Assessment of Turbulence Modeling for Compressible Flow Around Stationary and Oscillating Cylinders

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by

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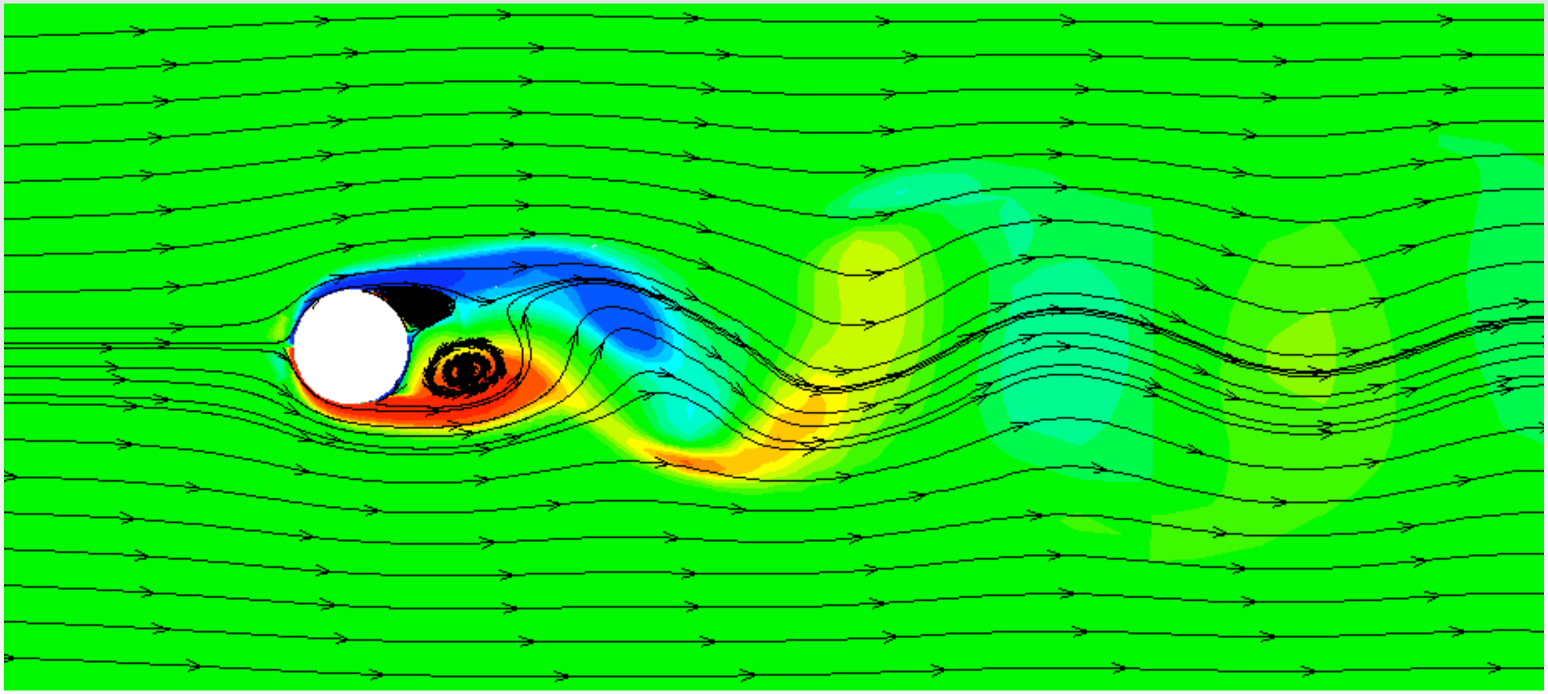
Outline

- Introduction
- Simulation Methodology
- Stationary Cylinder
- Oscillating Cylinder
- Conclusions

Introduction

Kármán Vortex Street

Periodic pattern of counter-rotating vortices caused by unsteady separation from a bluff body



Introduction

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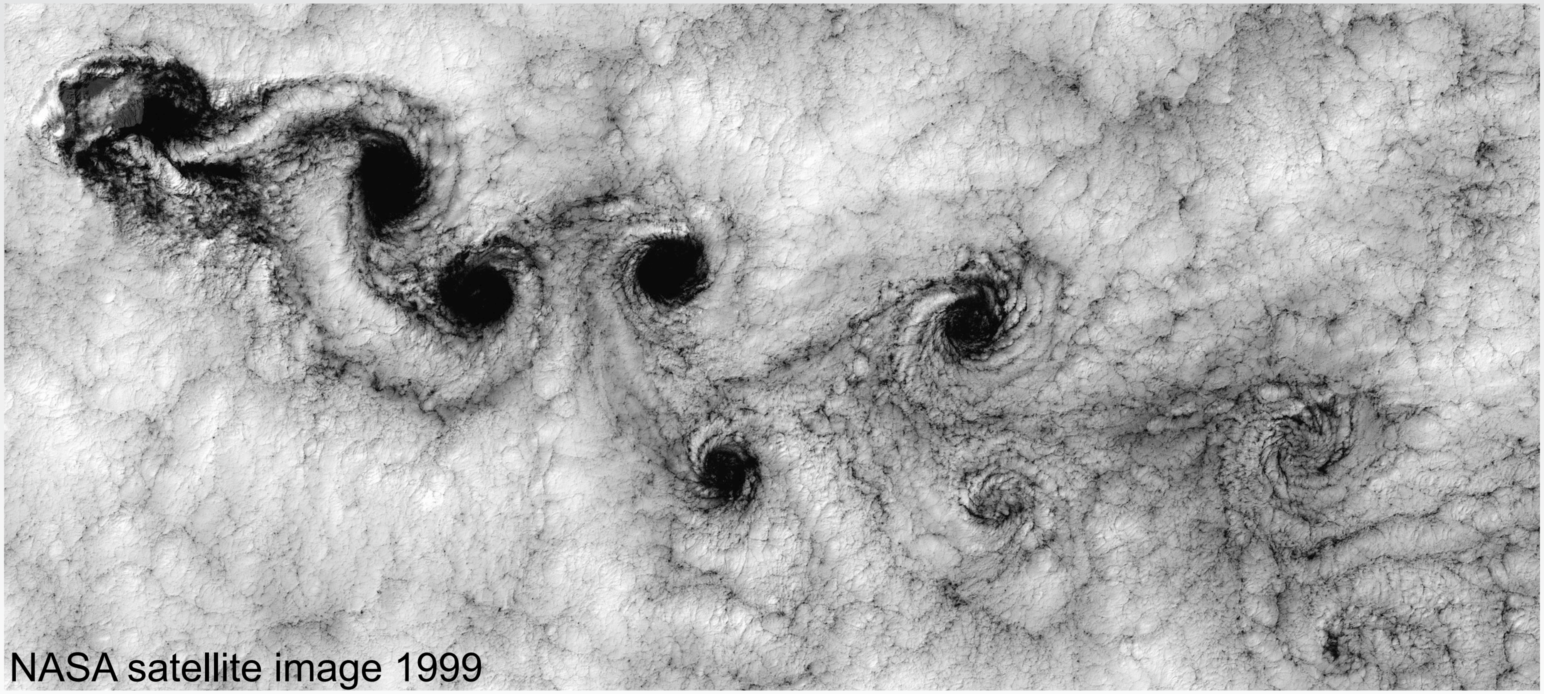
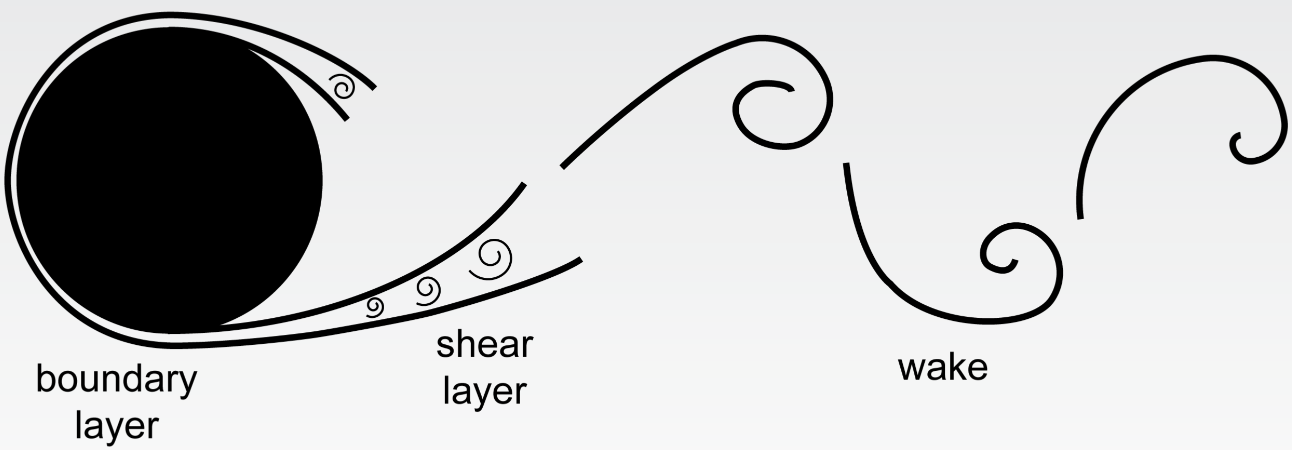
Periodic pattern of counter-rotating vortices caused by unsteady separation from a bluff body



