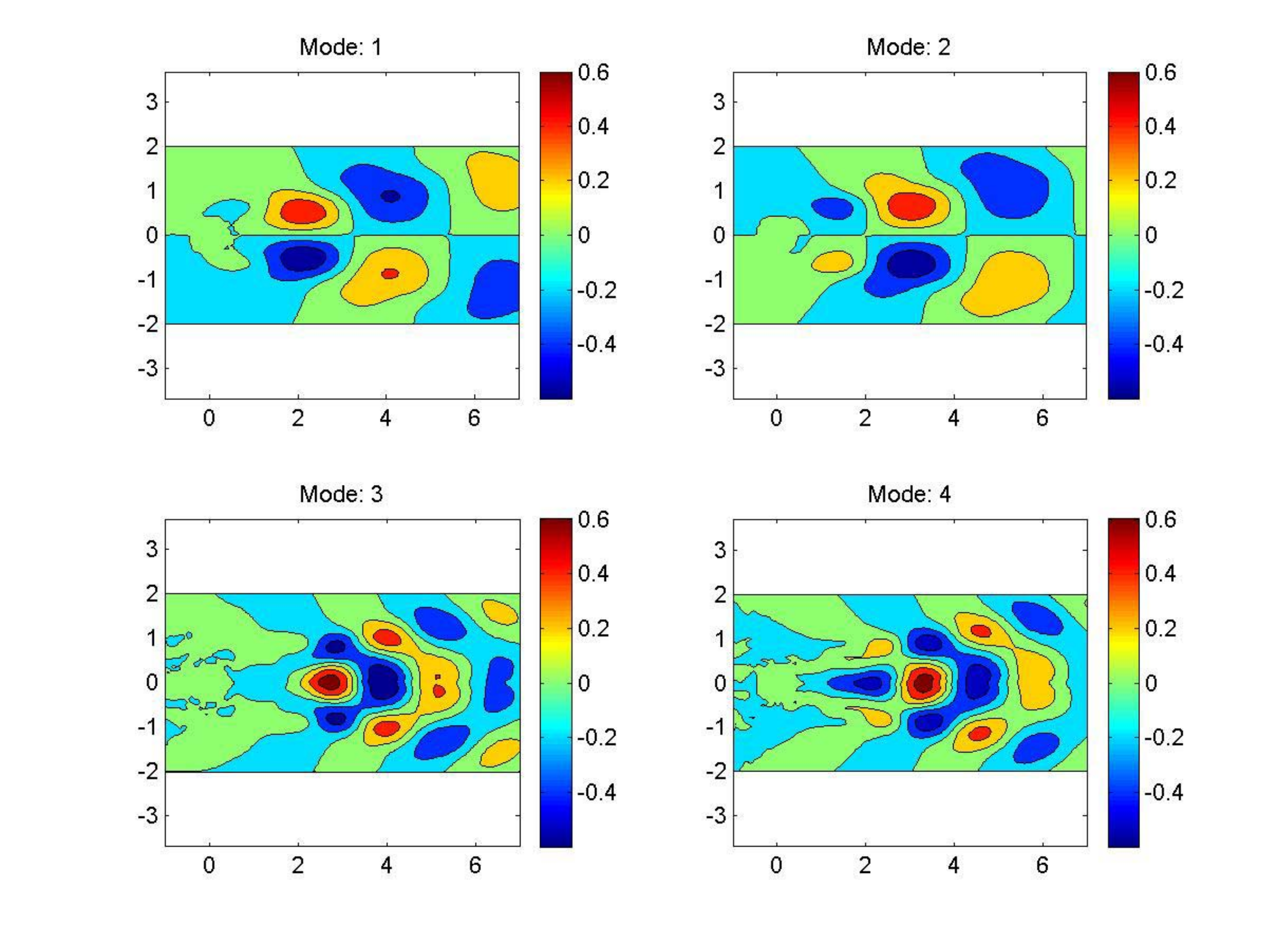
5 stations in spanwise direction



# POD analysis (cont)

3D Results

station 1

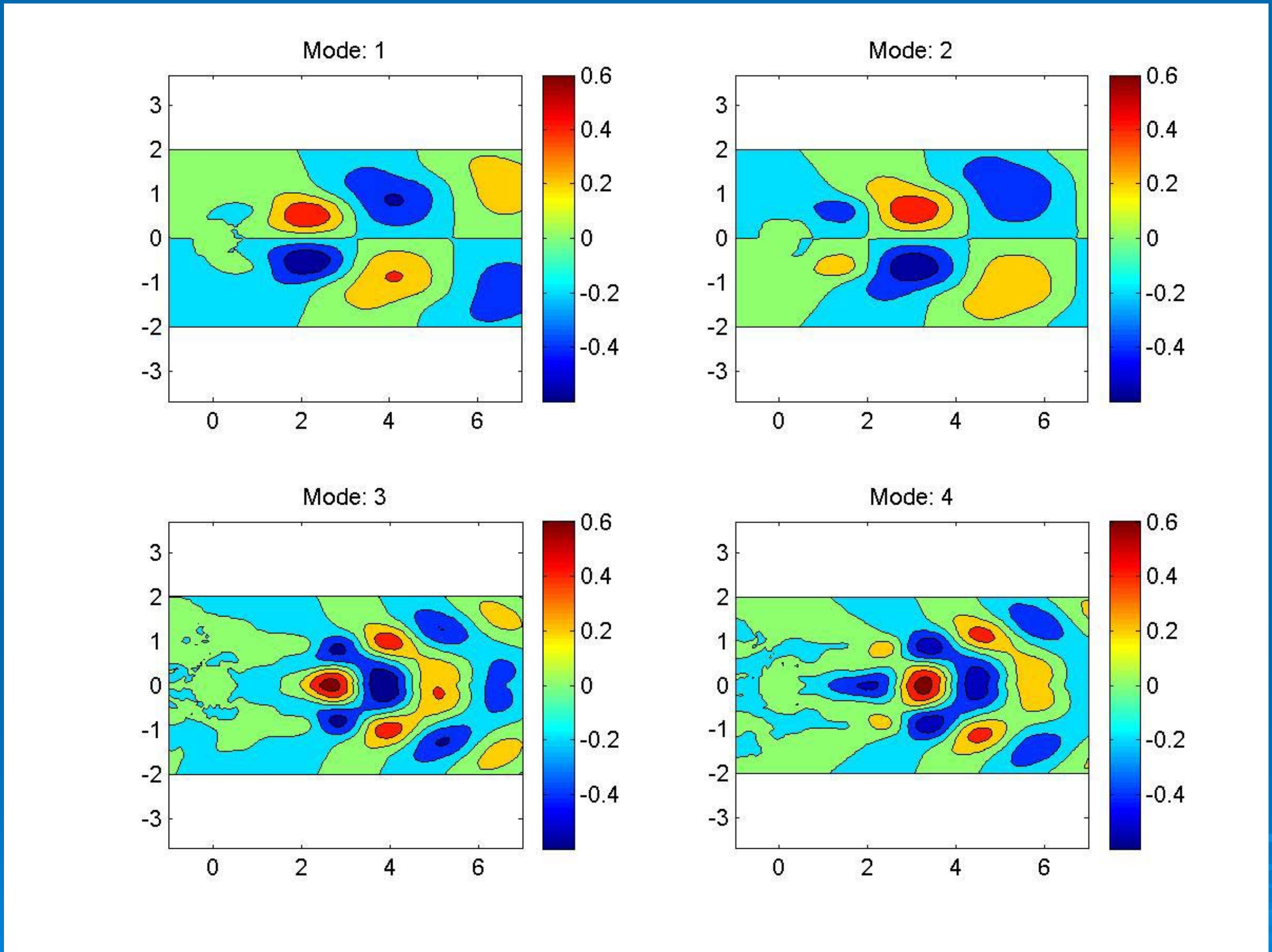



POD analyis of U-Velocity; **Re=100**

