# DEVELOPMENT OF A BENCHMARK PROBLEM FOR MODELING TRANSITIONAL UNSTEADY FLOWS

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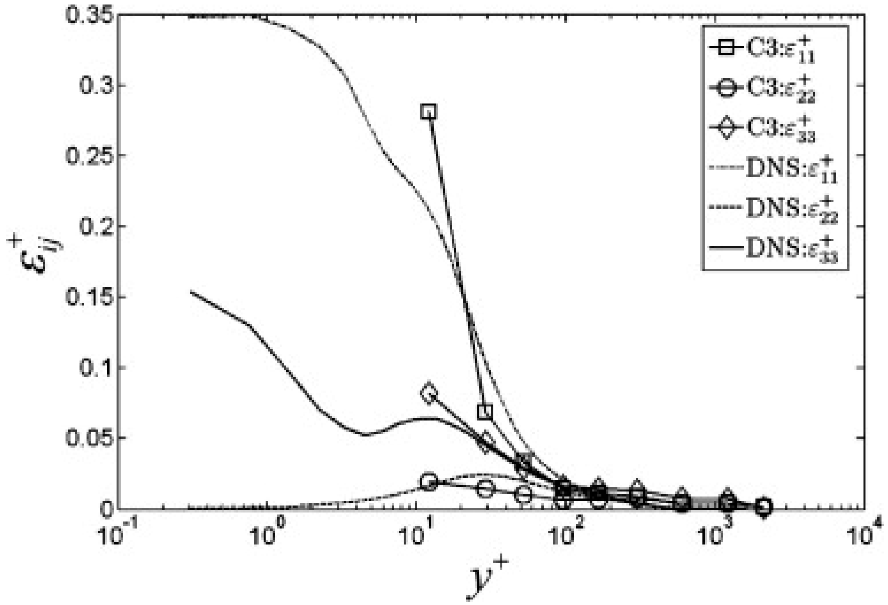
# Outline

- **Measurement overview**
- **Near-wall measurements**
- **Motiving a benchmark problem**
- **Benchmark problem details**
- **Selected experimental and computational results**
- **Status and directions**

# Measurements for incompressible flow modeling applications

**In order of difficulty (and relative uncertainty):**

- Mean velocity
- Reynolds normal stresses
- Reynolds shear stresses
- Mean velocity gradients
- Instantaneous rate-of-strain/vorticity
- **Any term above near a wall**
- Instantaneous flowfield pressure
- Derived modeling terms (e.g., pressure diffusion, dissipation rate)




Reynolds stress dissipation rate measurements (Lowe and Simpson, IJHFF, 29(3) 2008)

Which, if any, modeling terms hold the most value to the community if measured experimentally?

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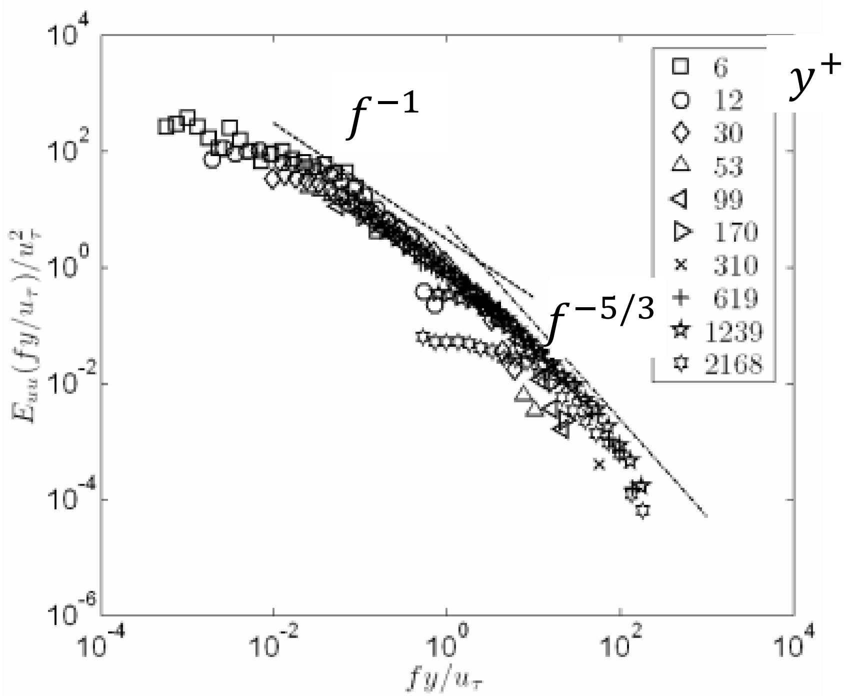


Stream-wise velocity spectra at $Re_\theta = 7500$

Which, if any, modeling terms hold the most value to the community if measured experimentally?

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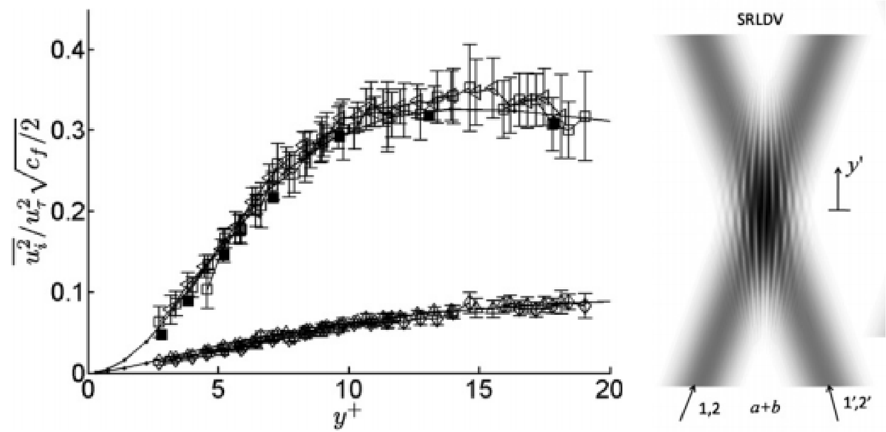
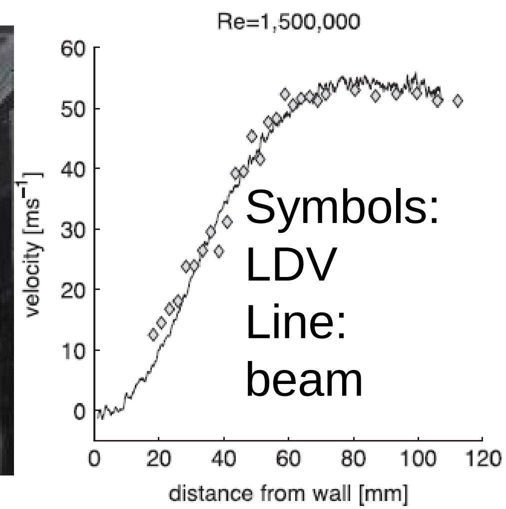
# Specialty: Near-wall velocimetry

**Fluorescent particle PIV**



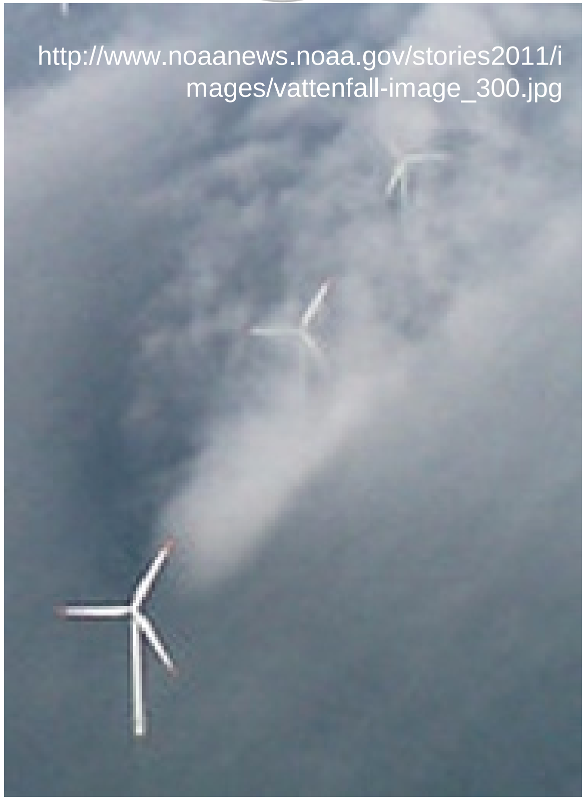

**Position-resolving LDV**


**Profile velocimetry using beam through airfoil pressure tap (scanning DGV)**

# Motivation: Unsteady Wind Turbine Aerodynamics Modeling

- Blade-turbulence interaction modeling is the primary need for successful high fidelity wind farm modeling
  - Past work (“PSU Cyber Wind Facility,” Fig 1) exposed deficiencies
  - Industry standard design tools even lower fidelity
- Combined computational/experimental approach to develop experiment that will optimally advance modeling
- Windplant modeling capabilities are a critical need:
  - Windplant layout for optimal performance, including addressing extreme cycling loads that may limit lifetime
  - Accurate acoustic impact prediction
  - Improved siting



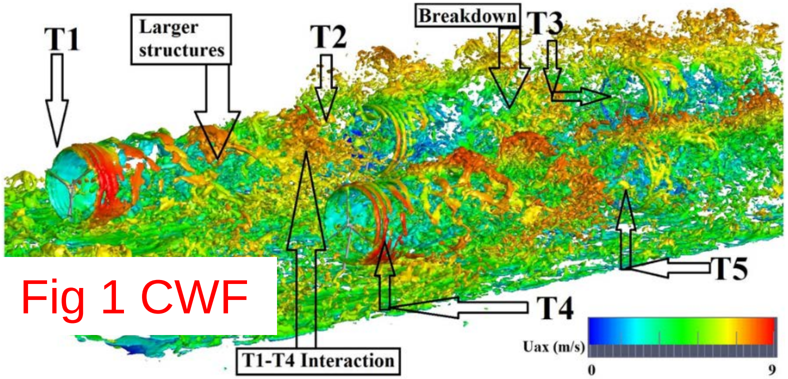




Fig 1 CWF

(Vijayakumar 2015)

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**Full-scale problem is too complicated and expensive for fundamental model development and VVUQ**


