Cylinder Wake Feedback Control

Development of Water Tunnel Experimental Setup and Benchmark Problem

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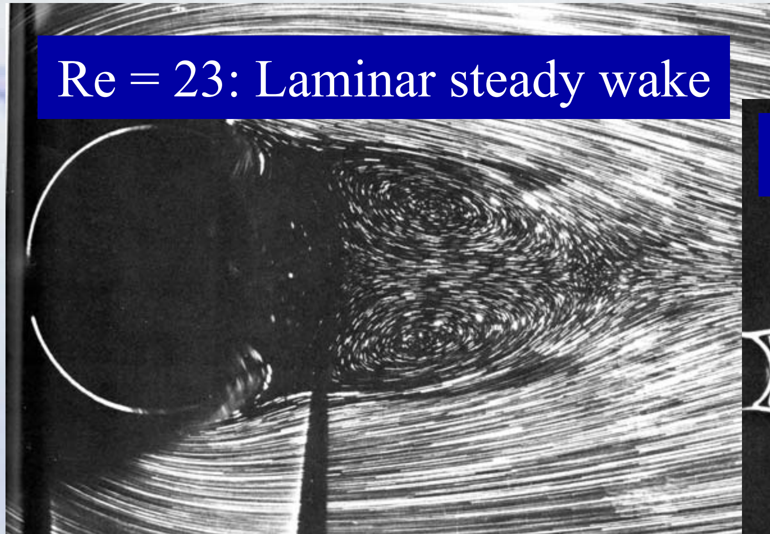
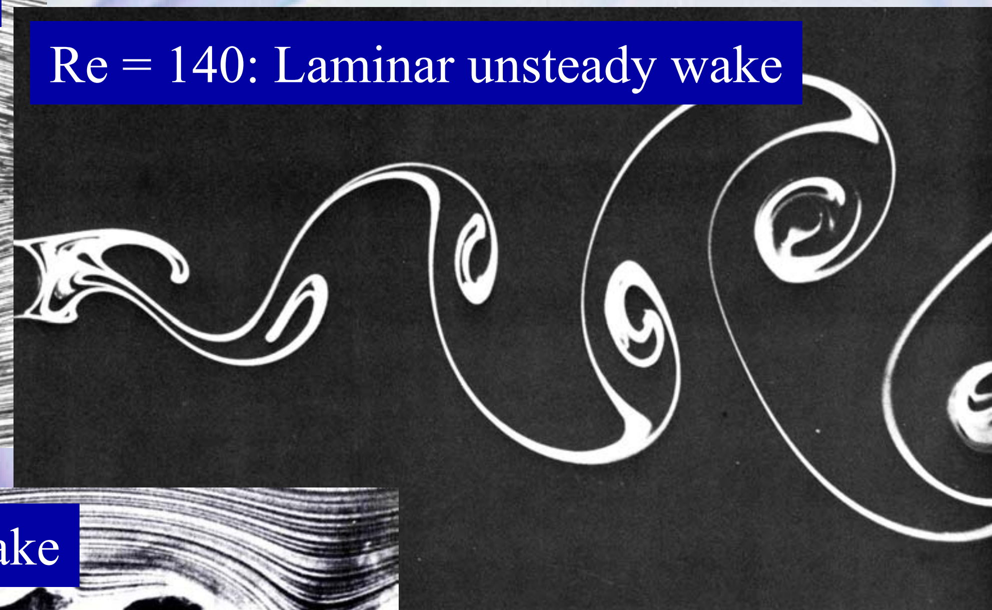
Outline

- Research Objective
  - Fluid Dynamic Properties of Cylinder Wake Flow
  - Why a cylinder wake
- Background
  - Past Research
  - E.A. Gillies JFM Paper
- Benchmark Problem
- Benchmark Infrastructure
  - – Experimental Facility and Setup
  - – CFD Simulations