Introduction

Flow Around a Circular Cylinder

- Interaction between 3 shear layers
  - Boundary layer
  - Free shear layer
  - Wake



Introduction

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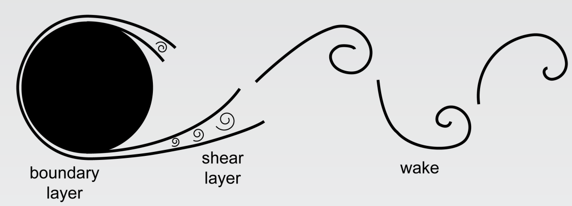


- Transition to turbulence in
  - Wake Re_D 200 → 400
  - Free Shear layer Re_D 400 → $150x10^3$
  - Boundary layer Re_D $150x10^3$ → $8x10^6$

Introduction

Scope

- Simulation of turbulent flow around circular cylinders
  - Stationary $Re_D = 3900$
  - Oscillating $Re_D = 3600$

- Compare accuracy of turbulence models

  using same numerical procedure

  with respect to experiments
  and other simulations

Methodology

Numerical Simulation
of Turbulent Flows

Methodology

The Need for Turbulence Models

Example: Incompressible Momentum Equation

Applying an average or filter operator (overbar) to the momentum equation yields

$$\frac{\partial}{\partial t}(\rho\overline{u_i}) + \frac{\partial}{\partial x_j}(\rho\overline{u_i}\,\overline{u_j}) = -\frac{\partial\overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}[\,\overline{\sigma_{ij}} - \rho(\overline{u_i u_j} - \overline{u_i}\,\overline{u_j})\,]$$

- The terms $\overline{u_i}$, $\overline{p}$, $\overline{\sigma_{ij}}$ are solved for
- The cross terms $\overline{u_i u_j}$ are unknown

closure problem

Methodology

Simulation of Turbulence

$$u_i = \overline{u_i} + u_i'$$

URANS
Unsteady Reynolds Averaged Navier-Stokes

(One-point closure)

$\overline{u_i}$ mean
u_i' fluctuating

Solve mean quantities $\overline{u}_i$

Model Reynolds stresses

$$\rho \overline{u_i' u_j'}$$

LES
Large Eddy Simulation

$\overline{u_i}$ large scale
u_i' Subgrid-Scale

Solve large scale eddies $\overline{u}_i$

Model subgrid-scale stress

$$\rho(\overline{u_i u_j} - \overline{u_i}\,\overline{u_j})$$

DNS
Direct Numerical Simulation

Solve all Scales u_i

very thin grid required

Methodology

Turbulence Models Considered

- URANS
  - One equation Spalart-Allmaras
  - K-tau Speziale et al.
- Large Eddy Simulation (LES)
  - Smagorinsky-Lilly
- Very Large Eddy Simulation (VLES)
  - Adaptive k-tau Magagnato & Gabi

  (uses a URANS type subgrid-scale model)