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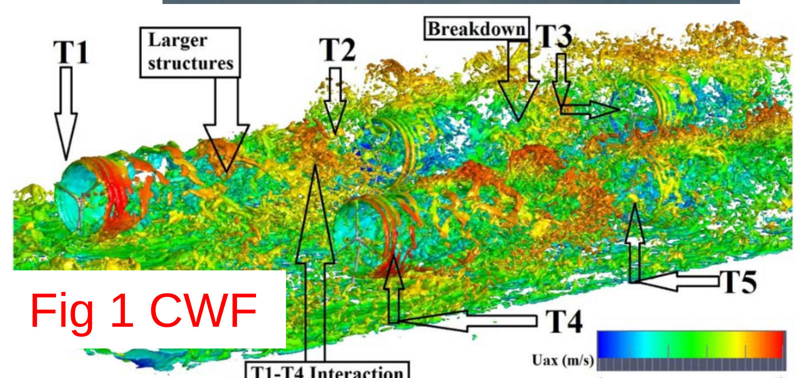
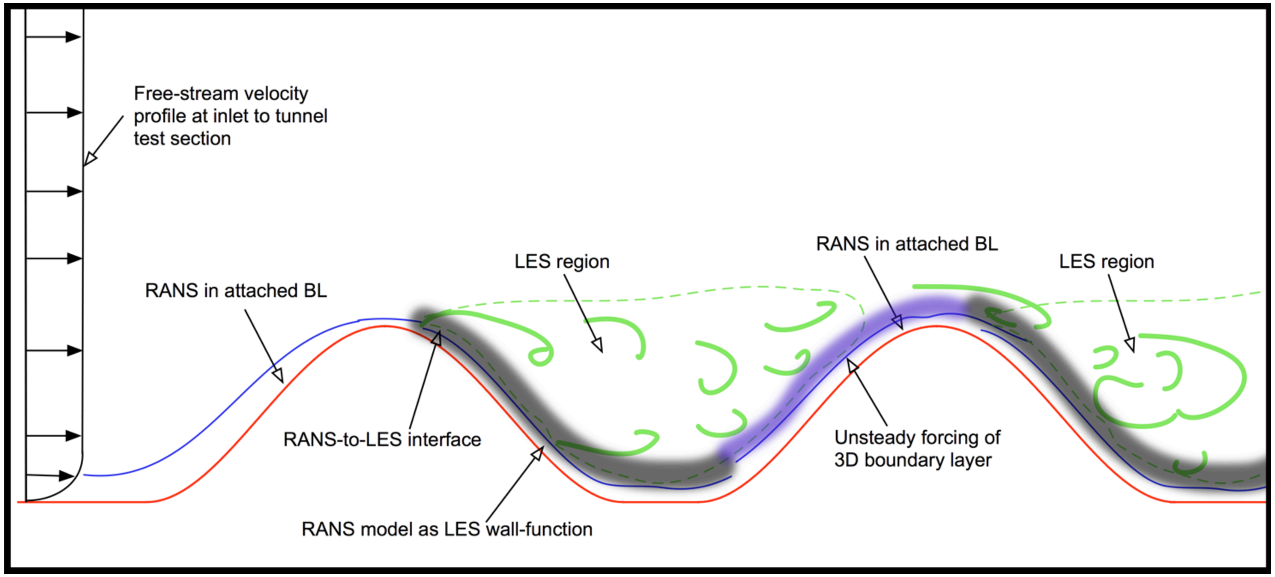


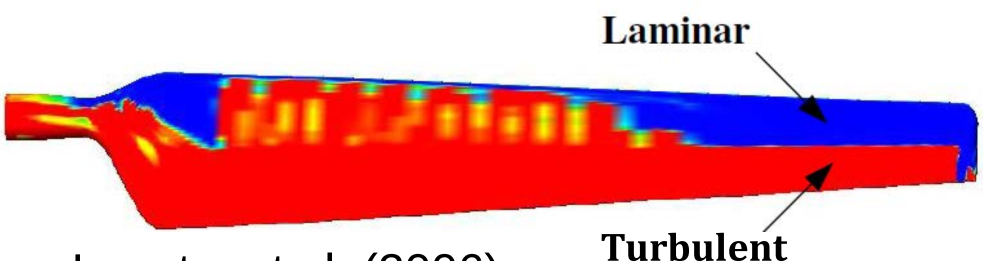

Fig 1 CWF

(Vijayakumar 2015)

# Fundamental/Modeling Assessment

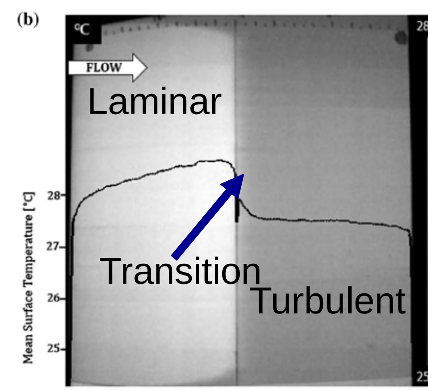



Large-scale, intense turbulence interacting with downstream wall layers.



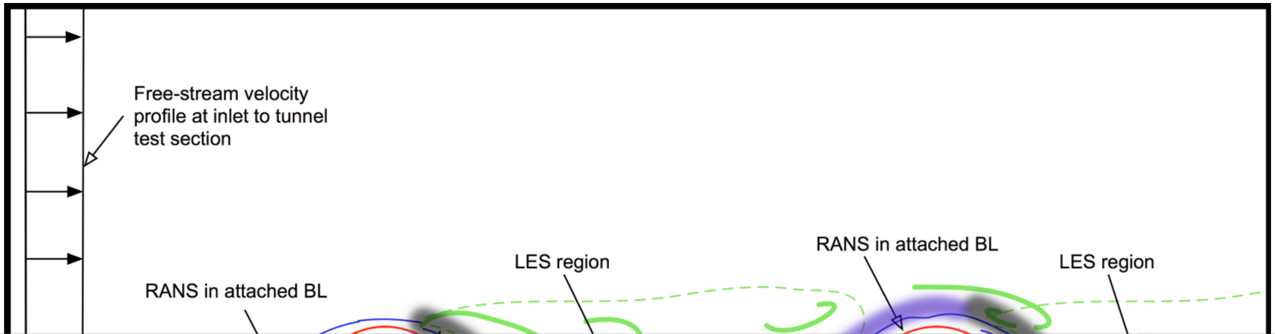

Langtry et al. (2006)

IR transition meas. @ $Re_c$=1.5M Joseph et al. (2016)



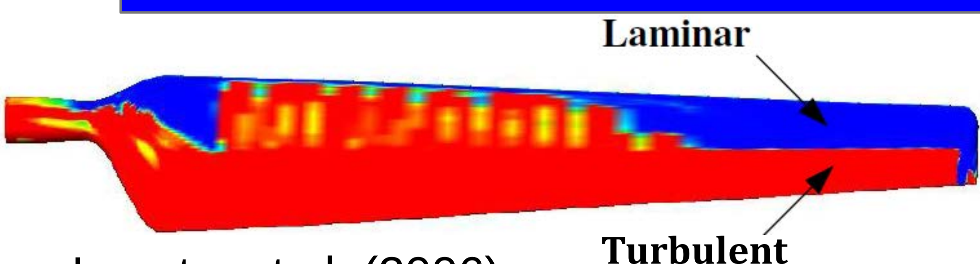

Wind turbine airfoils have appreciable laminar flow.

# Fundamental/Modeling Assessment




**Model problem should capture:**

1. ***Low reduced frequency unsteadiness in approach flow***
2. ***Transitional flow***
3. ***Airfoil loading unsteadiness***

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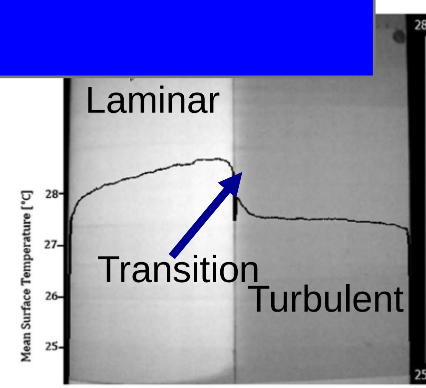



Wind turbine airfoils have appreciable laminar flow.

# Concept and parameter space considerations

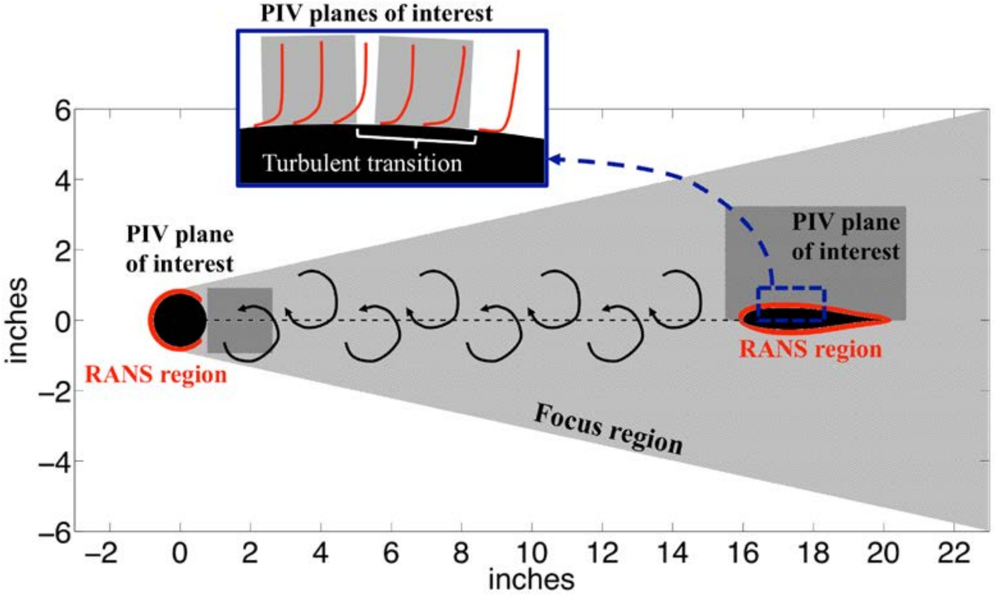
## Approach: cambered airfoil in wake of cylinder, $D \sim c$