# POD analysis (cont)

3D Results

station 2

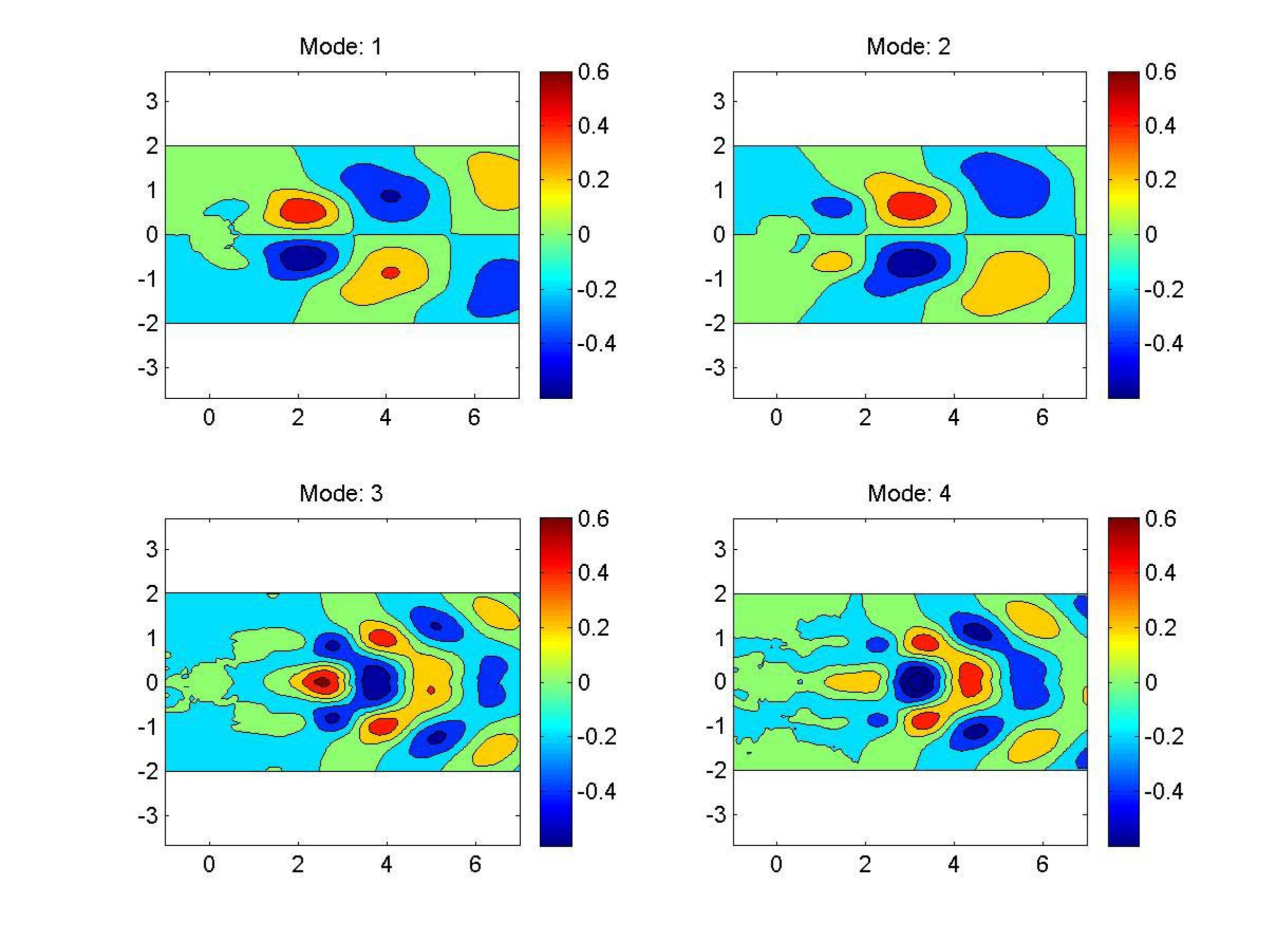



POD analyis of U-Velocity; **Re=100**

# POD analysis (cont)

3D Results

station 3