Methodology

Computational Code

- SPARC
  Structured PArallel Research Code

- Finite Volume, Cell Centered, Block-Structured, Multigrid

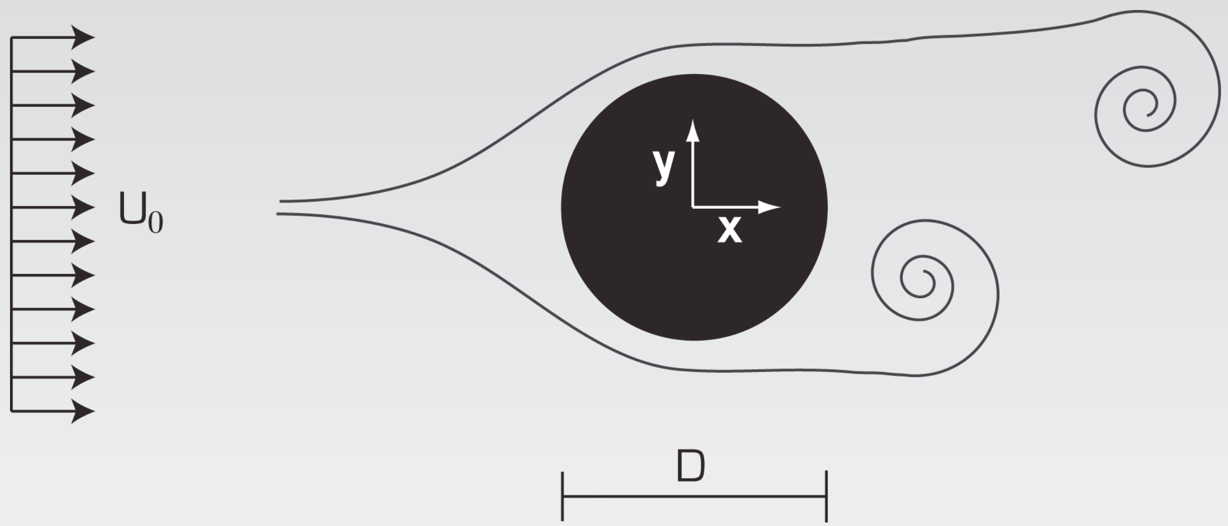
- Simulations are 3D
  Unsteady
  Compressible
  Viscous

Stationary Cylinder

Stationary Circular Cylinder
in a Uniform Flow

Stationary Cylinder

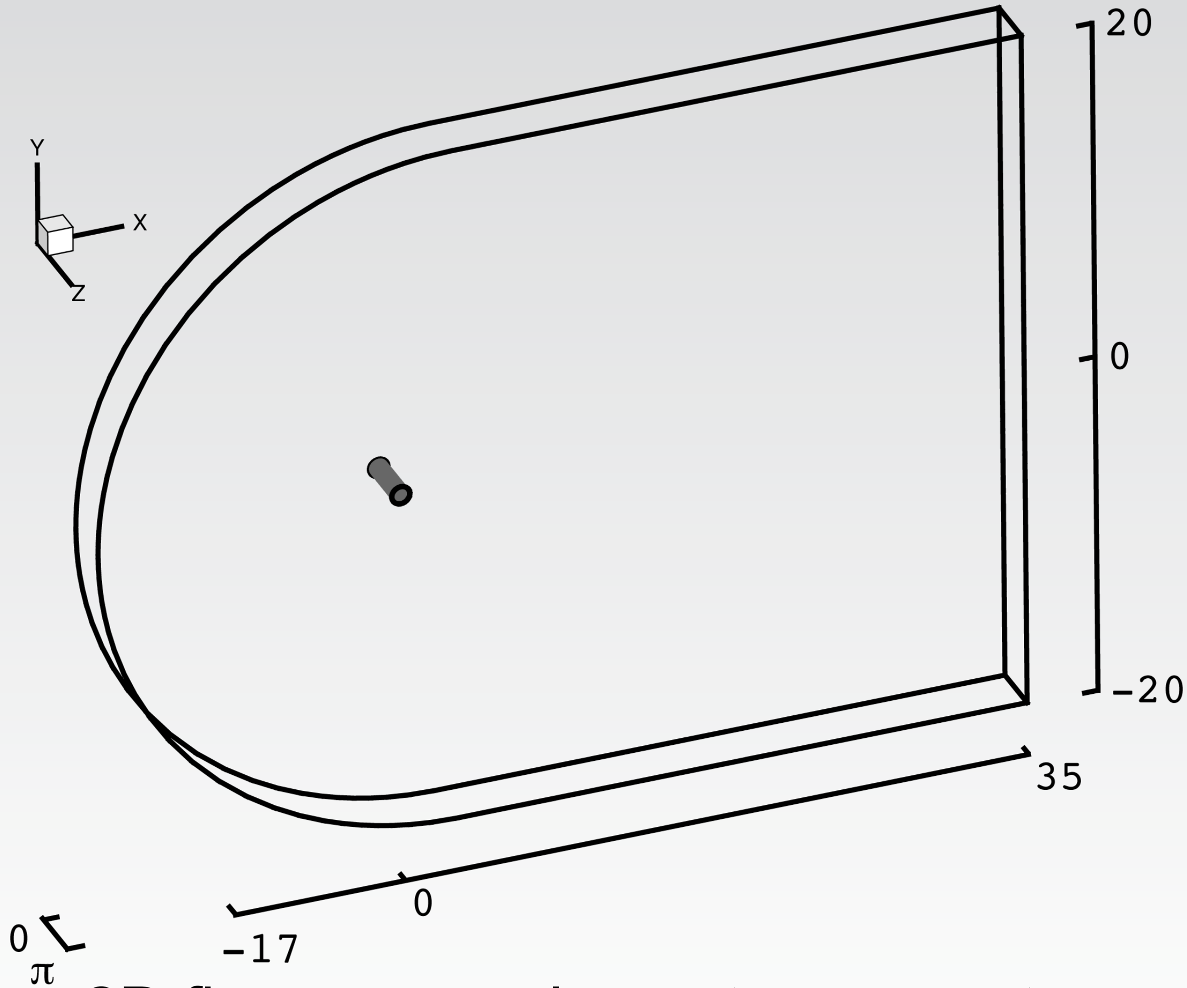
Problem Setup



- Cylinder diameter — $D = 1\text{m}$
- Flow velocity — $U_0 = 68.63\text{m/s}$
- Mach number — Mach 0.2
- Reynolds number — $Re_D = 3900$