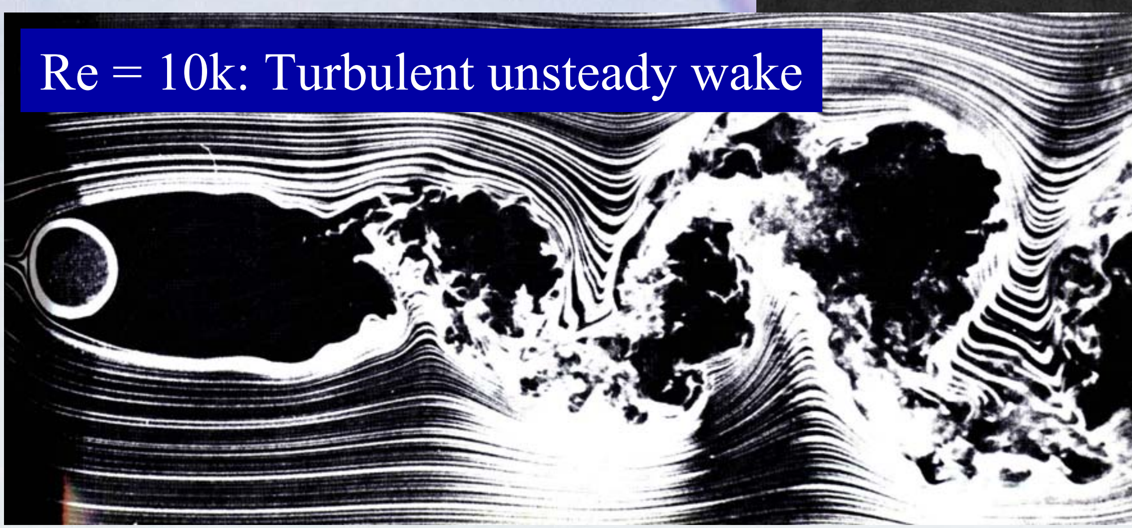
Influence of Re



Re = 23: Laminar steady wake



Re = 140: Laminar unsteady wake

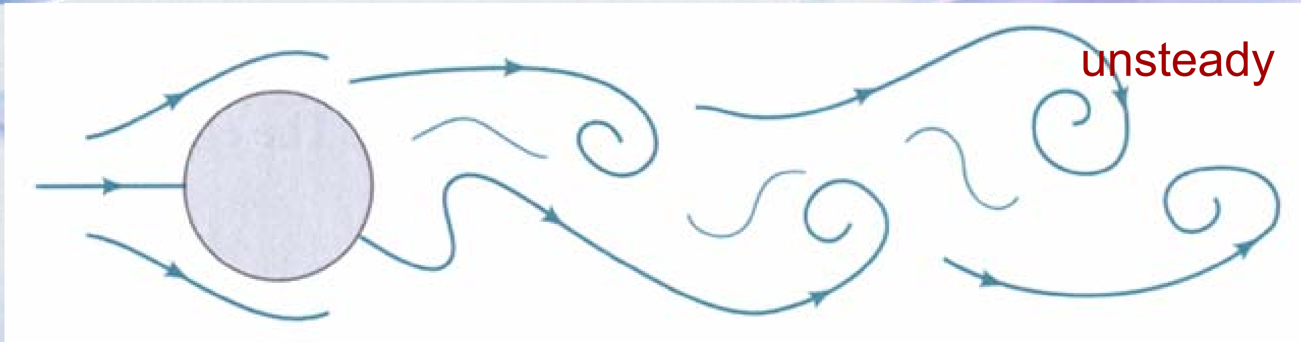


Re = 10k: Turbulent unsteady wake

Why a 2D Cylinder Wake?

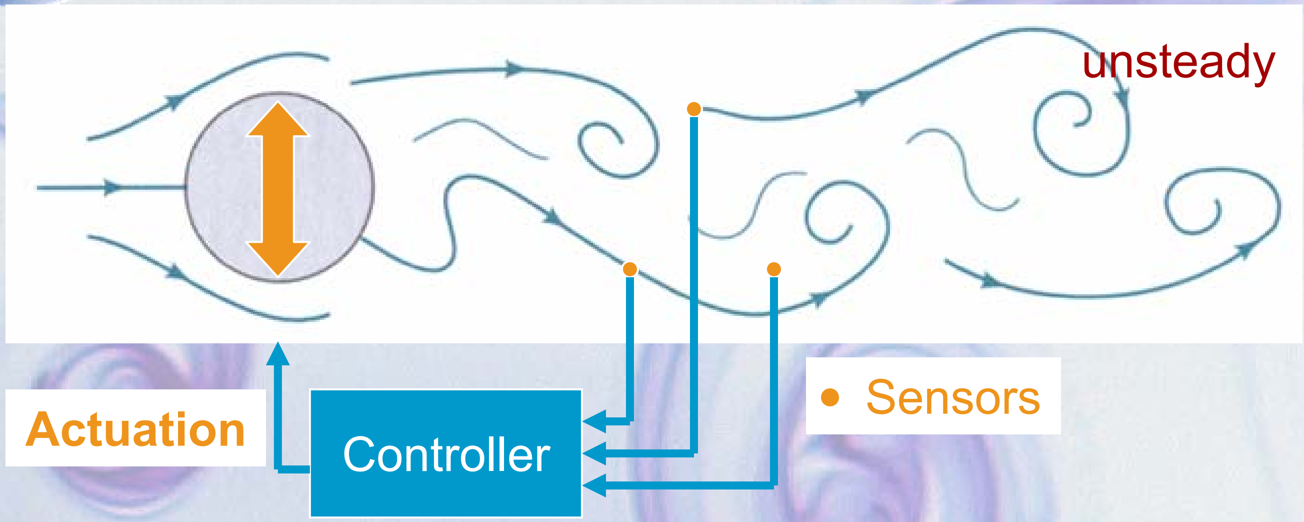
- Simplest Geometry with an absolute instability in the recirculation zone
- Many technical applications
- Natural and open loop forced cylinder wake has been well researched in the past
- Flow can not be stabilized at moderate Reynolds numbers by active, non-feedback control