## Considerations:

- **Minimize potential flow interactions**
- **$Re_c$, reduced frequency, D$/c$**

## Practical aspects:

- **Wind tunnel scale**
- **Instrumentation resolution**
- **Uncertainties**




Wind Turbine operating in ABL:

| Time scale | Length scale | Blade Reynolds number | Reduced frequency |
|---|---|---|---|
| ~O($10^{-3}$-$10^{1}$s) | ~O($10^{-6}$-$10^{2}$m) | ~O($10^{7}$) | <$10^{-2}$ |

Realistic in this benchmark problem:

| Time scale | Length scale | Blade Reynolds number | Reduced frequency |
|---|---|---|---|
| ~O($10^{-4}$-1 s) | ~O($10^{-6}$-0.1 m) | ~O($10^{5}$) | >1 |

# Benchmark Problem Parameters

| | Design condition |
|---|---|
| D | 1.5 inches, set to achieve desired Re |
| c | 4 inches, set to achieve desired k |
| profile | NACA 63215B |
| L | L/D=10.67 |
| h | AoA on centerline ±50deg |
| $U_\infty$ | 26 m/s, upper limit of tunnel |
| AR | 18, set by tunnel, Λ / D=3 |

$Re_D$ = 63,500

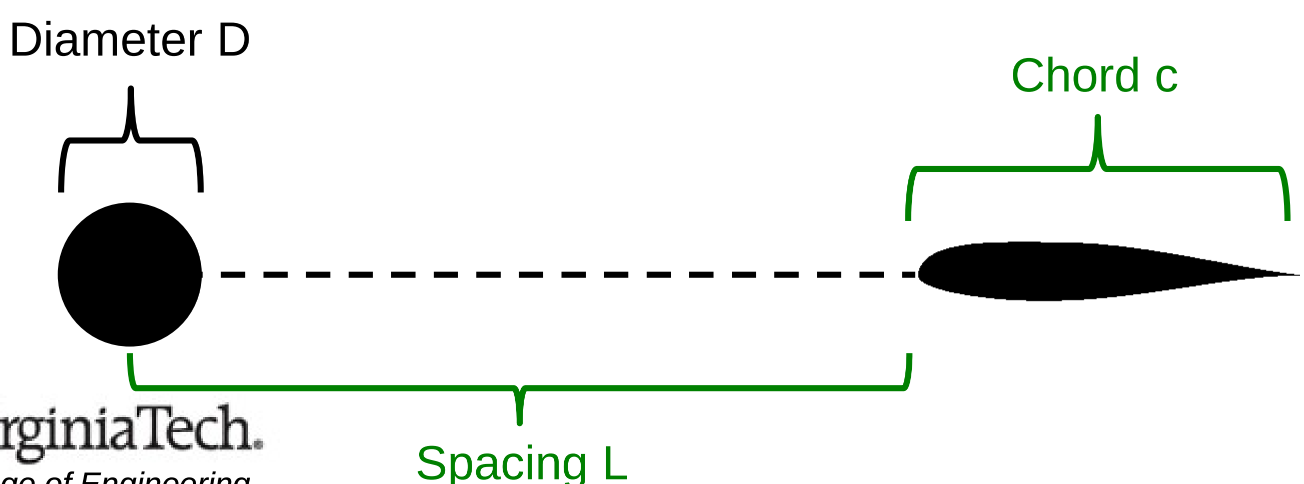
$Re_c$ = 170,000

k = 1.53

Lateral vortex spacing: 58 mm

Shedding wavelength: 200 mm

Pressure influence: 6D




NACA 63215b

- $t/c = 15\%$

From steady CFD model:

- $x/c_{trans} \sim 52\%$
- $x/c_{sep} \sim 70\%$

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Next step is Stability Wind Tunnel experiments to $Re_c \sim 3M$

58 mm

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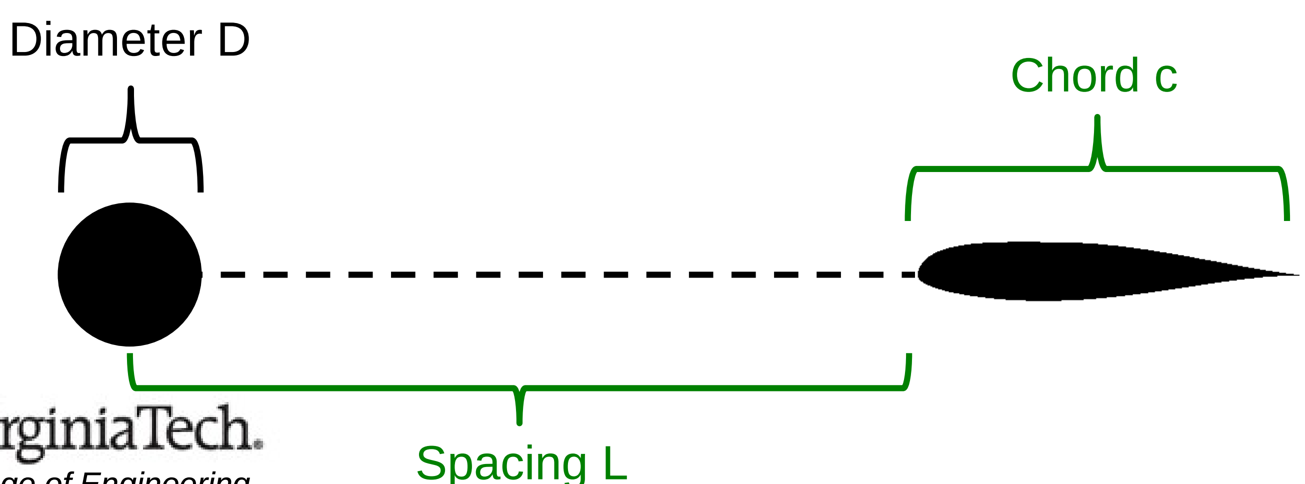


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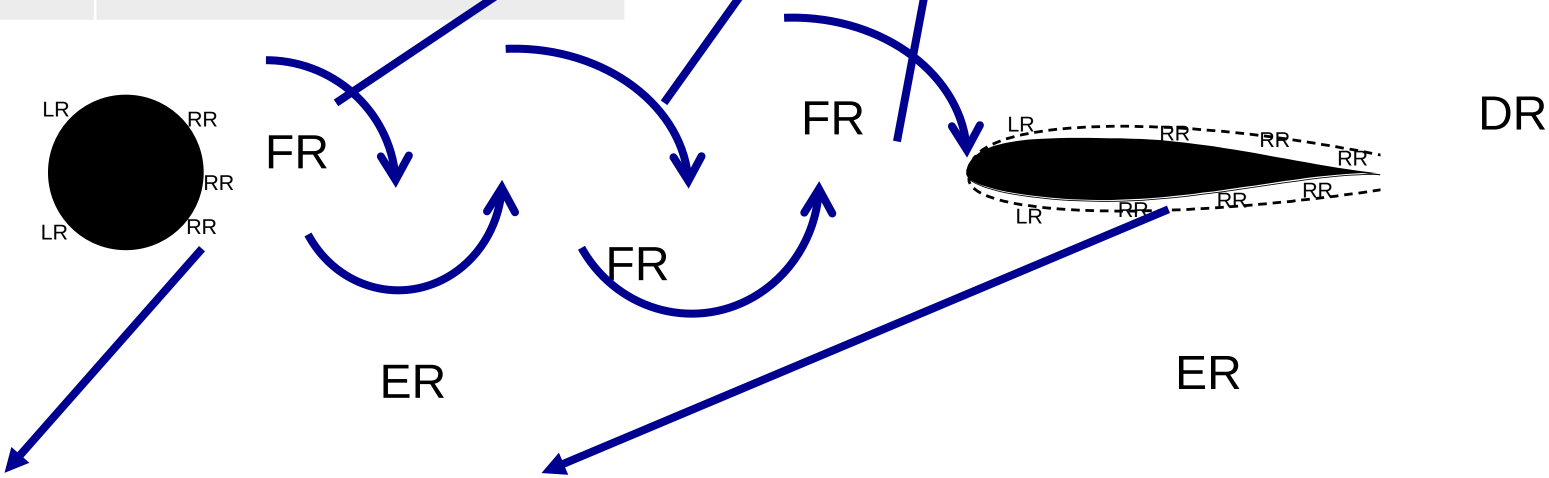
# Computational overview

| Regions | Descriptions |
|---|---|
| Euler Region(ER) | Laminar flow, never entered by turbulence |
| Laminar (LR)/RANS Region (RR) | Primarily the boundary layer |
| Focus Region(FR) | Part of the turbulence is resolved |
| Departure Region(DR) | Smoothly blend into ER |

