Feedback Control of a Circular Cylinder Wake

Integrating CFD and Experiments in Aerodynamics
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What is Feedback Flow Control?

- **Flow Control**
  - Influence the flow field to achieve a desired effect using *minimal* actuation power
    - **Passive**
      - Vortex generators
    - **Active**
      - Synthetic jets
      - Time-dependent (periodic) blowing and suction
      - Piezo-electric micro components

- **Feedback**
  - Sensors in the wake measure instantaneous flow quantities (velocity, pressure) at given points
  - Actuation based on sensor information
• Bluff bodies (e.g. on UAVs) serve vital operational functions, but they are aerodynamically detrimental
  - Flow separation results in a wake behind the bluff body
    - characterized by unsteady vortex shedding
    - results in drag, noise, and vibration
    - is detrimental for operation, structural integrity
  - “Passive” designs are impractical or inhibit functionality
  - “Active” methods are point designs
  - Feedback flow control is an effective way of suppressing self-excited flow oscillations without modifying the geometry
How to Feedback Flow Control?

Modeling wake dynamics for controller design

Model Independent Approach
- Simple to implement experimentally
- Little success in past 30 years

Direct Navier Stokes Approach
- Ideal control approach, complete set of equations
- Computationally very intensive
- Cannot be implemented in real time in the near future

Low-Dimensional Approach
- Recent developments in effective low-dimensional models
- Can be implemented with relative ease
- Model building is tough
Goal: Develop a feedback control strategy to suppress the vortex street of a cylinder at Reynolds numbers of 100.
Collaborative Research

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Collaborative Research

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Unforced and Open-loop forced

EXPERIMENTS
Unforced
Forced case 1

$St/St_n = 1$, $A/D = 20\%$
Forced case 2

$\frac{St}{St_0} = 1.26$, $A/D = 30\%$
• Conventional wisdom: the low-dimensional model should be valid for arbitrary control actions
  - There is a limited envelope of amplitude/frequency of the disturbance wherein the control is effective.
Experiments: Pros and Cons

• Pros
  ▪ Overview/visualization of flow field
  ▪ Easy scan of frequency/amplitude parameter space
  ▪ Final verification

• Cons
  ▪ Expensive model design and building
  ▪ Limited data available
    • Velocity, pressure
    • Field of view
    • State-of-the-art (e.g. PIV) only 2D
Unforced and open-loop forced

SIMULATIONS
Simulations

- Cobalt
  - Hybrid-Unstructured, Compressible Solver
  - Point Implicit with Subiteration
  - 2nd-Order Temporal and Spatial Accuracy
  - Turbulence Models
    - RANS: SA, SARC, SST, and others
    - Hybrid RANS/LES: SA-DES, SARC-DES, SST-DES
  - Domain decomposition using ParMETIS (Dr. Karypis, UMN)
  - MPI parallelization
    - Over 98% efficient on 1024 processors
  - Arbitrary Lagrangian Eulerian (ALE) for rigid body motion
  - Variety of motion types: 1DOF, 6DOF

- Matlab
  - Controller development
  - Data analysis
  - Post-processing

- Cobalt-Matlab interface for feedback flow control
  - Developed under current AFOSR STTR Phase I/II
  - HDF5 output
Transient Startup Data Set

Re = 300
3D cylinder: grid

- Body fitted “O” grid extruded along cylinder axis
- 163x198x31 (r, q, z) points
Simulation, Re=100

- L/D=96
- Grid:
  - 2M nodes
  - 31 spanwise planes
- Time:
  - 50 periods
  - 5.6CPUh/period
Simulations, Re=20,000

- L/D=4
- Grid:
  - 1M nodes
  - unstructured
- Time:
  - 180CPUh/period
Simulations: Pros and Cons

• Pros
  ▪ Detailed flow field information
    • Time
    • Space
  ▪ Range of possible flow conditions
    • Reynolds number transients

• Cons
  ▪ Time consuming model/grid design and building
  ▪ Time consuming data generation
  ▪ Limited number of conditions possible
    • Parameter space
MODELING AND CONTROLS
Control of a Ginzburg-Landau cylinder wake model

- The complex Ginzburg-Landau (GL) equation model
  - vortex dynamics in bluff-body (such as a circular cylinder) wakes
  \[
  \frac{\partial A}{\partial t} + U \frac{\partial A}{\partial x} = \mu(x) A + (1 + j c_d) \frac{\partial^2 A}{\partial x^2} - (1 + j c_n) |A|^2 A + F(x, t)
  \]

- Wake stability of the GL model is defined by the growth parameter \( \mu(x) = \mu_o + \mu'x \)
  - \( \mu_o \) is similar to a Reynolds based on the cylinder diameter.
  - For \( \mu' < 0 \), the stability features similar to 2D cylinder wake.