Stationary Cylinder

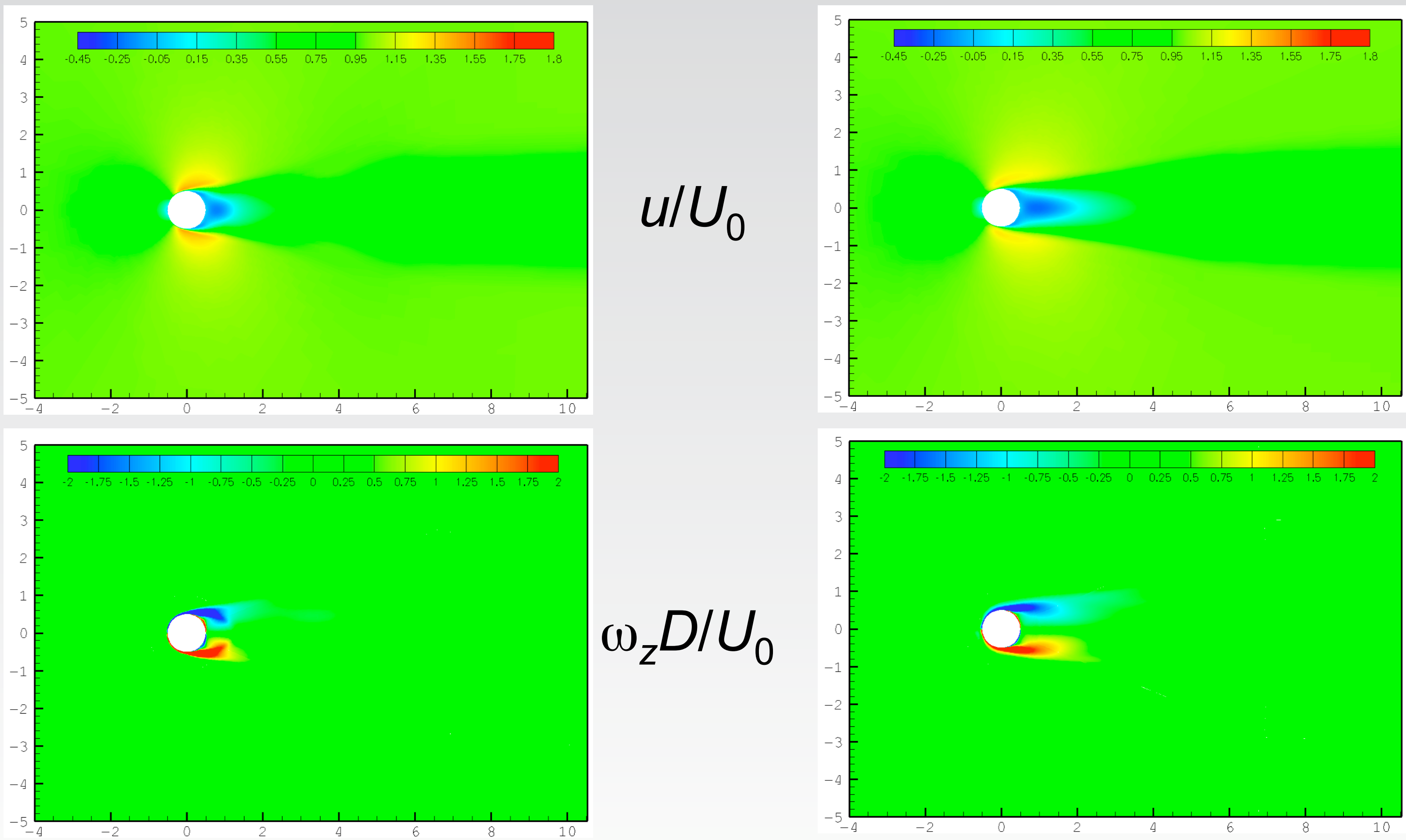
Computational Domain



2D figures: x-y plane at span center

Stationary Cylinder

URANS : Average Fields

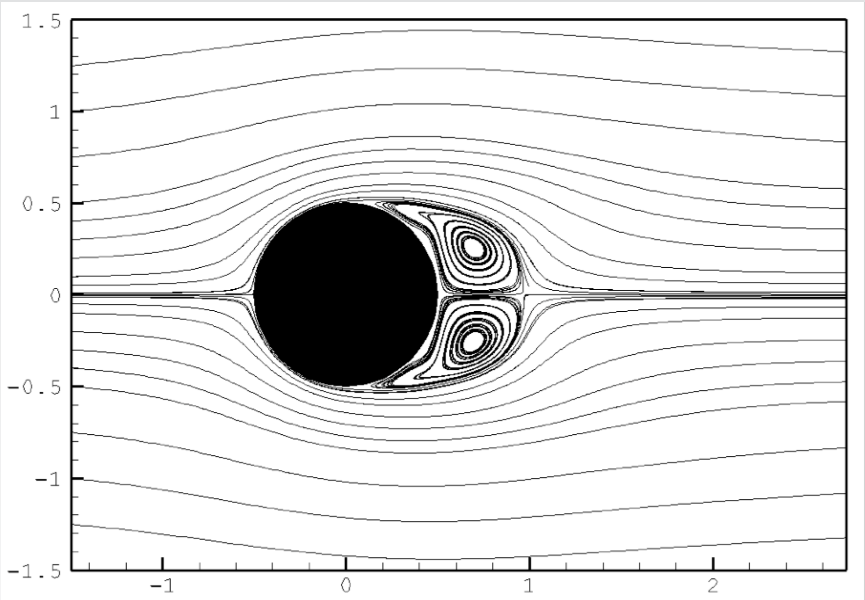


SA

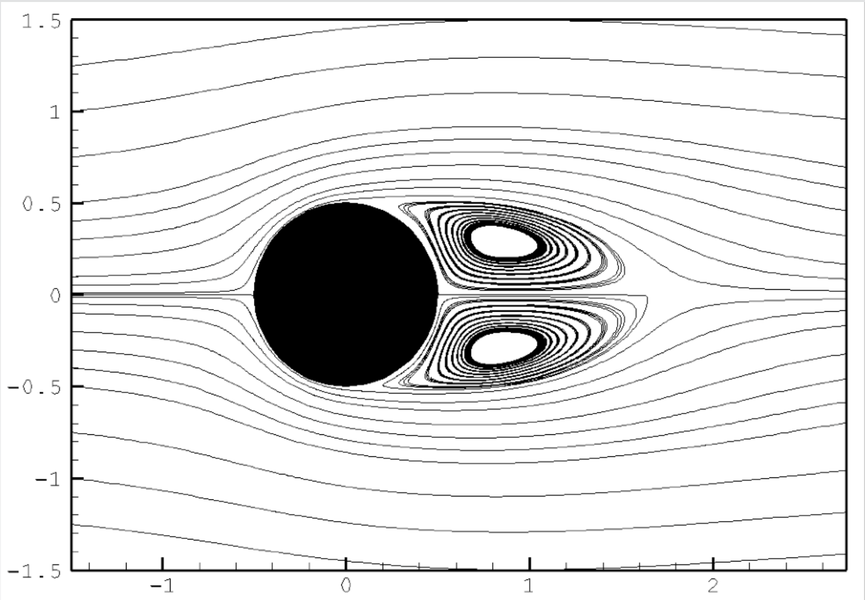
Sp

Stationary Cylinder

URANS : Average Streamlines



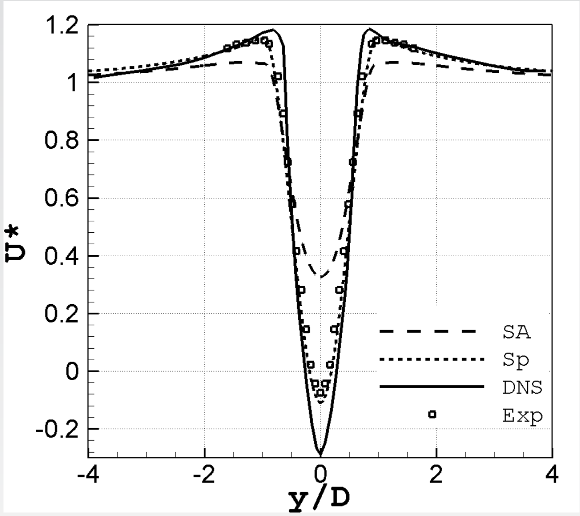
SA

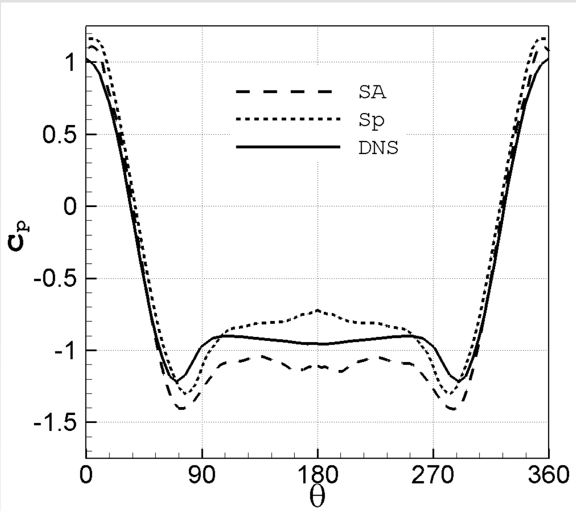


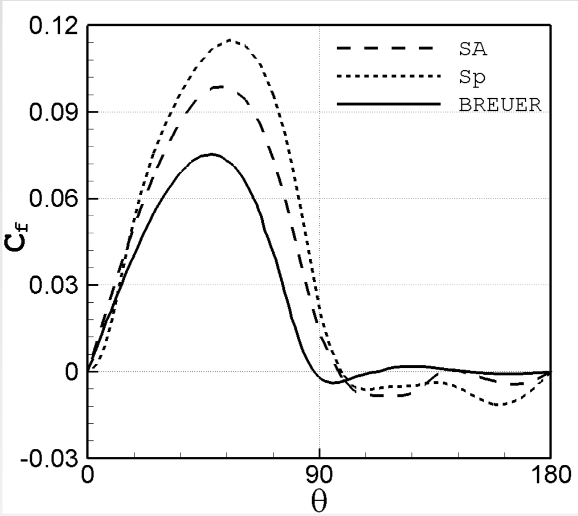
Sp

Stationary Cylinder