Delayed Detached-Eddy Simulation(DDES)(Sparlart, 2006):

$$\tilde{d} \equiv l_{RANS} - f_d \max(0, l_{RANS} - C_{DES}\Delta)$$



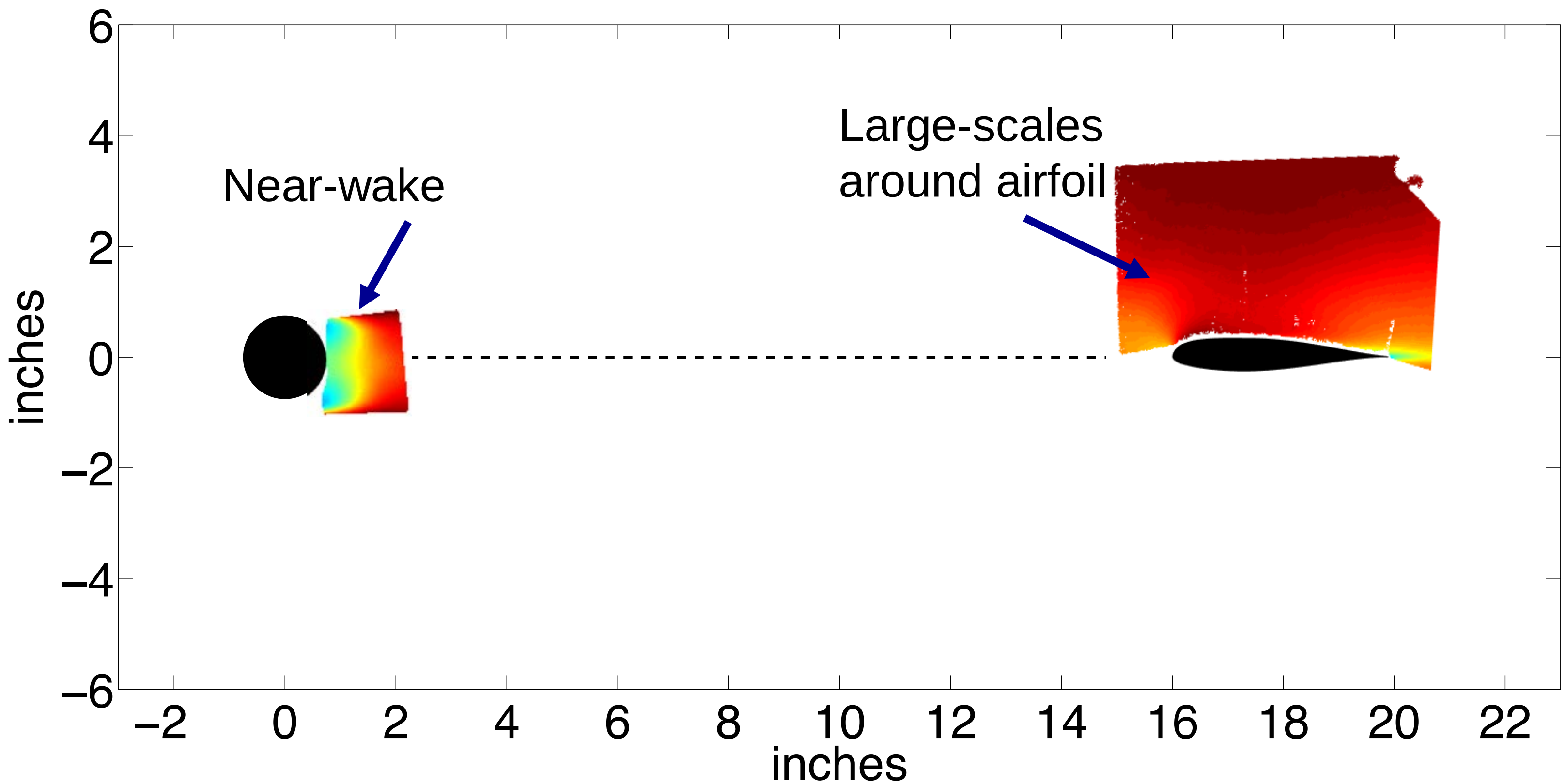

Boundary layer is preserved for RANS model $k-\omega$SST integrated with two-equation transition formulation (Langtry et al. 2006)

- Transition momentum thickness Reynolds number $\widetilde{Re}_\theta$
- Turbulence intermittency $\gamma$

- OpenFOAM implementation
- Grid includes wind tunnel side walls, but truncated out of plane
- Inflow conditions from experiment

# Experimental overview

- Time-resolved, 2D particle image velocimetry
- Three focal regions for optimized spatial resolution
  - Extra effort to obtain near surface measurements




More details in Cadel (2016)

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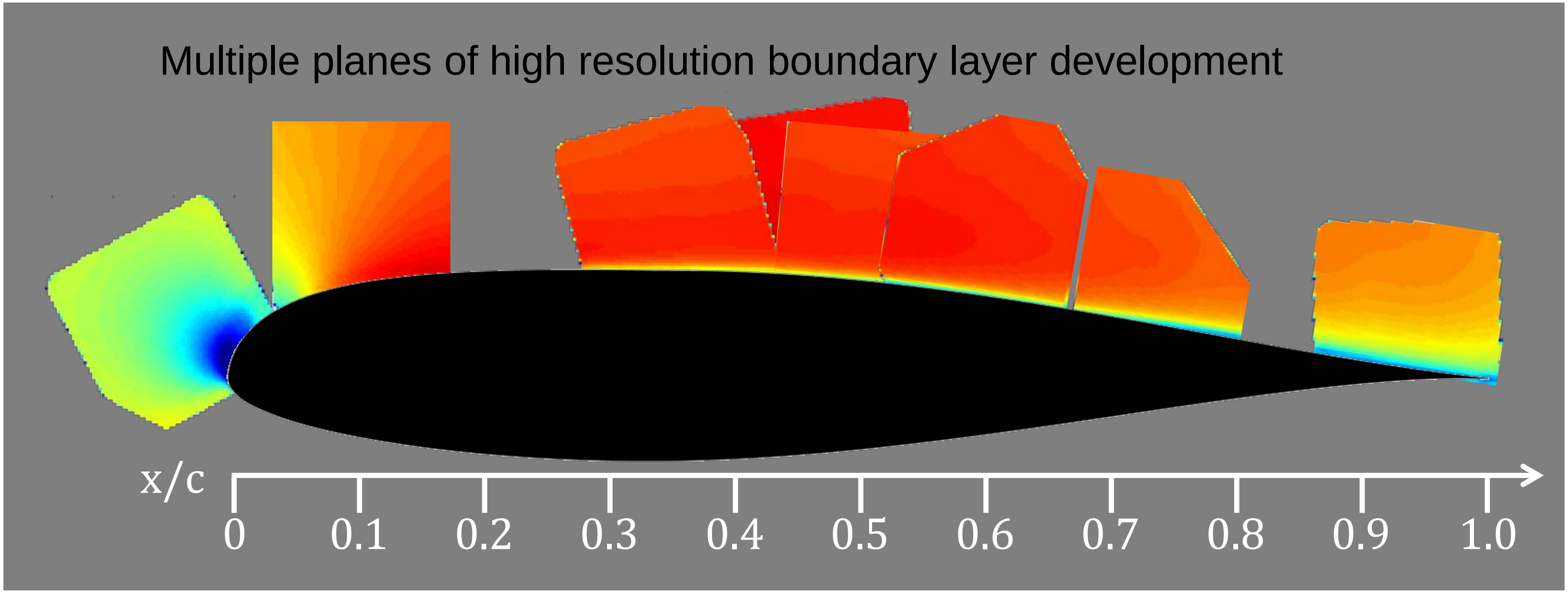


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# Experimental overview

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  - Extra effort to obtain near surface measurements

**Mean velocity:** $\pm 0.006 U_\infty$ / $\pm 0.1 u_\tau$

**Reynolds stresses:** $\pm 0.001 U_\infty^2$ / $\pm 0.5 u_\tau^2$

**Local flow angle:** $\pm 1^o$

**Distance from wall:** $\sim 50\ \mu m$/$\sim 4-5^+$

More details in Cadel (2016)

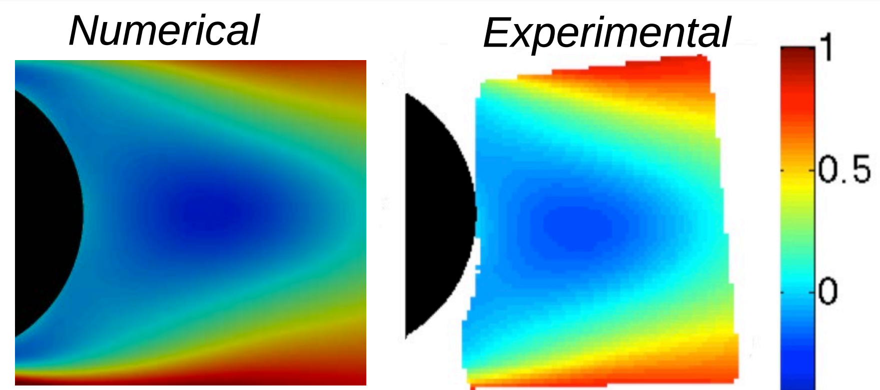
# Circular cylinder flow

**Objective**: assess basic unsteady circular cylinder wake flow ($Re_D = 6.4 \times 10^4$) and prediction performance

- Strouhal number

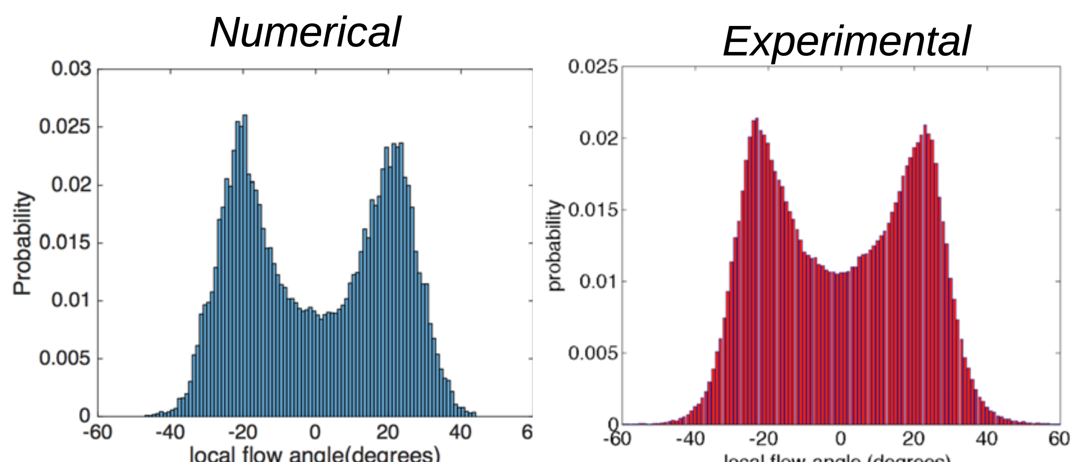
| | Experiment | Simulation |
|---|---|---|
| $St = fD/U_0$ | 0.19 | 0.2 |

- Simulation shows slightly longer recirculation zone




*Normalized mean streamwise velocity*

- Local flow angle range is higher than full-scale blade in real conditions.
- Histogram of AOA at airfoil LE
  - Both peak at $\pm 25°$ with extreme value up to $\pm 50°$