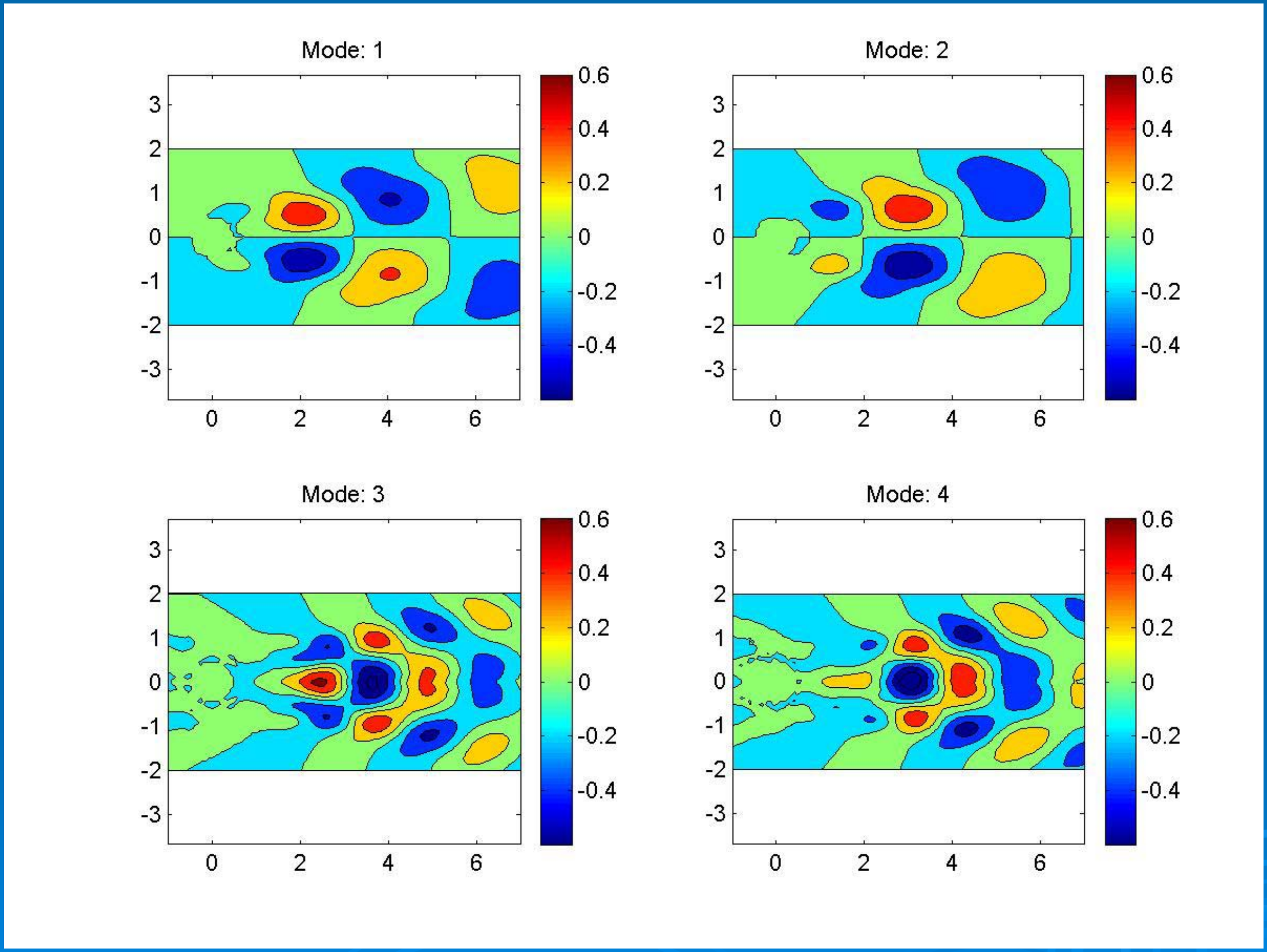



POD analyis of U-Velocity; **Re=100**

# POD analysis (cont)

3D Results

station 4

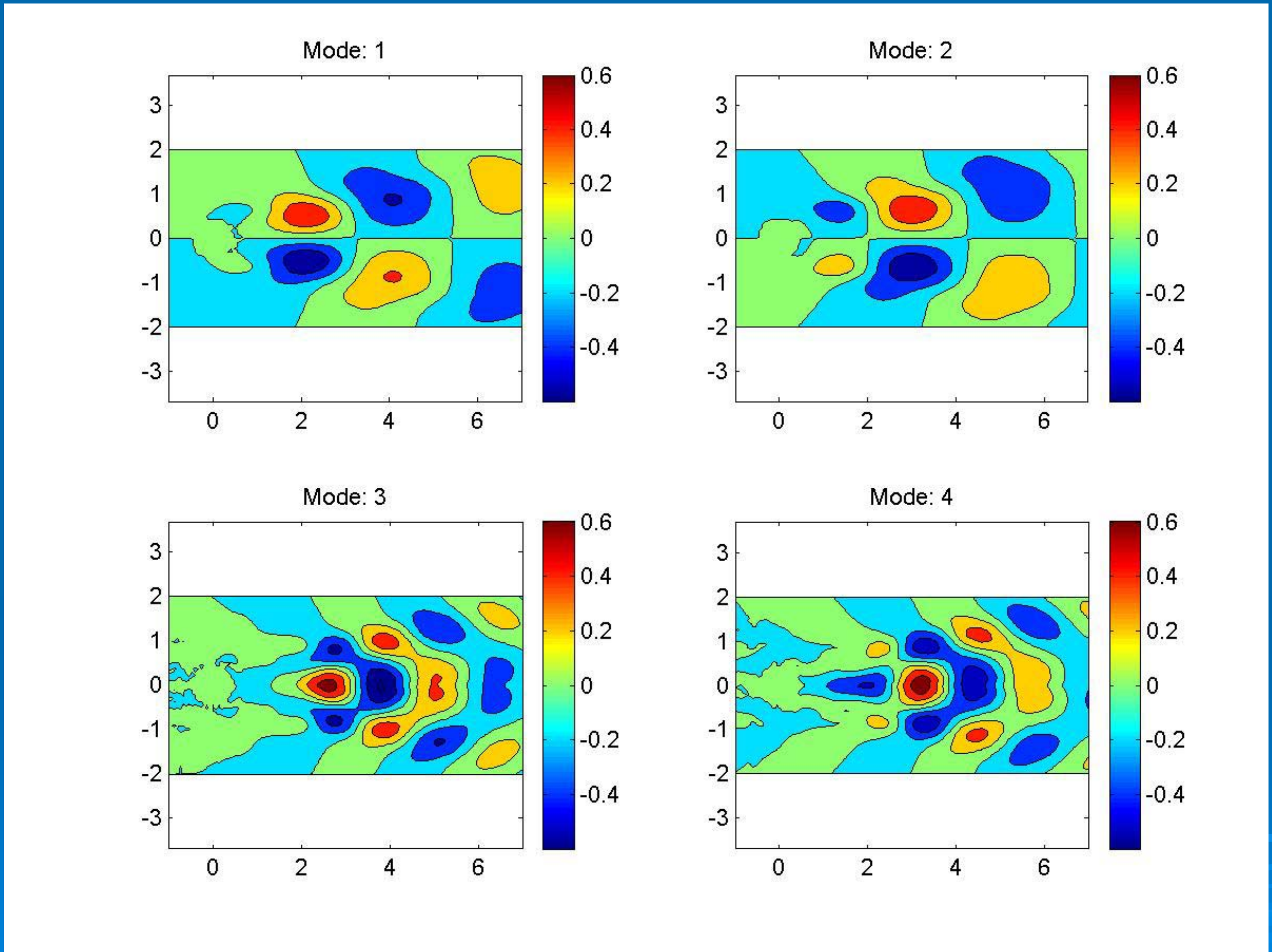



POD analyis of U-Velocity; **Re=100**