Cylinder Wake Feedback Control



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

Cylinder Wake Feedback Control



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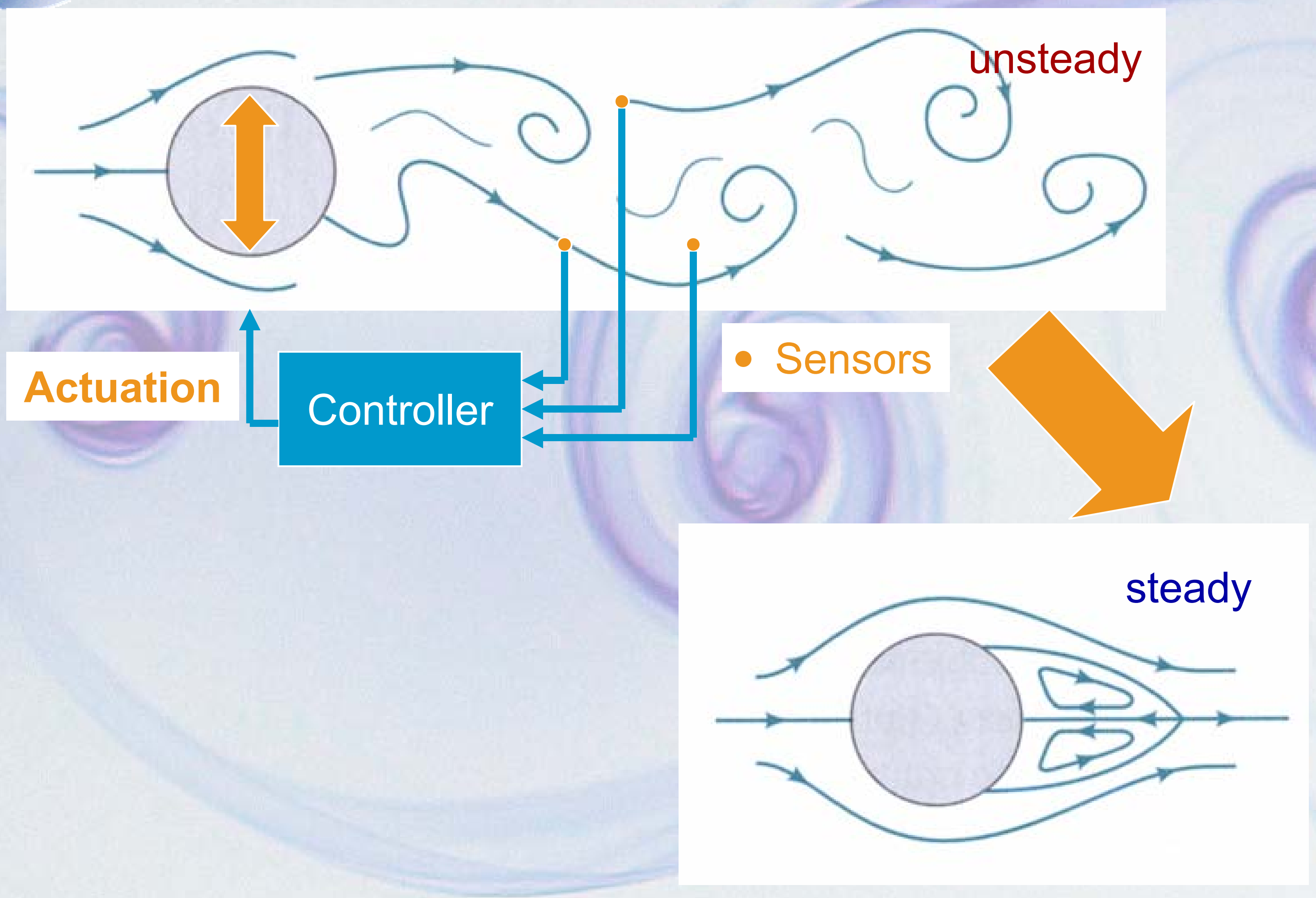
Cylinder Wake Feedback Control



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Literature

- Roussopoulos, Monkewitz
  - "Nonlinear modelling of vortex shedding control in cylinder wakes", Physica D 97, 1996
  - Wake cannot be stabilized beyond Re ~90 using single sensor feedback
- E.A. Gillies
  - "Low-dimensional control of the circular cylinder wake", J. Fluid Mechanics vol. 371, 1998
  - Achieved stabilization at Re=100

Gillies Approach

- Developed a four mode POD model of the forced cylinder wake based on N-S CFD data
- Used a neural network estimator and predictor to determine mode amplitudes
- A self training neural network controller was used to close the feedback loop based on mode amplitudes
- Was successful in stabilizing the POD modeled wake at Re = 100

Circular Cylinder Wake

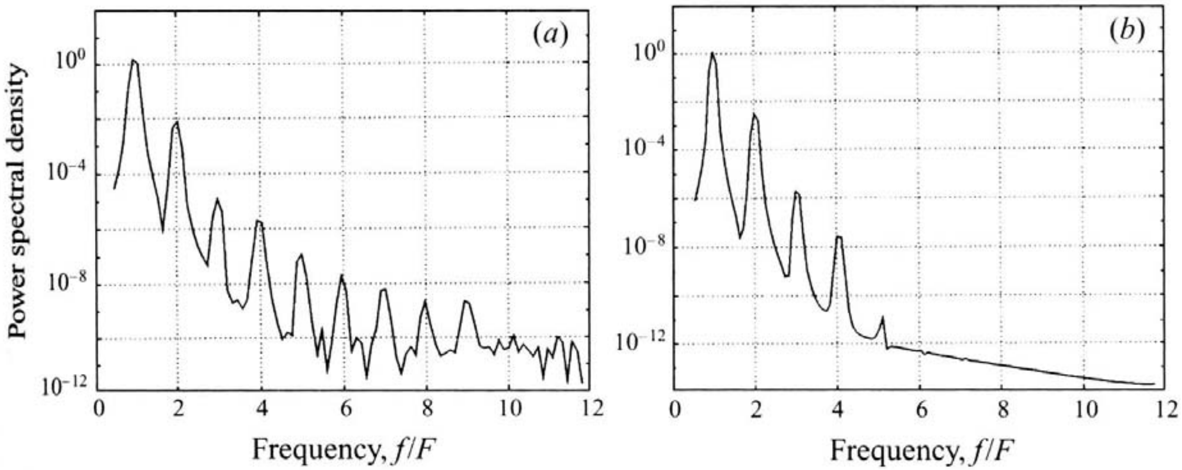


FIGURE 3. Power spectral density of velocity signal: (a) CFD solution, and (b) prototype wake.

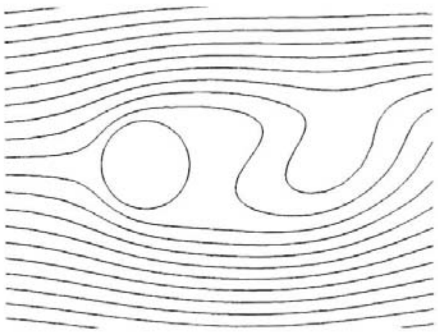


FIGURE 4. Typical instantaneous flow streamlines.