*Local angle of attack at airfoil leading edge position*

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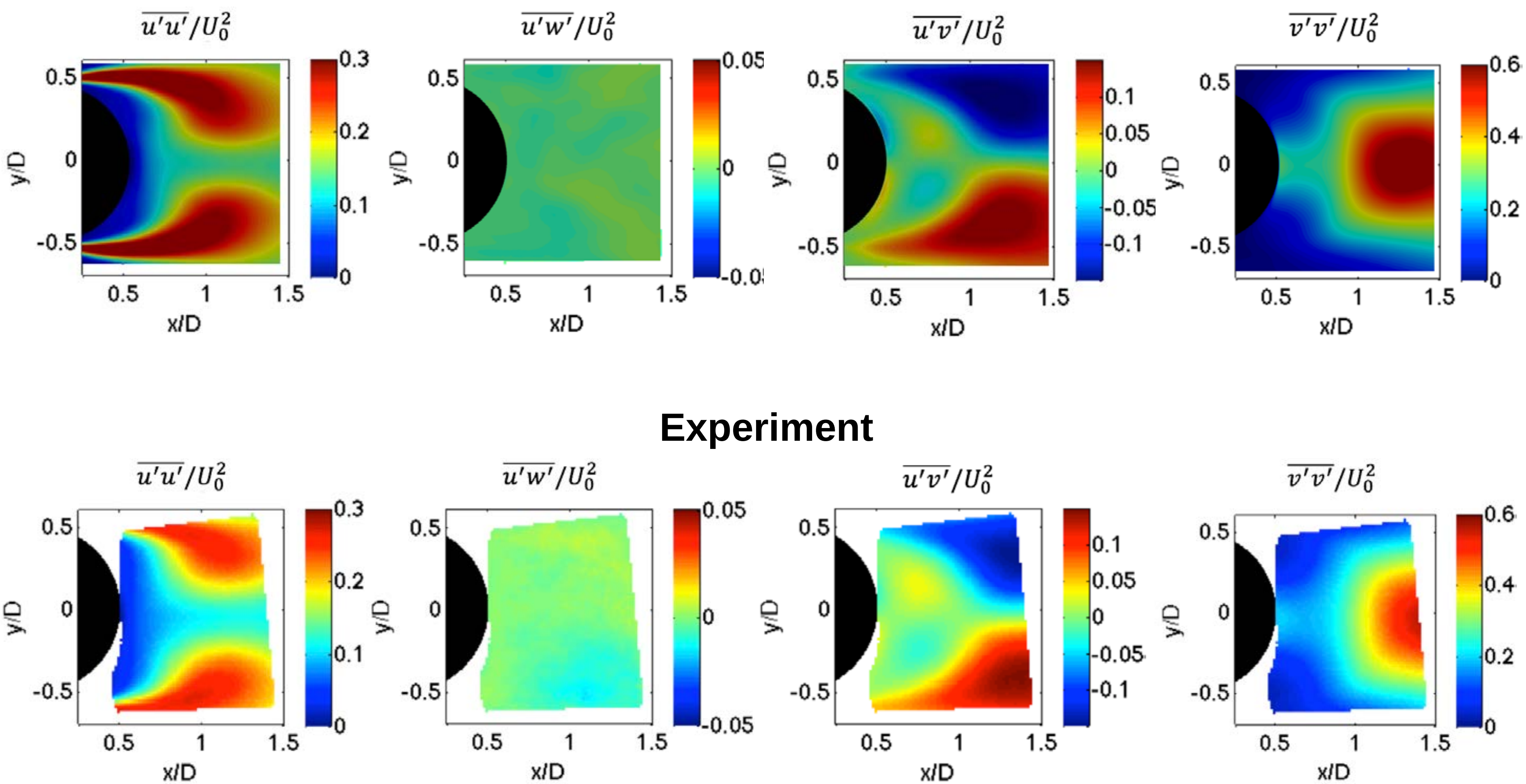
# Reynolds stresses near cylinder