URANS : Average Profiles







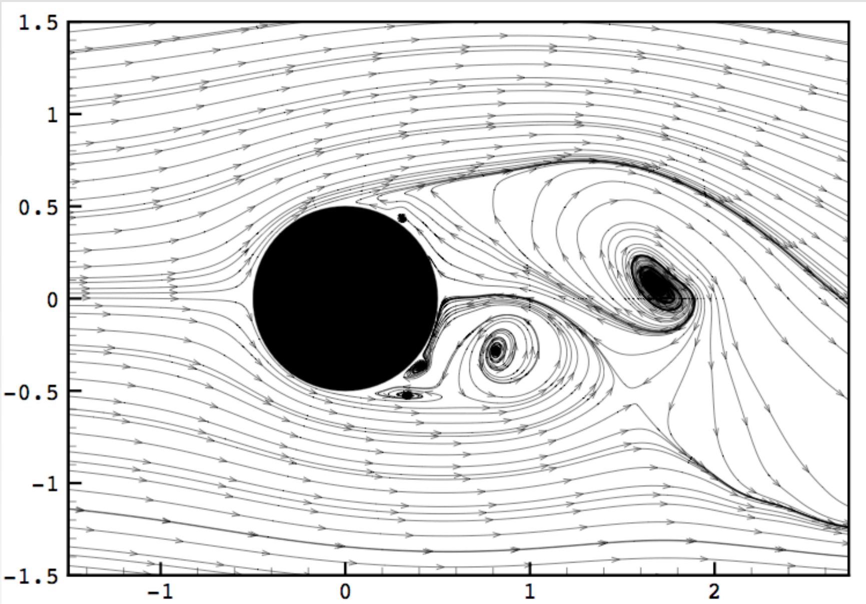
u/U_0 at $x/D = 1.54$

c_p around cylinder

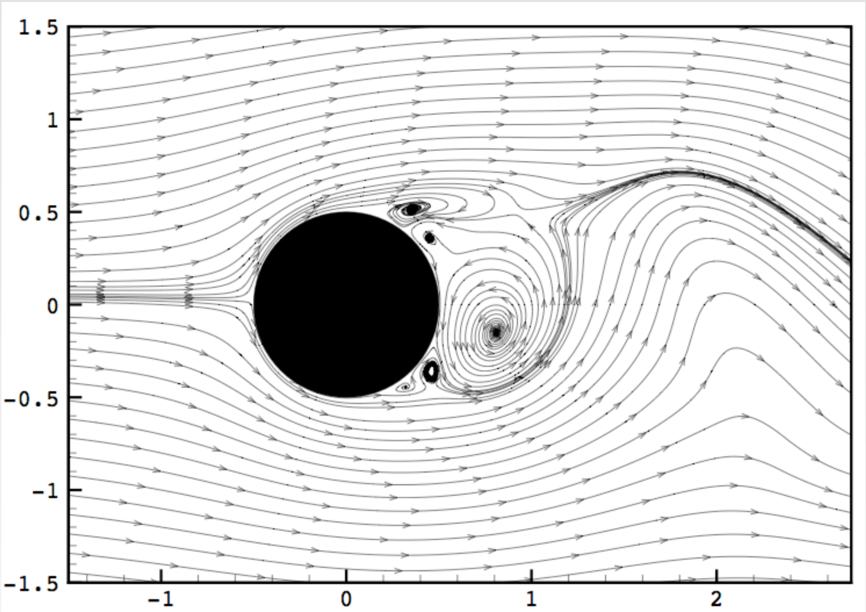
c_f around cylinder

Stationary Cylinder

LES-VLES : Streamlines



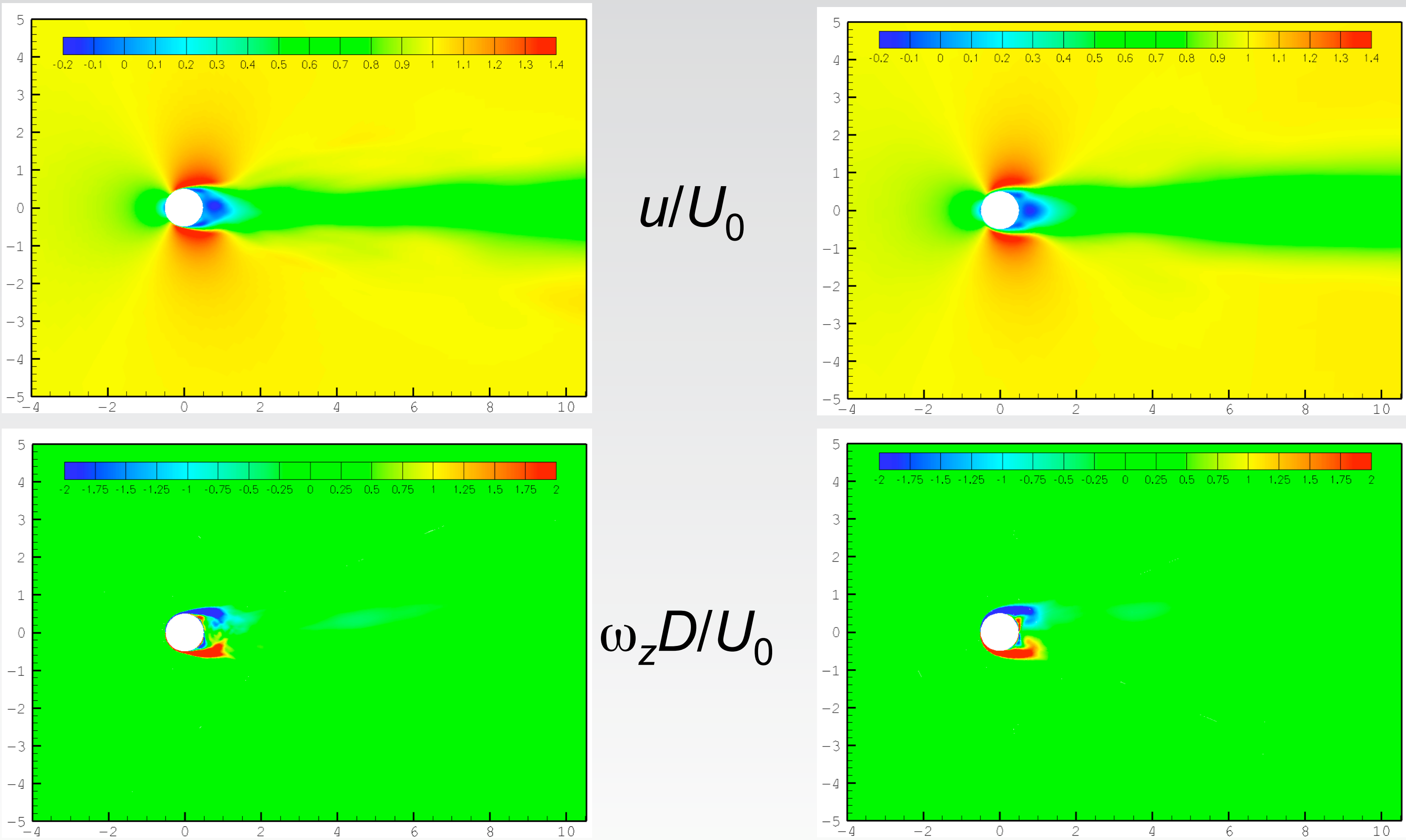
LES



VLES

Stationary Cylinder

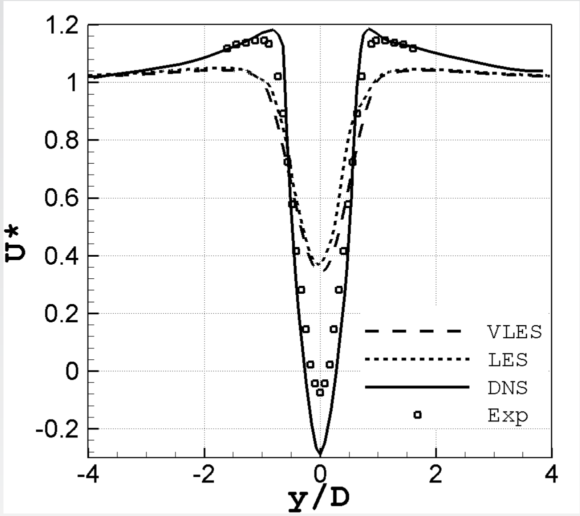
LES-VLES : Average Fields

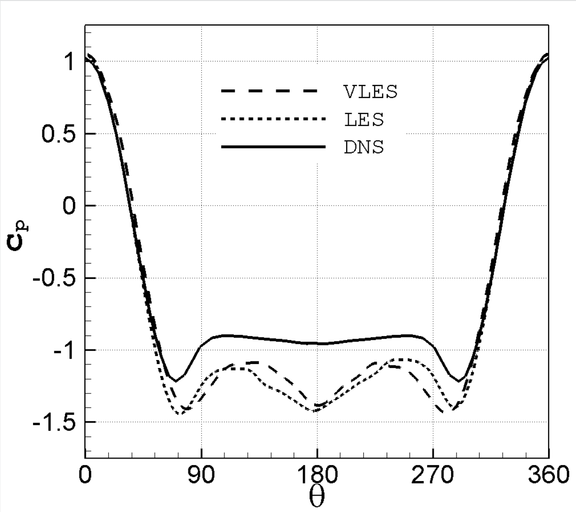


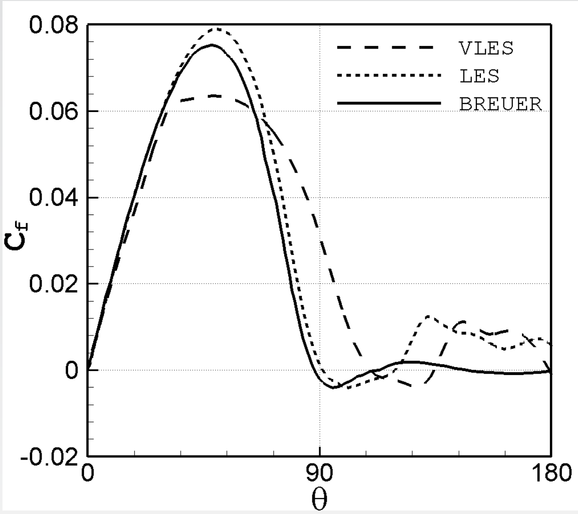
LES VLES

Stationary Cylinder