Proper Orthogonal Decomposition

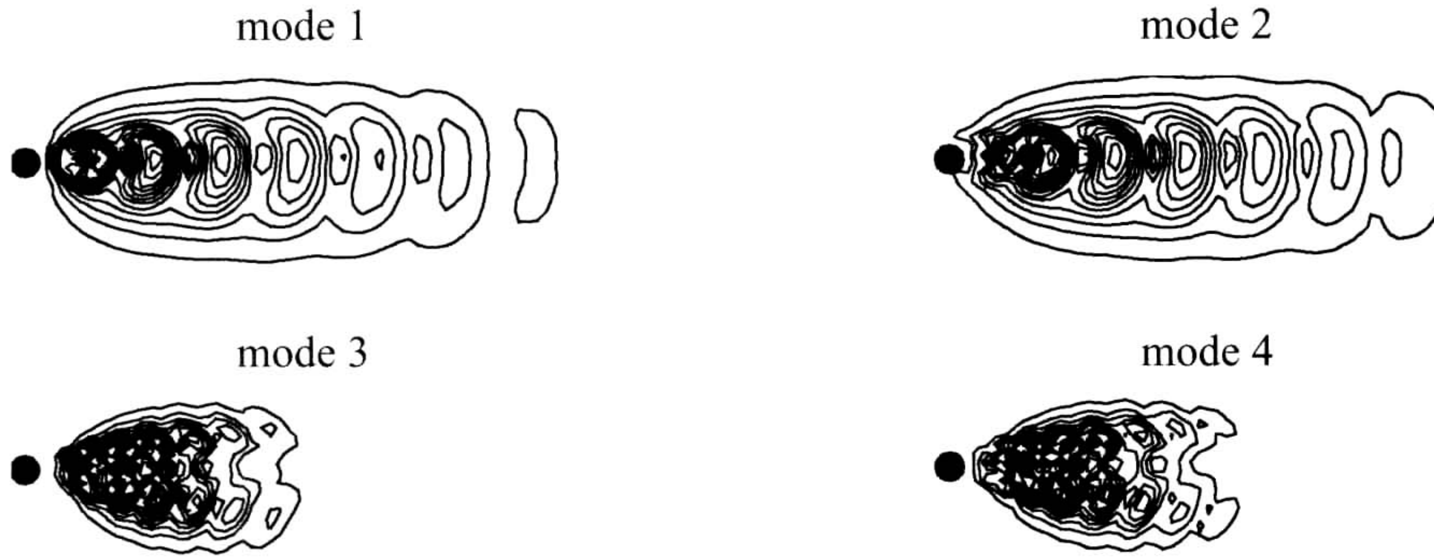


FIGURE 5. Contours of velocity magnitude of the first four POD modes.

Controlled Wake

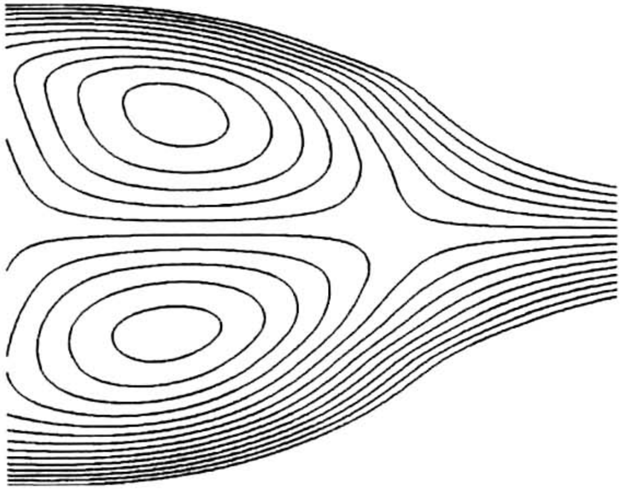


FIGURE 13. Streamlines of prototype wake immediately behind cylinder after successful suppression of oscillations.

Why a Benchmark ?

- Feedback Flow Control requires a multi-disciplinary approach
- Lack of effective “plant” models that enable design of real-time estimation and control strategies
- For control community, investment in experimental infrastructure is substantial in terms of time, money and manpower

Benchmark Goals

- Develop a benchmark that will enable the control specialist to engage in the problem without necessarily setting up an in-house multi-disciplinary team.
- Provide a forum for the application of a variety of control design methodologies.
- Develop a single experimental system, based on the existing infrastructure at USAFA, which will serve as an impartial T&E center for evaluating different strategies.
- Benchmark based on water-tunnel experiment of the cylinder wake, capable of translational motion, with real-time PIV for multi-sensor study, as well as CFD simulation

USAFA Circular Cylinder Wake Benchmark Specs

- Circular Cylinder Wake at Re = 120
- Actuation through cylinder translation
- Multi sensor capability
- Controller implementation in SIMULINK
- Implemented as
  – Water tunnel experiment
  – Computational Fluid Dynamics, DNS based