# POD analysis (cont)

3D Results

station 5




POD analyis of U-Velocity; **Re=100**

# POD analysis (cont)

3D Results, Discussion

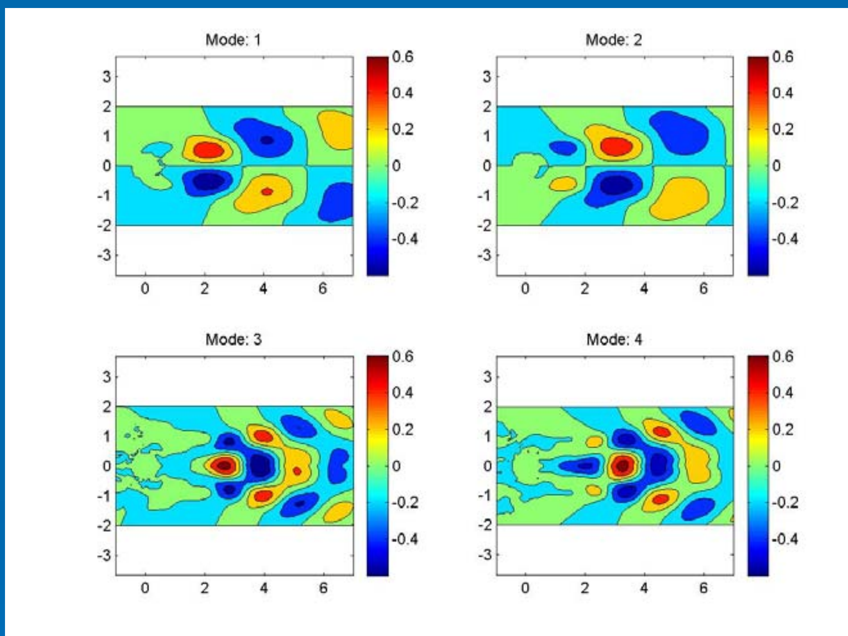
- The POD modes in spanwise direction show only small differences
- Probably the differences become smaller when using more snapshots for 3D case

- From this it can be argued that the flow on the average behaves two dimensional