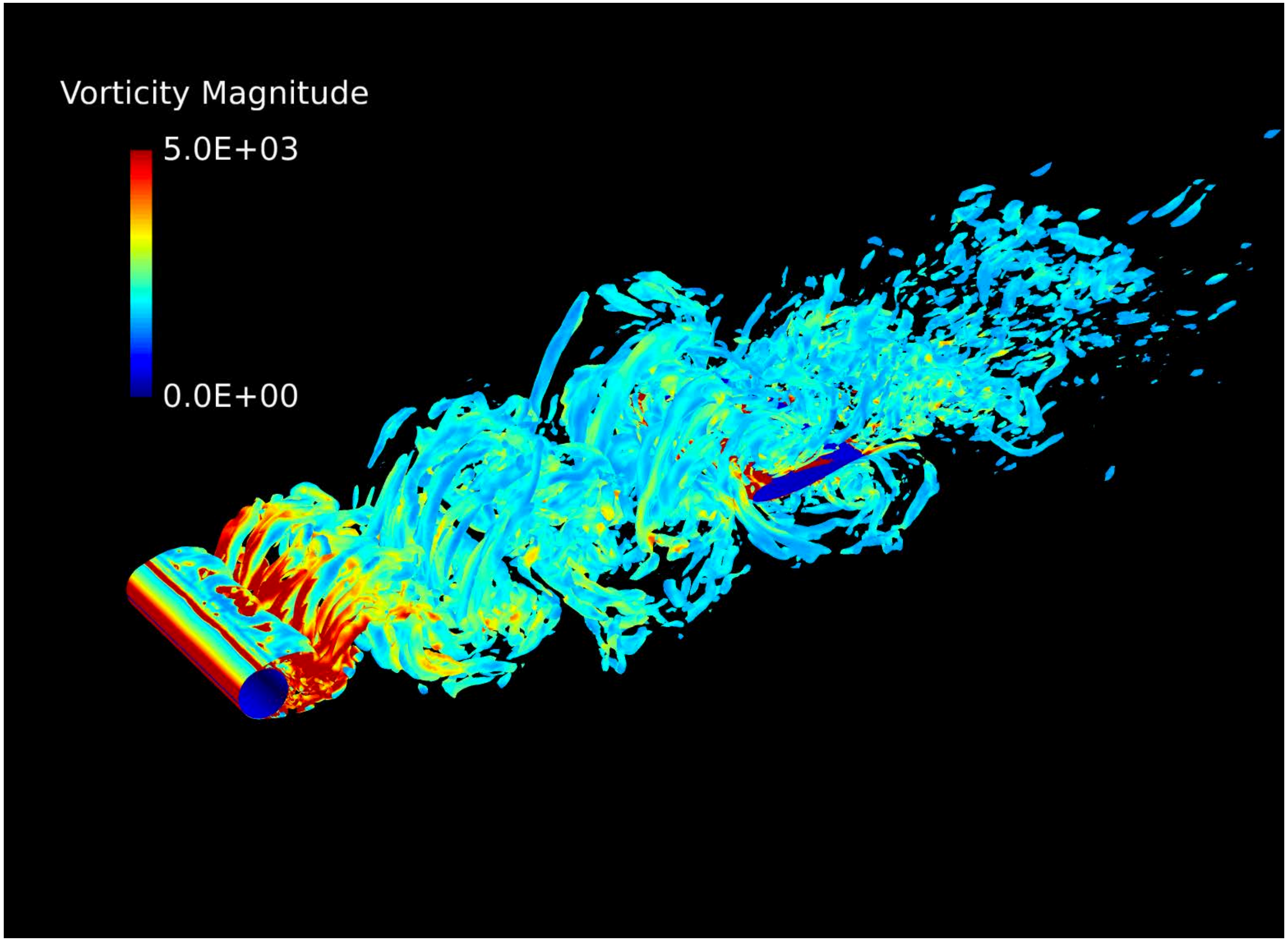
Computation

Experiment




**Qualitatively consistent, still needs detailed quantitative comparisons.**

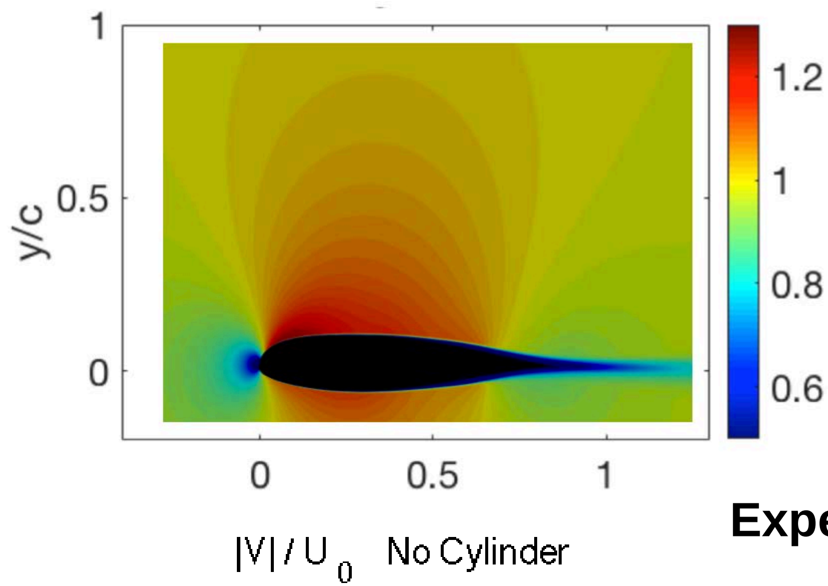
# Cylinder/airfoil unsteady flow

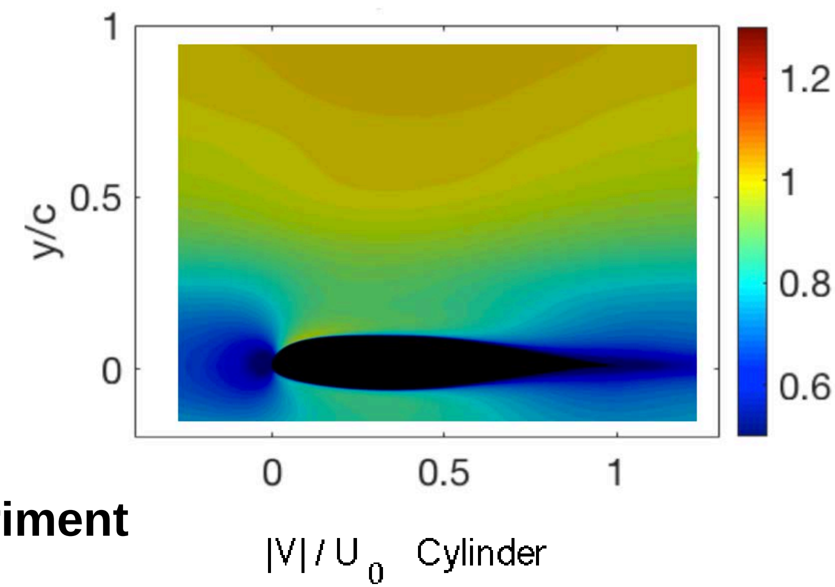


# Airfoil mean flow

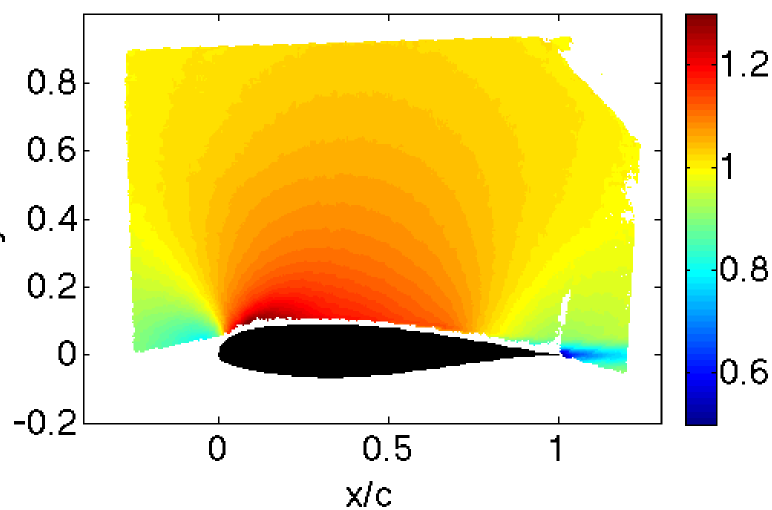


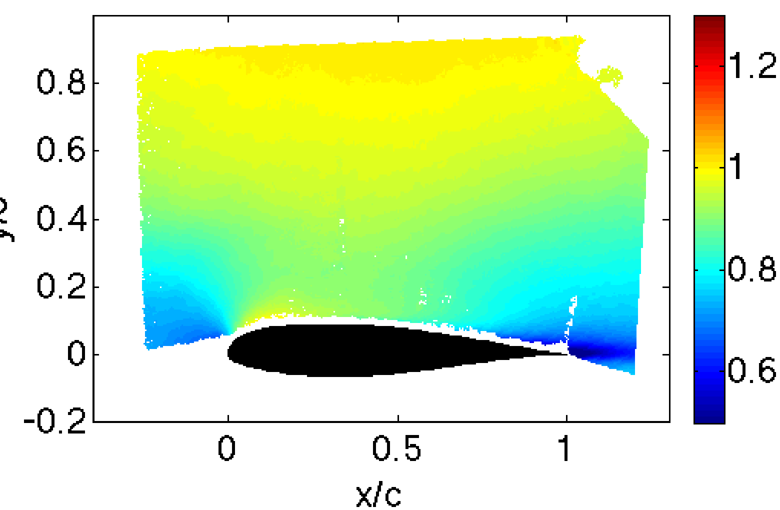
## Computation




## Experiment

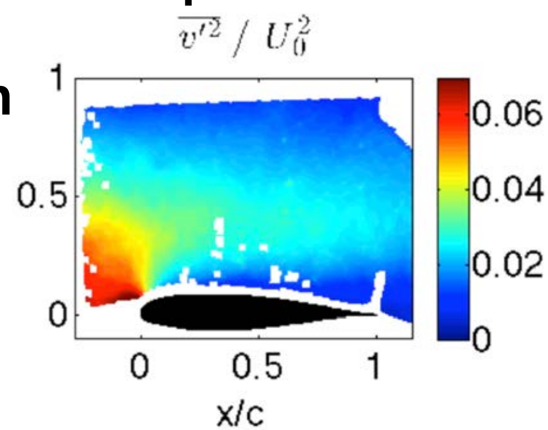


# Value of detailed experimental data during implementation

- **Basic checks during model development, such as Strouhal number consistency**
- **Correlation of major observations**
  - Rapid distortion/pressure redistribution of wake turbulence around airfoil
  - Airfoil *does not separate* in wake, even instantaneously
- **Physics-based insights**

**Experiment**

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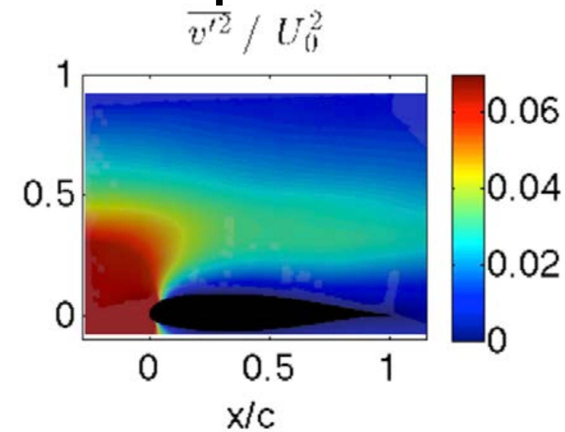


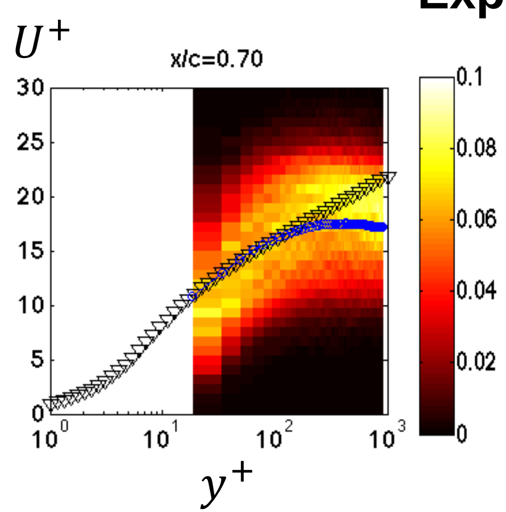


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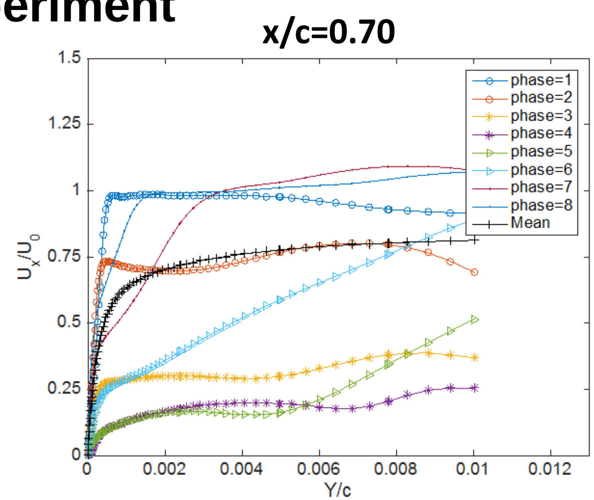

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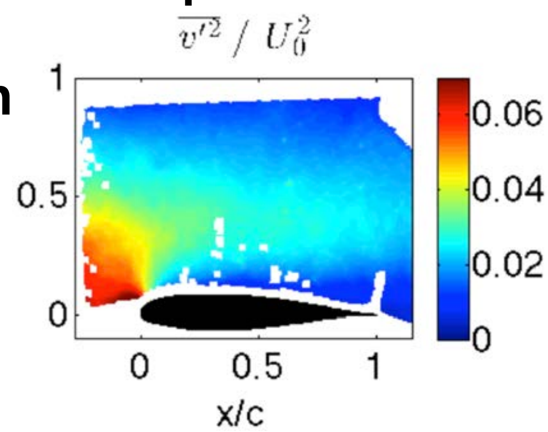


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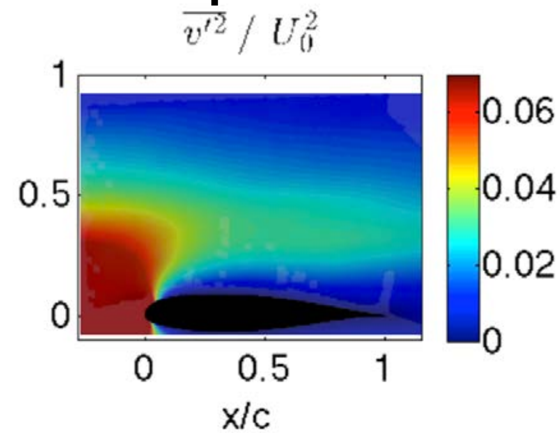


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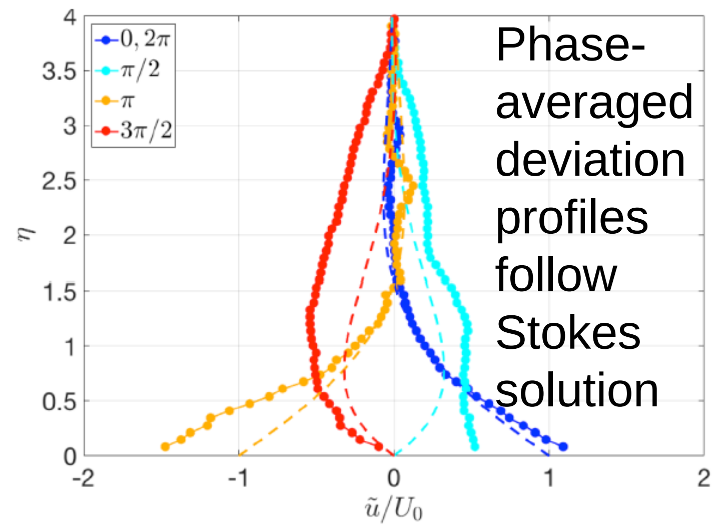



Phase-averaged deviation profiles follow Stokes solution

# Status and directions

- **Benchmark case has simple geometry which creates complex unsteady flow with transitional features.**
- **Detailed experimental measurements for one configuration**
  - Solid model, extensive database to be made available.
  - As Heng Xiao noted yesterday, more parametric variation would be useful data-driven methods
- **Incorporated Langtry-Menter transition model into OpenFOAM DDES framework**
  - Method qualitatively captures many key characteristics of problem.
  - Additional validation and comparison of modeling terms needed.
  - How do gray regions perform for this case/model? What do the experimental results tell us about discrepancies there?
- **Even with advanced diagnostics, very difficult to measure many desired terms**
  - e.g., We can measure intermittency, but is this the same as transported in the model? What does the intermittency mean in unsteady flow?