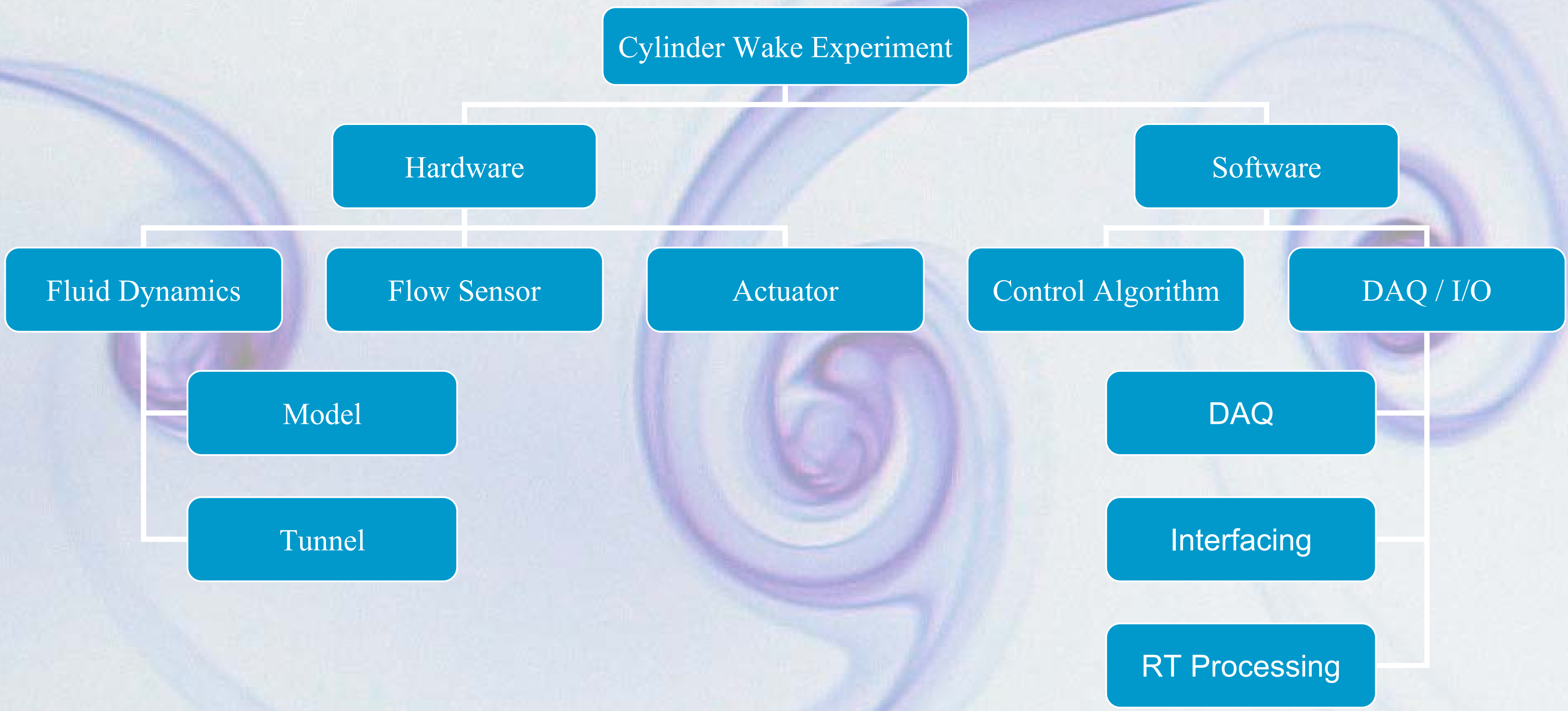
Summary Benchmark

- USAFA proposes an experimental benchmark, based on the closed-loop flow control of a cylinder wake.
- This benchmark will enable contracted researchers access to a cost-effective experimental infrastructure.
- It will provide the USAF with an objective method of experimentally testing and evaluating different closed-loop control strategies.
- USAFA welcomes any possible collaboration in this area.

Experiment Objectives

- Create a cylinder wake experiment suitable for feedback control including sensors, actuators and the model itself
- Provide Hardware and Software to integrate the experiment with MATLAB/SIMULINK
- Attempt to implement a control strategy based on a low dimensional POD model to stabilize the wake

Experiment Design Blocks



Fluid Dynamics Issues

- Low Reynolds Number
  - Low Flow Speed
    - Negligible dynamic pressure
    - Turbulence Level increases
    - Convection
  - Small Model Size
    - Difficulty finding small sensors
    - Machining, precision issues
- Absolute Instability
  - Flow will be disturbed by infinitesimally small objects
- High Aspect Ratio
  - Model Accuracy
  - Runout, machining Problems

Tunnel Options

- Re=120 , St = 0.2
- Wind Tunnel
  - U_{inf} = 5 m/s, D = 0.36 mm
  - f = 2.77kHz
- Water Tunnel
  - U_{inf} = 30 mm/s, D = 4.97 mm
  - f = 1.2 Hz