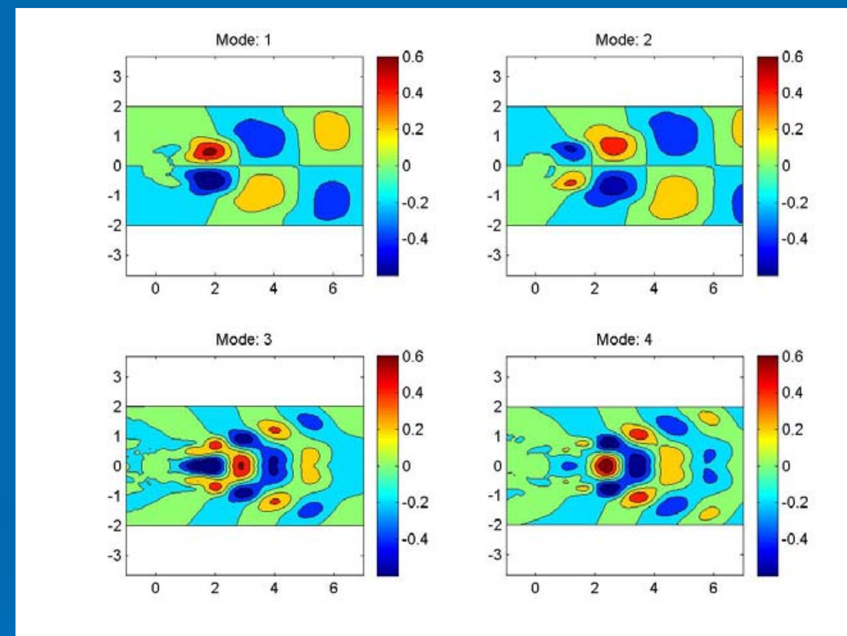
# POD analysis (cont)

3D Results, comparison of Re=100 and Re=160

Re=100, Z=32




Re=160, Z=32



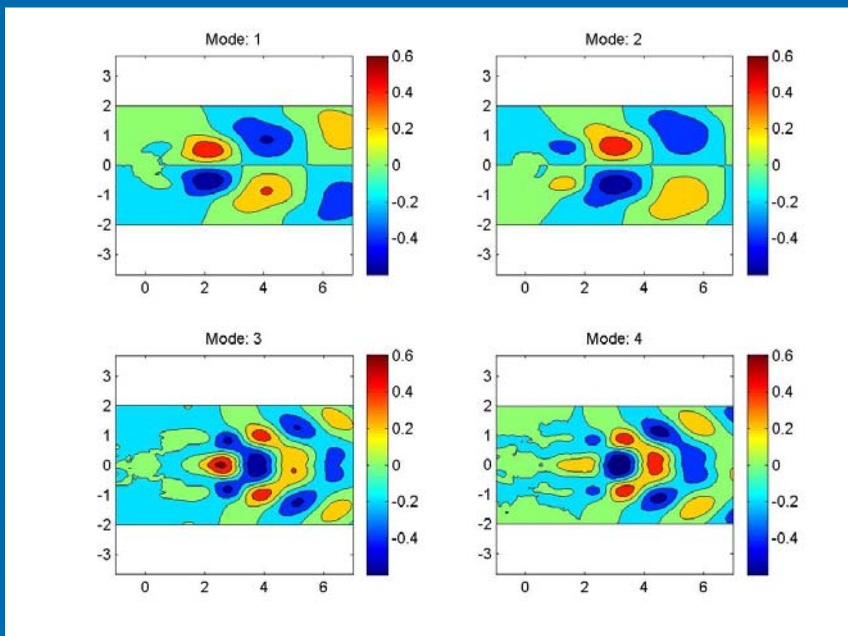

→There is little difference between the two Reynolds numbers

POD analyis of U-Velocity; **Re=100 / 160**

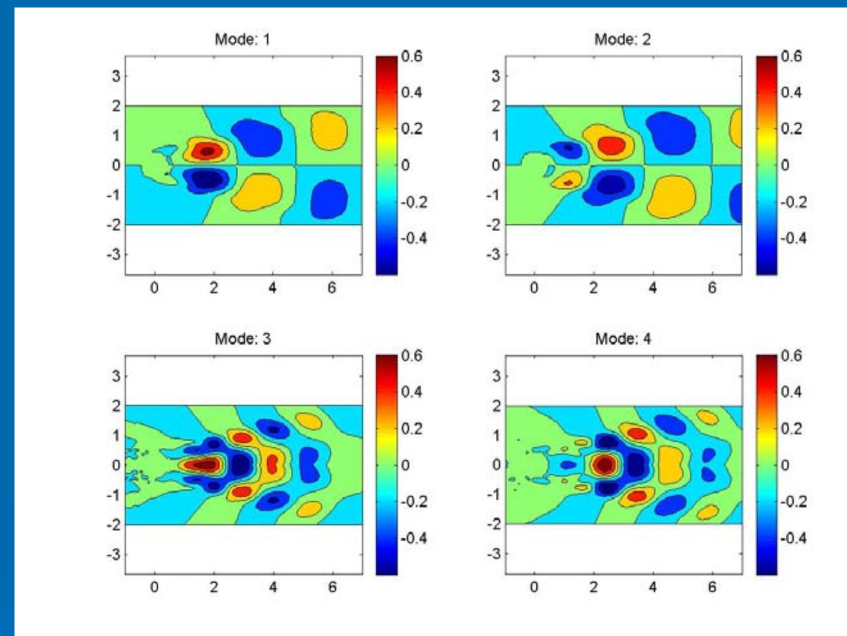
# POD analysis (cont)