# Associated references

CREATe
Virginia Tech Center for Renewable Energy and Aerodynamic Technology


Zhang D, Cadel DR, Paterson EG and Lowe KT, 2017 "Numerical and experimental study of the unsteady transitional boundary layer on a wind turbine airfoil" *AIAA SciTech 2017, 35th Wind Energy Symposium*, paper AIAA 2017-0917. (https://arc.aiaa.org/doi/pdfplus/10.2514/6.2017-0917)

Cadel DR, 2016 "Advanced Instrumentation and Measurements Techniques for Near Surface Flows," Ph.D. Dissertation, Dept. Aerospace and Ocean Engineering, Virginia Tech. (https://vtechworks.lib.vt.edu/handle/10919/72968)

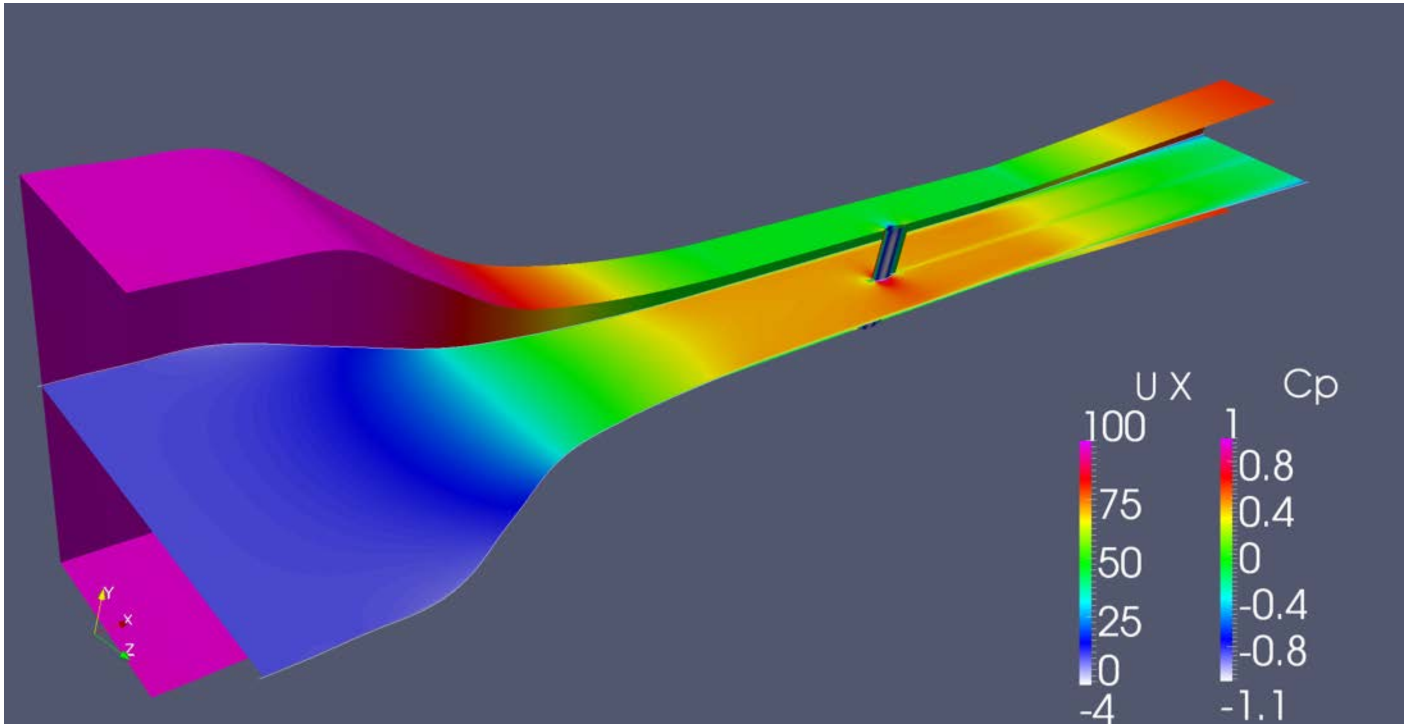
Petrosky BJ, Lowe KT, Danehy PM, Wohl CJ and Tiemsin PI 2015 "Improvements in laser flare removal for particle image velocimetry using fluorescent dye-doped particles," Measurement Science and Technology, 26(11), 115303. (https://doi.org/10.1088/0957-0233/26/11/115303)

Lowe KT and Simpson RL 2008 "Turbulence structural measurements using a comprehensive laser-Doppler velocimeter in two- and three-dimensional turbulent boundary layers," International Journal of Heat and Fluid Flow, 29(3), 820-829. (https://doi.org/10.1016/j.ijheatfluidflow.2008.03.003)

# Extra slides

# Example: advanced diagnostics

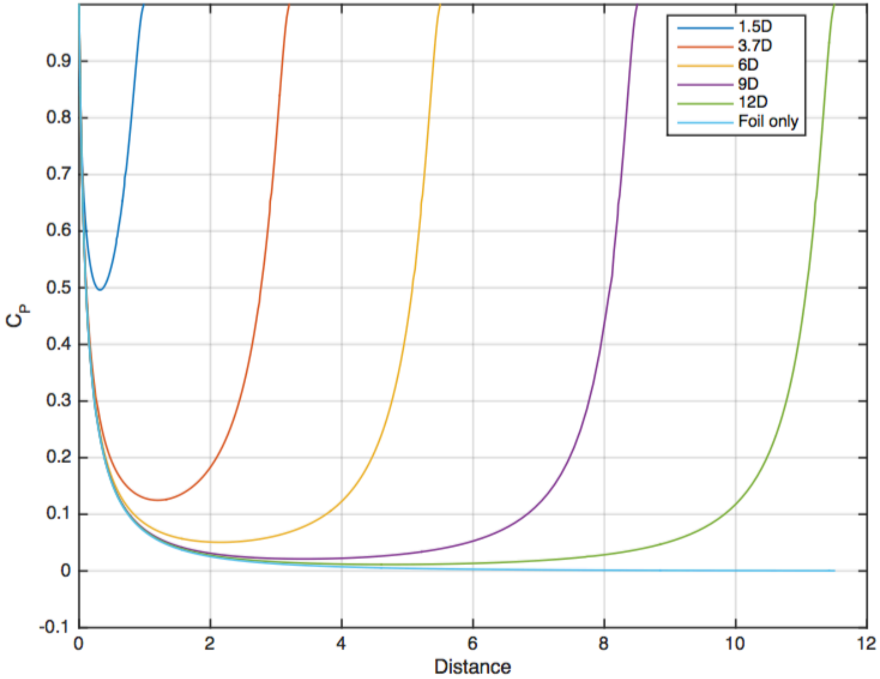
**Approach: RANS simulations of wind tunnel and NACA 4412 airfoil model**




Facility Simulation example from Eric Paterson

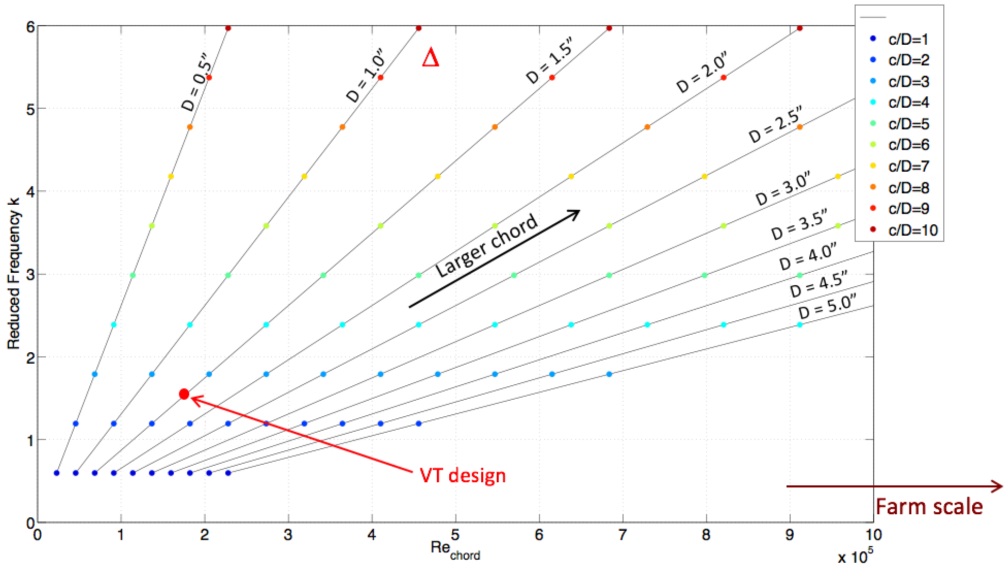
# Example: a priori parameter study

Cylinder/airfoil potential flow interaction




PotentialFoam result of pressure recovery along the centerline from cylinder rear stagnation point to airfoil leading edge