⇒ Use Water Tunnel

⇒ Re 10k U_{inf} = 10 m/s, D = 15 mm
f = 13.3 Hz; still laminar flow

$$\mathrm{Re} = \frac{U_{\inf} \cdot D}{\nu};$$

D = Cylinder Diameter

$U_{\inf}$ = Freestream Velocity

ν = Kinematic Viscosity

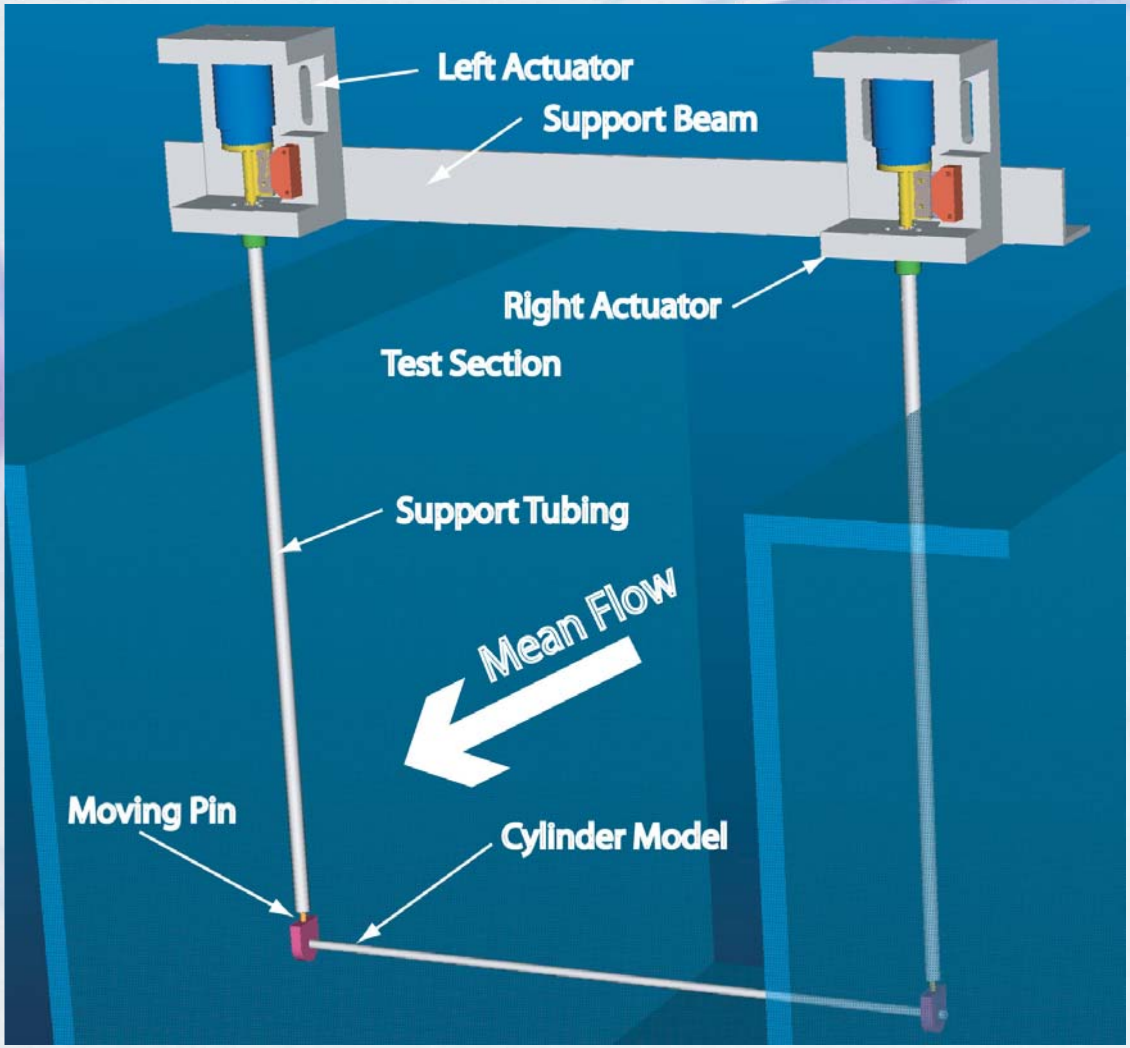
$$\nu_{H_2O} = 1 \cdot 10^{-6}$$

$$\nu_{Air} = 15 \cdot 10^{-6}$$

$$St = \frac{f \cdot D}{U_{\inf}}$$

f = Frequency

Cylinder Model



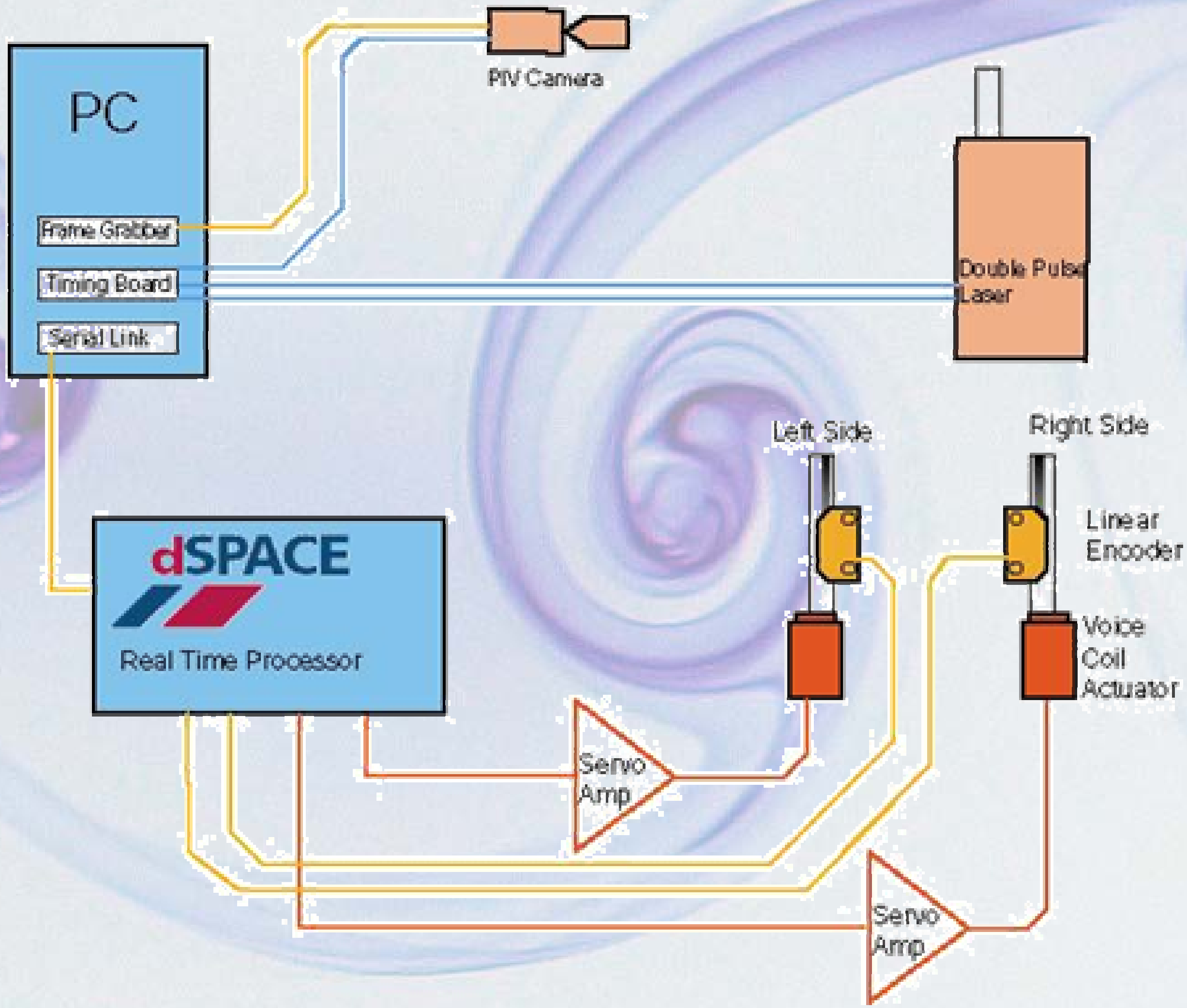
Sensor Issues

- Non-Intrusive
- Multiple Sensor Locations
- Real Time capable