LES-VLES : Average Profiles







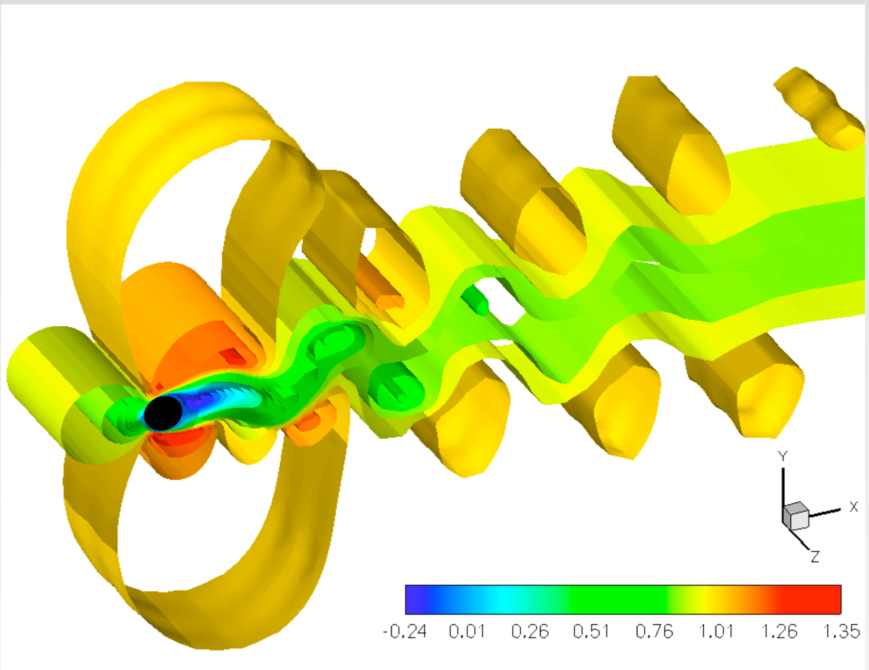
u/U_0
at x/D=1.54

c_p
around
cylinder

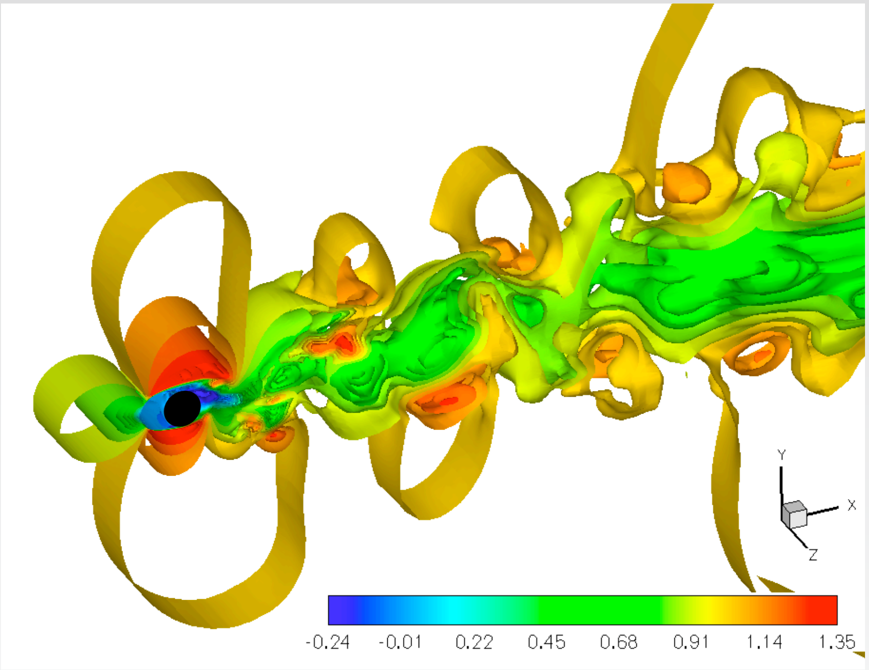
c_f
around
cylinder

Stationary Cylinder

3-Dimensionality
Streamwise velocity iso-surfaces



URANS Sp



LES

Stationary Cylinder

Comparison

Model		$St = fD/U_0$	$< c_D >$	$< c_{p_b} >$	$< \theta_s >$
DNS	Tremblay *et al.* (2000)	0.220	1.03	−0.92	94.3°
URANS	Spalart-Allmaras	−0.8%	25.5%	−46.0%	9.8%