3D Results, comparison of Re=100 and Re=160

Re=100, Z=48




Re=160, Z=48



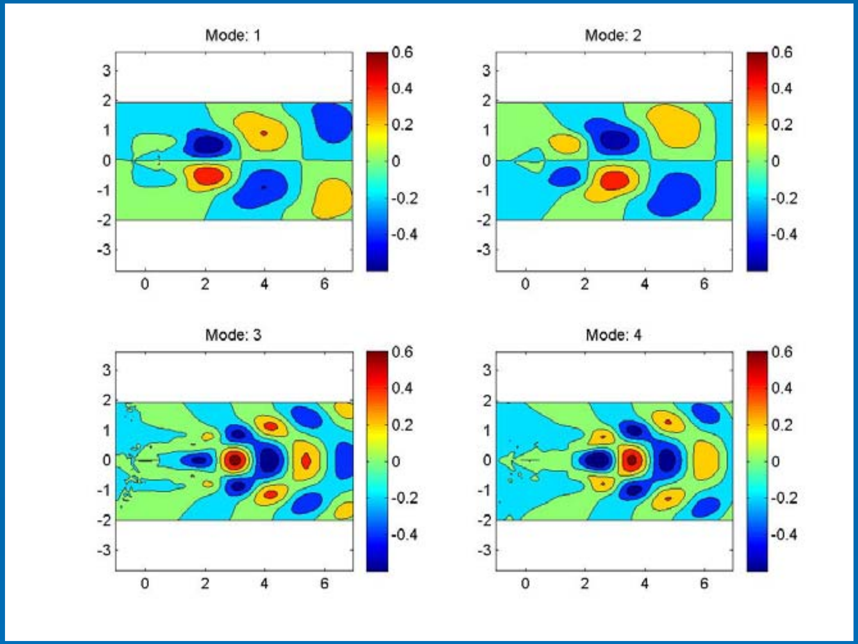

→There is little difference between the two Reynolds numbers

POD analyis of U-Velocity; **Re=100 / 160**

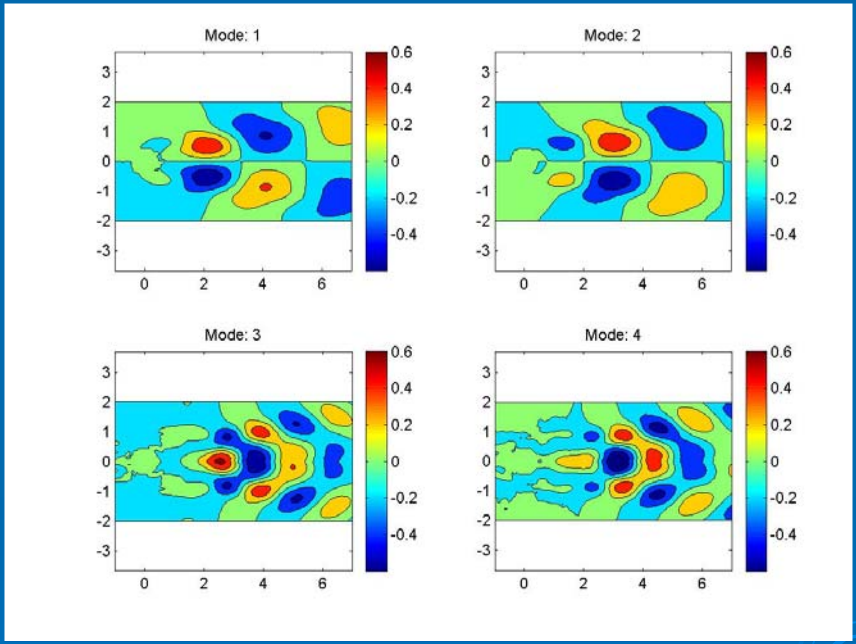
# POD analysis (cont)