- High Positioning Accuracy Requirements for Sensors
- Reproducibility

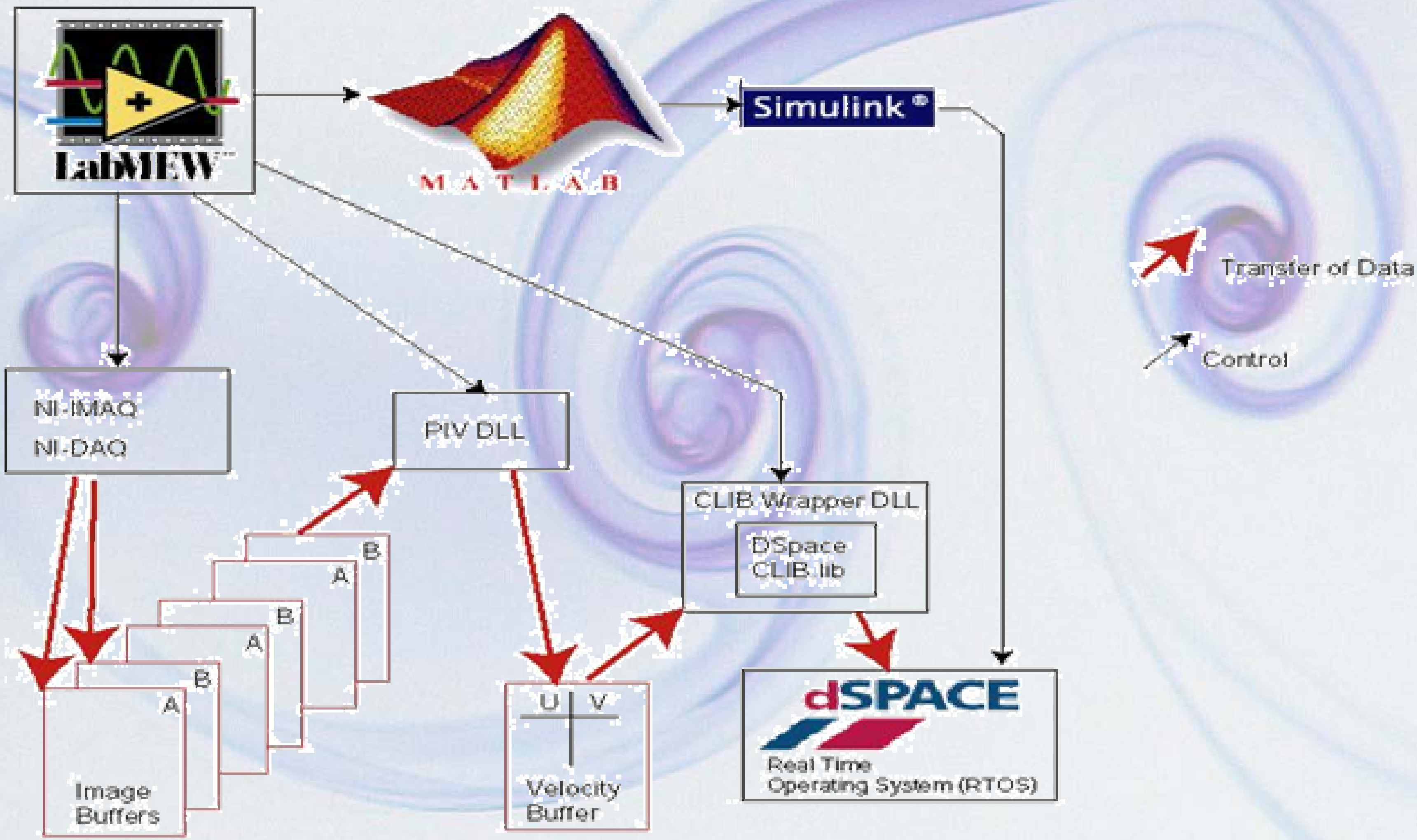
Sensor Selection

- Laser Doppler Anemometry
  - only one sensor location per unit, does not lend itself to multi-sensor studies
- Hot Film Probes
  - Intrusive
- Particle Image Velocimetry
  - \+ Many sensor locations
  - \+ Non-intrusive
  - \+ Separate velocity components
  - \+ Easy to calibrate and position
  - \+ moderately expensive
  - \- Limited time resolution
  - \- No real-time system commercially available, only off-line processing