URANS	$k - \tau$ Speziale	−10.6%	−3.0%	20.9%	4.7%
LES	Smagorinsky-Lilly	−10.6%	29.1%	−53.1%	−1.9%
VLES	adaptive $k - \tau$	−3.9%	29.0%	−49.0%	6.0%

Oscillating Cylinder

Circular Cylinder
in Cross-Flow Oscillations

Oscillating Cylinder

Motion and Cases

- Vertical sinusoidal motion

$$\frac{y(t)}{D} = \frac{A}{D} \sin(2\pi f_c t)$$

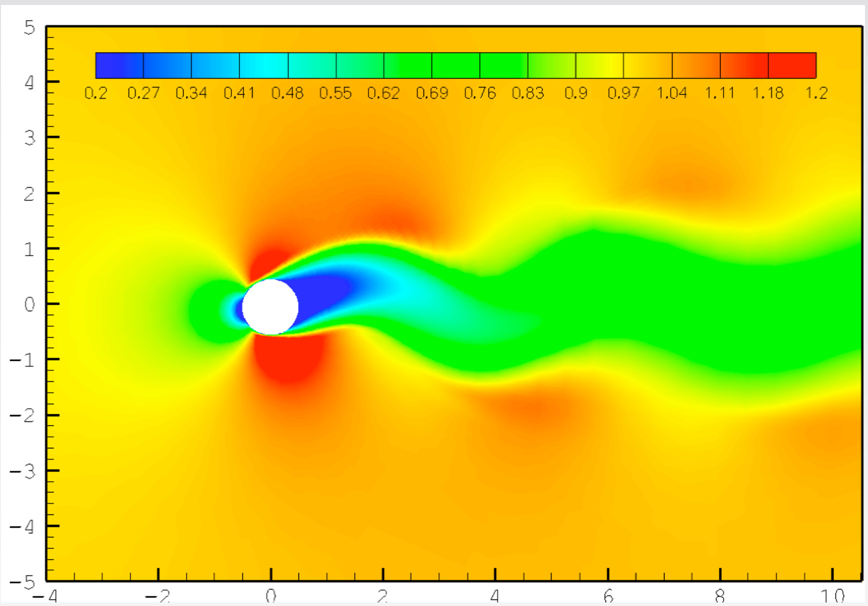
- 2D URANS k-tau Speziale
- Reynolds number 3600
- Lock-in: vortex shedding frequency matches cylinder motion frequency