Airfoil reduced frequency/$Re_{chord}$

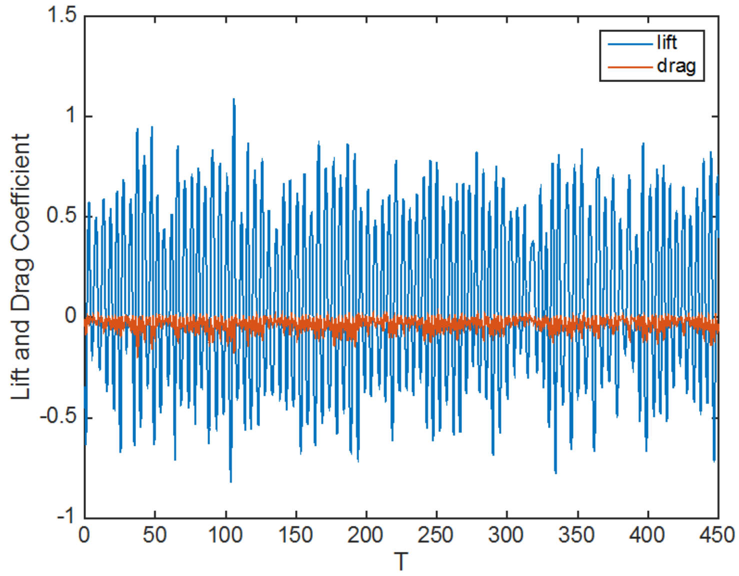


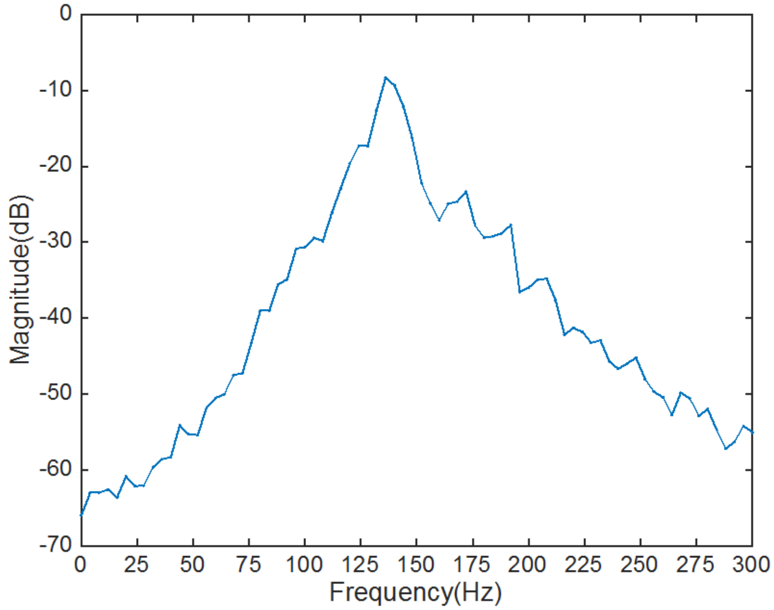

Cylinder diameter D=1.5inches, NACA64215b airfoil chord c=4inches, L=16inches(10.67D), reduced frequency k=1.53. ReD=63,500, Rec=170,000

# Unsteady airfoil results

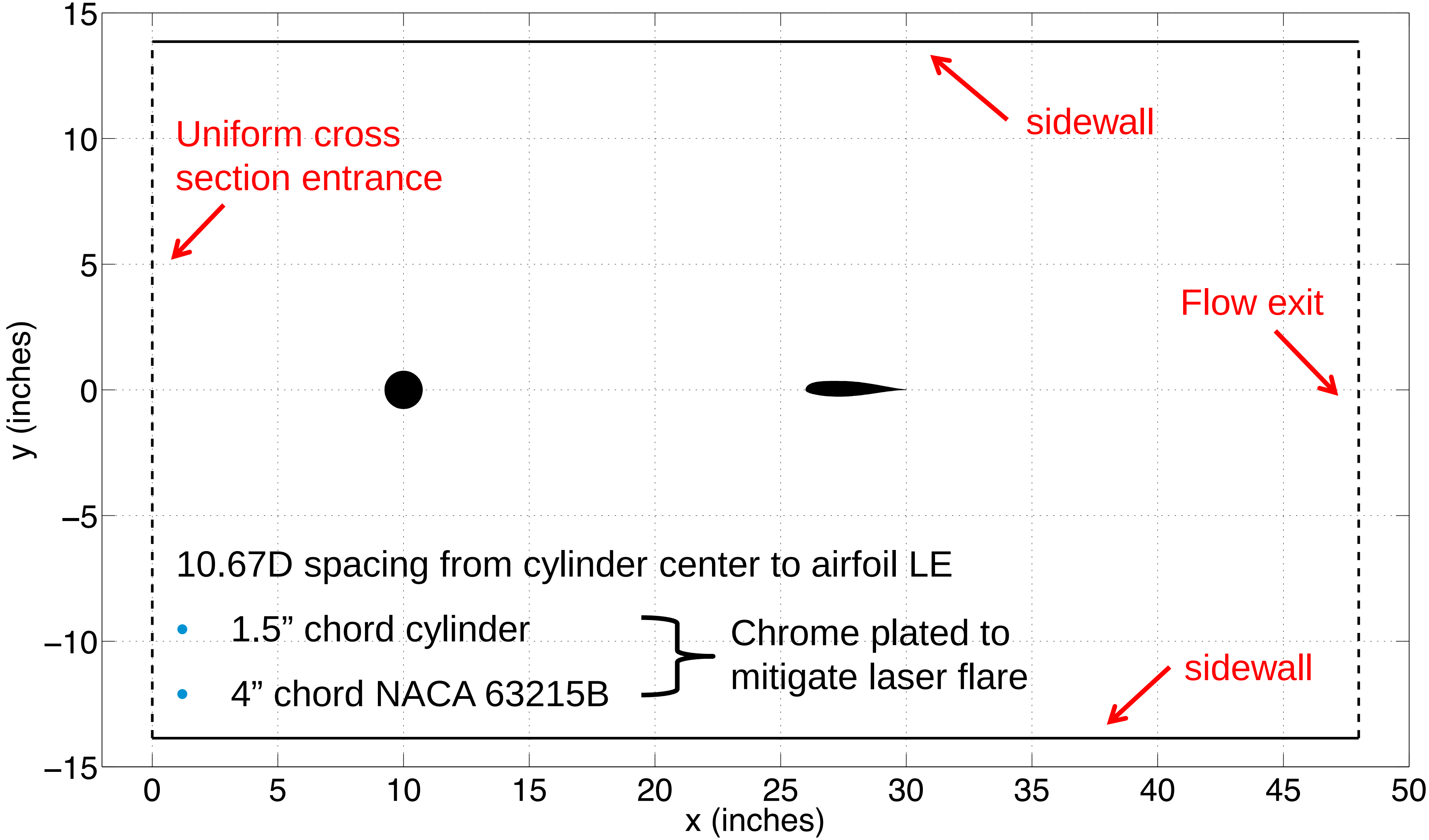
Cylinder Strouhal frequency seen in boundary layer planes and in lift and drag.

Computational lift and drag:



# Final experimental design



# Unsteady inflow PDFs

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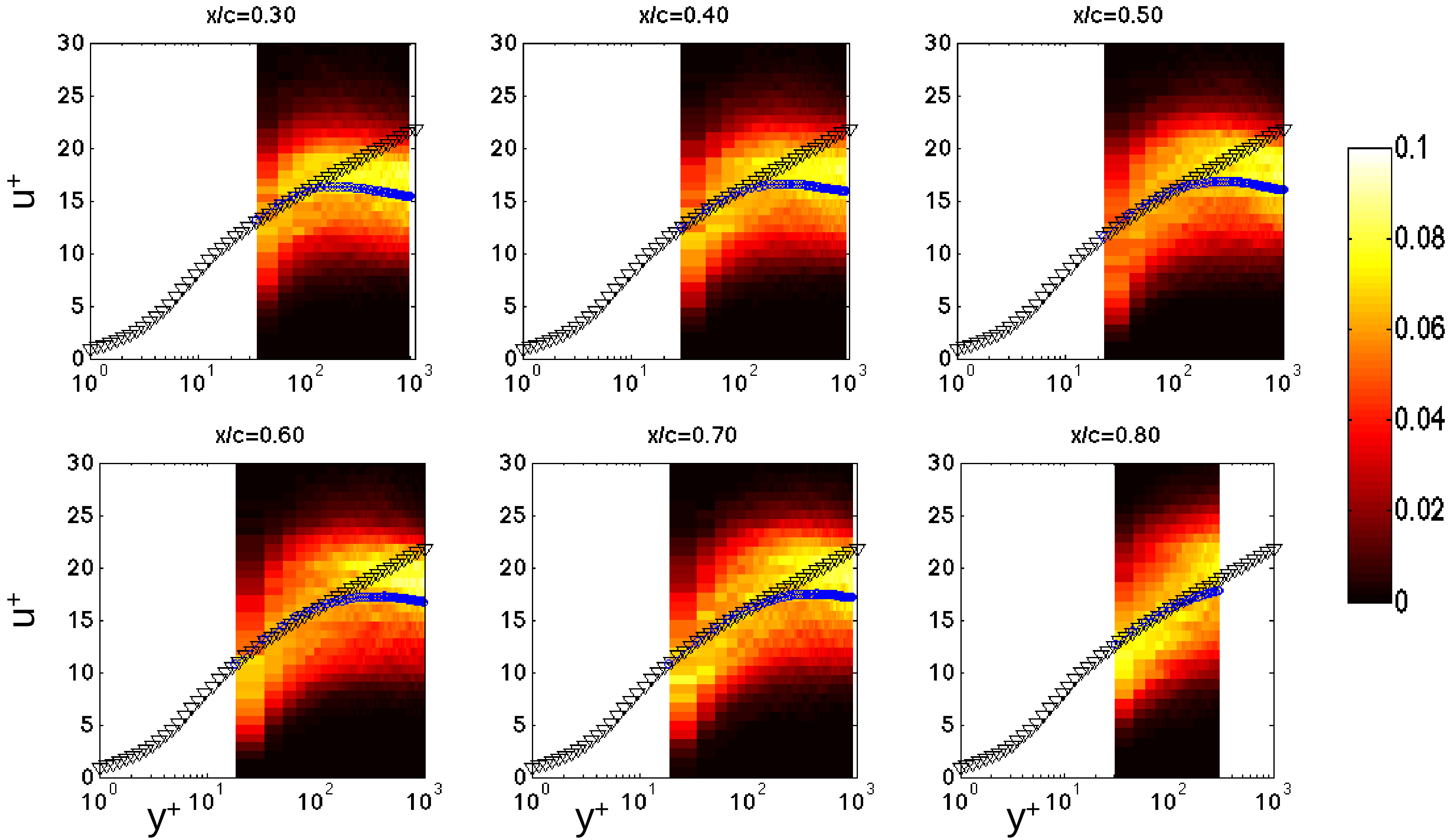
- Large spread seen in the probability density function of instantaneous velocities

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Variation suggests time-dependent nature of profile