Computer System



Software Layout



PIV System Development & Accomplishments -1

In-House System	Original System COTS
On-line operation, real time	Only off-line operation
Advanced trigger capabilities	Limited synchronization options
Interfaces to Matlab, LabVIEW, Tecplot, C	Only ASCII export
Modular, open architecture, easy to modify, hardware independent	“Black Box” closed, fixed system, no customization possible
>3k Vectors/s in direct Correlation	~2k Vectors/s in frequency domain

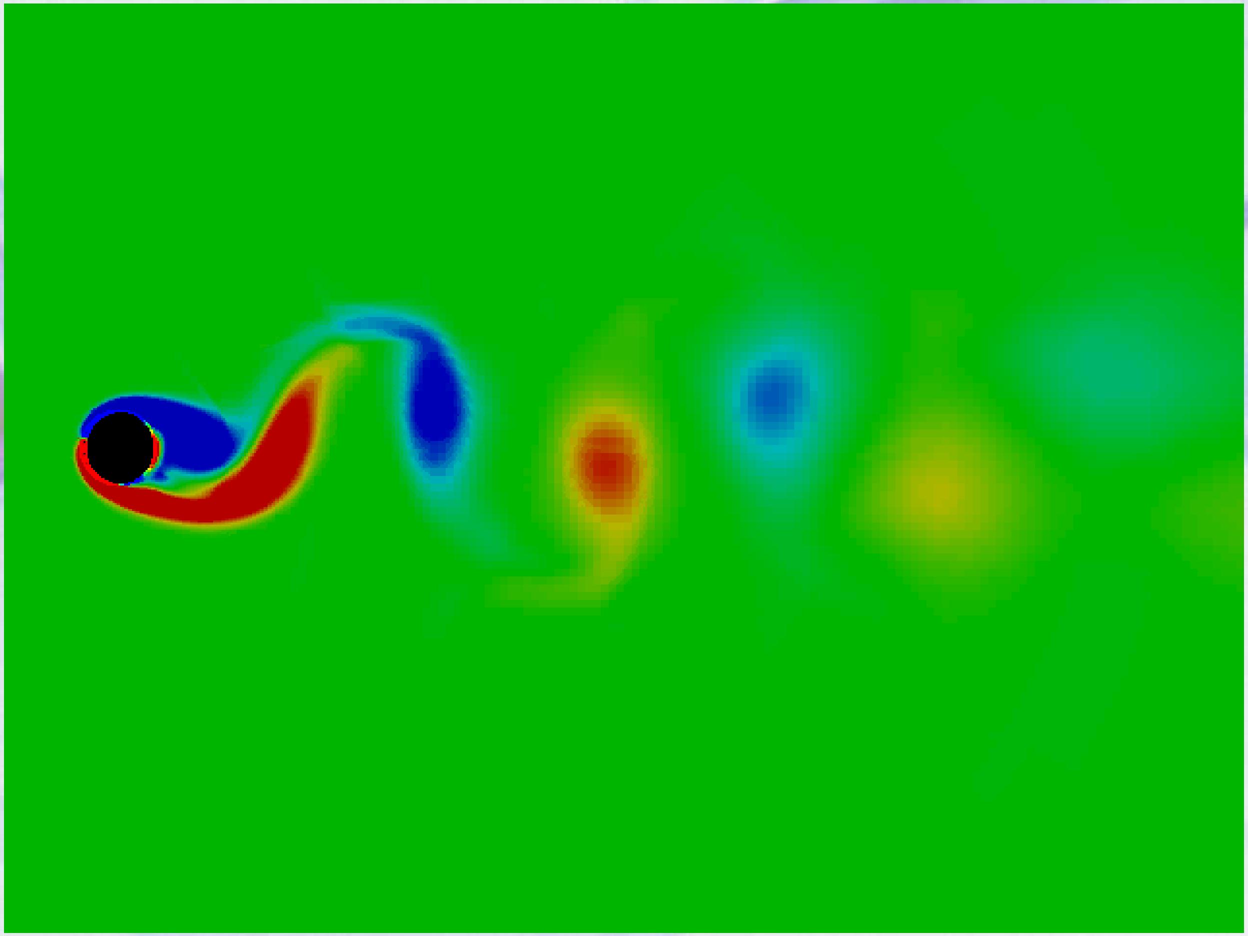
PIV System Development & Accomplishments -2

In-House System	Original System COTS
Data available on-line in PC Memory – 1000x faster	Data needs to be uploaded from Processor (slow)
Source code owned by AF, available public domain for non-commercial use	No access to source code, additional license is $14k
$3500 for Hardware	$40,000 for Hardware
Data acquisition process one order of magnitude faster	-
Multi-Sensor Real time capability	-

Simulation

- Uses Cobalt as flow solver
  - Unstructured Grid, 2nd Order, Finite Volume, 2D/3D
  - Runs on USAFA's Beowulf Linux Cluster (32 Nodes / 64 Processor P3/1GHz)
- Custom Feedback Control Module for Cobalt
  - Writes Sensor information after calculating one time step to a interface file
  - Waits for Control algorithm to update file with actuator position command before calculating next time step
- Control Algorithm Implementation
  - On separate PC running MATLAB/SIMULINK
  - Independent from CFD solver

Open Loop CFD Results



Next Steps

- Open loop dynamic system response measurements to develop POD model
- Development and implementation of control algorithm
- Experiment:
  - Implementation and test of CLIB interface between PC and Real Time Processor
  - Overall timing analysis
- CFD:
  - Coding and Test of Interface to Simulink

Summary

- Defined a benchmark flow control problem
- Conceptual design, implementation and test of a low Re Cylinder wake experiment suitable for closed loop feedback control
- Developed and tested a real time PIV system from scratch
- Implemented feedback control capabilities into commercial CFD code