Oscillating Cylinder

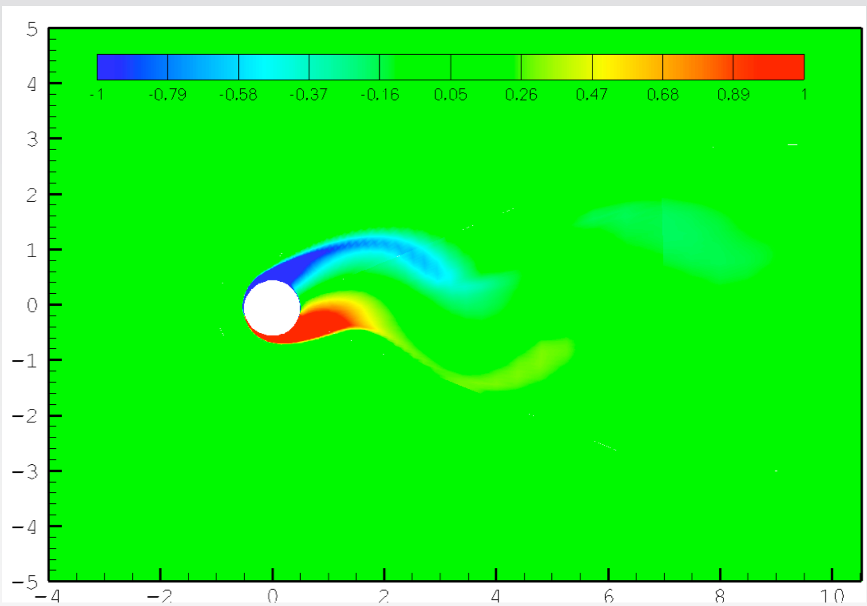
URANS Sp Fields

Case IV

$f_c / f_0 = 0.800$



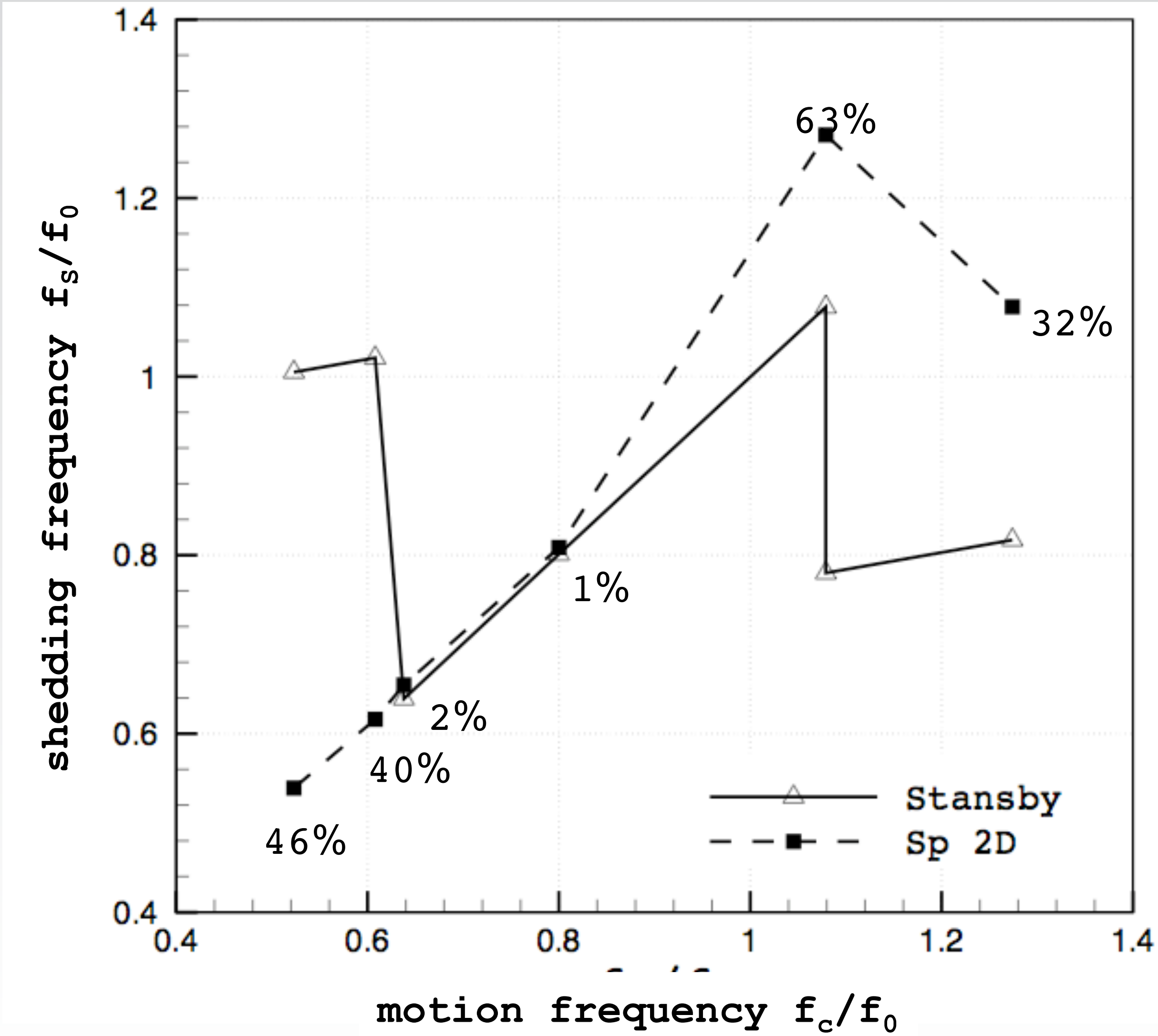
u/U_0



$\omega_z D/U_0$

Oscillating Cylinder

Lock-in



Conclusions

Summary and Further Work

Conclusions

- comparison of results from different turbulence models with same numerical procedure

- Spalart-Allmaras model
  - error in separation point
    - ↳ flow remains attached too long
    - ↳ small recirculation zone
    - ↳ low back pressure
    - ↳ large drag
  - Accurate Strouhal number

Conclusions

- K-tau Speziale model
  - Good mean global quantities
    - Strouhal number, drag, back pressure, separation point
    - velocity profiles along the wake
- LES and VLES
  - reveal secondary eddies
  - LES resolves dynamics in boundary layer
- Oscillating Cylinder
  - No other numerical results in same regime
  - Lock-in over large range of motion frequencies
  - Further investigation required

Conclusions

Further Work

- Better averages on LES and VLES
- LES with Dynamic and Dynamic Mixed subgrid-scale models
- LES of oscillating cylinder

Questions