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<tr>
<th>Condition Studied</th>
<th>C_{11}</th>
<th>C_{12}</th>
<th>C_{21}</th>
<th>C_{22}</th>
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<td>12.5% Above Critical</td>
<td>1.4524</td>
<td>4.1250</td>
<td>5.1486</td>
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<td>20.0% Above Critical</td>
<td>4.2744</td>
<td>6.9612</td>
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Look-up table for Coefficients \( C_{ij} \) of the modal estimator

Wake Signal at 20% above Critical
Proper Orthogonal Decomposition (POD)

N Snapshots of Flow Field
U(x,y,t)  
V(x,y,t)

K Temporal Mode Amplitudes
A_1(t)  
A_2(t)  
...  
A_K(t)

K Spatial Modes
U_1(x,y)  
V_1(x,y)  
U_2(x,y)  
...  
V_K(x,y)
POD and Low Dimensional Modeling

- POD spatial modes
  - Flow characteristics
  - Sensor placement studies

- POD mode amplitudes
  - Low Dimensional Model Development
    - Develop real time nonlinear mapping based on neural networks between measurable quantities (pressure, velocity) and low dimensional states
    - Linear and nonlinear system identification tools
    - Develop control strategies

- Reconstruction of the flow field possible

- Massive reduction of CFD simulation data
SPOD Segmentation

![Graph showing Lift Force vs. Simulation Time]

- Simulation Time [s]
- Lift Force [N]
- Bin 4
- Bin 18

Legend:
- Lift Force
- Segmentation
DPOD Basis Construction

- **POD:** \( u(x, y, t) = \sum_{j=1}^{J} a_j(t) \varphi_j(x, y) \)

- **SPOD:** \( u^{(i)}(x, y, t) = \sum_{j=1}^{J} a_j^{(i)}(t) \varphi_j^{(i)}(x, y) \).

- **DPOD:** \( u^{(i)}(x, y, t) = \sum_{j=1}^{J} \sum_{k=1}^{K} \alpha_{jk}^{(i)}(t) \Phi_{jk}(x, y) \).

\( f(x, y, t) \) snapshots
\( k \) bins
\( n \) snapshots

POD (Sirovich)
Truncation to \( m \) Phys. Modes

Truncation to \( n \) Shift Modes

Orthonormalization

\( m \times n \) DPOD Modes \( f(x, y) \)
Modeling: Pros and Cons

• Pros
  ▪ Rapid exploration of controller parameter space
  ▪ Implementable in real-time with relative ease
  ▪ Effectively targets the large coherent structures in the flow

• Cons
  ▪ Model building is tough
  ▪ Quality/validity of model depends on underlying data
    • Parameter space
Feedback controlled

EXPERIMENTS
Experimental setup

Flow Vis Camera

Cylinder Actuation System

Test Section

Cylinder Model

PIV Camera

Strobe Light

PIV Laser
Sensor and Flow Vis Setup

- Dye Ports for Flow Vis (@ far end of model)
- Laser Light Sheet and Feedback Measurement Plane (@ center of model)
- Flow Direction
- Cylinder Model
- PIV Laser
Phase 115° Flow Vis

Time 10s: Flow is 2D, Locked-In

Time 20s: Flow develops spanwise phase variation, vortices shedding delayed in phase at laser light sheet
Phase 115° Flow Vis – Cont’d

Time 30s: Stronger Spanwise phase variation

Time 33.3s: Spanwise phase becomes chaotic, incoherent
Experiments: Pros and Cons

• Pros
  ▪ Verification of entire feedback flow control concept
  ▪ Visualization of flow field
  ▪ Easy scan of controller parameter space

• Cons
  ▪ Expensive feedback control implementation
  ▪ Limited data available
    • Sensors for real time feedback are limited to 2D
      ▪ Wake
      ▪ Surface
    • 3D information only available through flow visualization (offline)
  ▪ Debugging of feedback controller difficult
Feedback flow control

SIMULATIONS
3D cylinder: wake sensors

35 Sensor Locations
Feedback controlled

Isocontours of Vorticity colored by U Velocity

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Feedback controlled

Centerline

¼ span
Summary

- Develop feedback flow control strategy based on low dimensional model
  - Global flow state estimation using POD
  - State based feedback controller
- Otherwise, this flow is not controllable
Best use for feedback flow control

• Experiments
  ▪ Initial qualitative flow physics understanding
  ▪ Open-loop parameter scans
  ▪ Final testing of controllers

• Computations
  ▪ Detailed data production of key cases (determined by experiments)
  ▪ Debugging of feedback flow control
    • Data availability, no measurement errors

• Modeling
  ▪ Crucial for controller development
  ▪ Initial controller testing
  ▪ Model provides global flow state estimation for real time implementation
Conclusions

• Integration of theory, experiments and simulations
  ▪ more than the sum of all three
  ▪ evaluate best possible use of each at beginning of project

• Need experts in all involved fields
  ▪ But: each expert needs working knowledge of all other fields involved

• Communication is paramount

• State based feedback flow control impossible without IFD
Outlook

• Application of developed feedback flow control methodology
  ▪ Higher Reynolds numbers
  ▪ Turbulent flows

• New applications
  ▪ Aero Servo Optics
  ▪ Unsteady aerodynamics (MAV, flapping flight)