3D Results compared to 2D results

Re=100, 2D




Re=100, Z=48

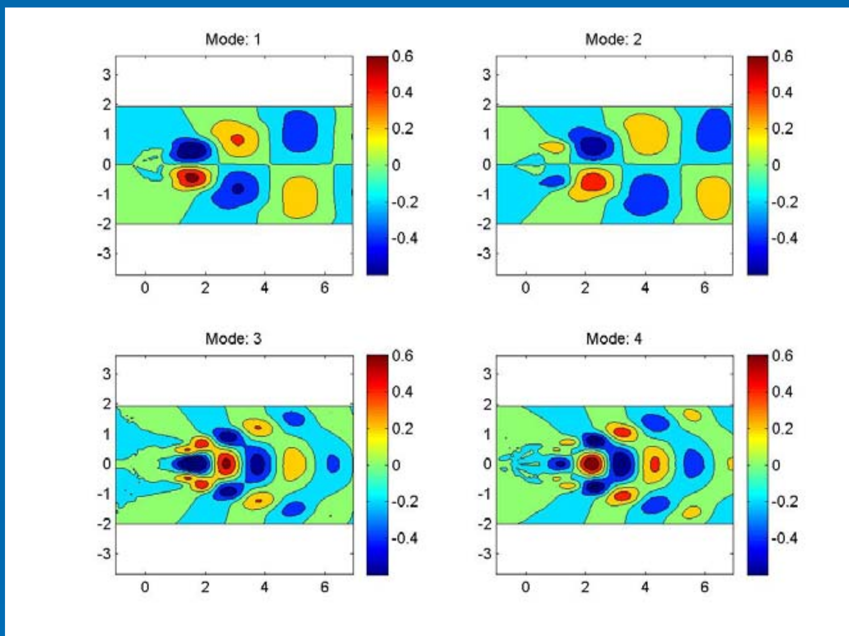



POD analyis of U-Velocity; **Re=100**

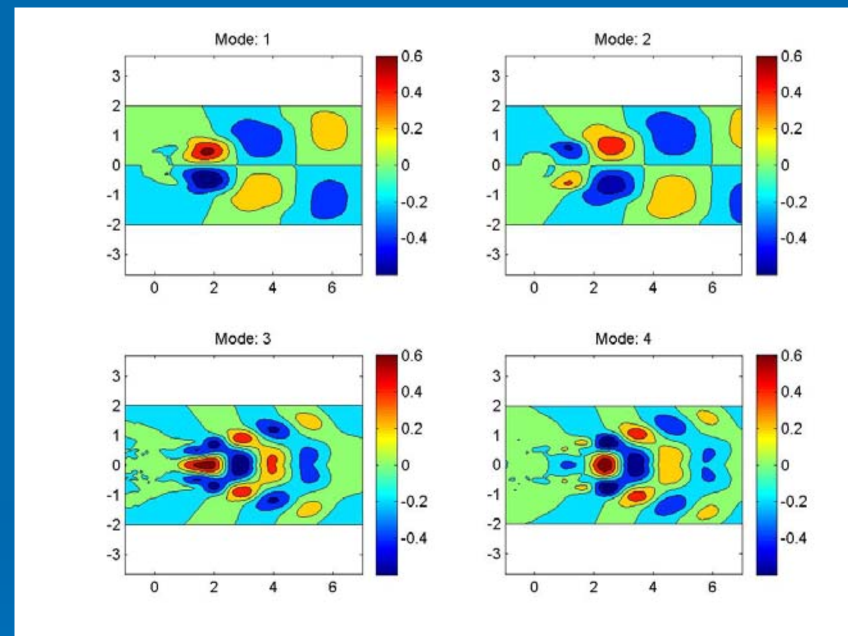
# POD analysis (cont)

3D Results compared to 2D results

Re=160, 2D




Re=160, Z=48




POD analyis of U-Velocity; **Re=160**

# POD analysis (cont)

3D Results compared to 2D results, Discussion

- The 3D- and 2D POD modes show similar behavior
- This is in agreement with the observations of Williamson's survey paper, who concluded from experiments that there is a 2D and 3D regime
- The first four modes contain 98% of the mean energy of the flow field → Most probable the controller will also work in three dimensions (if the controller does not excite more modes)

# Recommendations

Future work

- A grid sensitivity study should be performed besides the time step study
- Shrink the cylinder in spanwise direction to L/d~=4 → more resolution and still a 3D flowfield (Barkley & Henderson, 1996)
- A more thorough study of POD should be performed, to come up with the best possible description of the flow field (steady-transient-controlled)
- A strong criterion for the error should be defined, to compare different POD data sets

# Questions?