Active Control of Separated Flow

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Overview

Applications
Closed-Loop Flow Control Technology
Adaptive Control

Actuators
Sensors

Flashed Light Sheet
Cavity
Vortices
Leading Edge
Trailing Edge
Cavity Oscillation Control

Separation Control

MEMS PZT Actuator
MEMS piezoresistive microphone

Performance Signal
Control Signal
Control off
Control on

4 mm
1 mm

-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0
10
20
30
0 1 2 3 4 5 6 7 8 9 10
0 1 2 3 4 5 6 7 8 9 10
What is Active Flow Control?

- **Active Flow Control** is a multidisciplinary field aimed at the control of fluid flow
  - *Active vs. Passive* → active means energy addition
    - Actuators needed for input
    - Sensors needed for feedback control
  - *Flow* → involves Fluid Mechanics AND
  - *Control* → more than just turning the frequency and amplitude knobs
    - Most flow control has been open-loop (not closed-loop) control
Why Active Flow Control?

- Active Flow Control has demonstrated improved performance in:
  - Suppression of flow-induced cavity oscillations
  - Separation control
  - Flow-induced noise
  - Combustion instability control
  - Mixing Enhancement
  - Viscous Drag Reduction
  - Thermal-transport enhancement
  - Vehicle control
  - ...
• Model problem is to control post-stall separated flow over an airfoil at conditions amenable to companion Large Eddy Simulations (LES)

6 in. chord NACA 0025 Airfoil
\[ \alpha = 12^\circ, \; \text{Re}_c \sim 10^5 \]
Applications and Payoff

- 10% drag reduction leads to annual fuel savings of 1500 gallons per truck, resulting in $4.5B annual fuel savings courtesy of Prof. Ken Visser at Clarkson.

- 10% drag reduction leads to $1.6B annual fuel savings in US commercial fleet based on 2000 prices (Gad-el-Hak, 2001).

courtesy of Jim Underbrink at Boeing

courtesy of Prof. Ken Visser at Clarkson
Previous Research

- Benefits of open-loop (OL) oscillatory blowing documented in literature → often via a zero net mass flux jet
- Significant increase in lift and reduction in drag
- Effective over wide range of Reynolds and Mach numbers
- But optimization achieved via trial and error open-loop control process
  - Frequency → $F^*$
  - Amplitude → $C_{\mu}$

NACA 0015 airfoil with a deflected flap and control applied at $x/c=0.7$. (ref: Seifert & Pack, AIAA-98-0214).
Background - Key Concepts

- Key parameters for control of separated flow using unsteady excitations
  - Actuation amplitude $\Rightarrow$ Momentum coefficient $C\mu = u_{jet, rms}^2 h / 0.5 U_\infty^2 c$
  - Characteristic frequency $\Rightarrow$ $F^+ = f e L_{sep} / U_\infty$

- Evidence exists for multiple effective excitation frequencies – What is optimal?
  - Nishri and Wygnanski (1998) found $F^+ = O(1)$ is most effective
  - Amitay et al. (2001) found $F^+ \geq 10$ is most effective

- Objectives
  - Control separated flow in an adaptive closed-loop fashion
  - Search for optimal low-power control schemes using feedback control and seek physical explanations
Adaptive Control System

from Åström & Wittenmark
Challenges for Feedback Control I

- **Observations:**
  - Fluid Dynamics governed by N-S Equations
    - Time-dependent, nonlinear, PDEs → infinite number of degrees-of-freedom
  - Most actuators and sensors suffer from nonlinearities, saturation effects, and bandwidth limitations

- **Question:**
  - How to model the fluid dynamics to obtain a physically-realizable controller?

- **Potential Solutions:**
  - Obtain a system model using parametric or non-parametric schemes
    - Proper Orthogonal Decomposition (POD) or physics-based approaches to develop reduced-order models
  - System Identification for low-order model
Challenges for Feedback Control II

- **Real-time** feedback control virtually nonexistent in flow control \( \rightarrow \) paradigm shift from open-loop control
  - *Real-Time* \( \equiv \) within 1 sample interval \( \Delta t \)

- **Critical Scaling Issue**
  - Governing nondimensional frequency in Fluid Mechanics is the Strouhal number
    - \( S = \frac{(freq \cdot length)}{speed} = \frac{fL}{U} \sim constant \)
      \( \rightarrow f \sim U/L \)
    - Most experiments are scaled down in size
      \( \rightarrow \) Leads to \( \uparrow f \) and \( \downarrow \Delta t \)
      - Less time is available for calculations
Experimental Setup

- \( c = 6" \) chord, two-dimensional NACA 0025 airfoil
- Tripped BL, unused slots covered, \( \text{Re}_c \sim 1.2 \times 10^5 \) and AOA > 10°
- Testbed with multiple ZNMF actuators (1/3rd span), unsteady pressure sensors, & lift/drag balance

![Diagram of experimental setup](image-url)
ZNMF Actuators

- For phasing control w/o feedback, limited to $f < 2.2 \text{ kHz}$

![Diagram of ZNMF Actuators]

- Diaphragm $f_n \sim 2.2-2.6 \text{ kHz}$
Lift and Drag Balance

- Balance can only provide static or dc response

- Link established between flow field and pressure impulse response \( \rightarrow \) establishes suitability of real-time control based solely on surface measurements.

Phase-locked \( \Delta C_p' \) impulse response due to actuator 1

Corresponding phase-locked vorticity movie from PIV measurements
First Approach: Dynamic Control

Flow Control Approaches

- Passive Control
  - Open-Loop
    - Quasi-static: Works on time scale of mean flow
  - Dynamic: Works on time scale of flow dynamics

- Active Control
  - Closed-Loop
    - Energy added via:
      - Steady blowing
      - Steady suction
      - Periodic excitation
    - Use feedback to improve performance
    - Advantages:
      - Save energy
      - Adaptivity
      - Search large design space

No energy added
Manually adjust excitation

Ref: Cattafesta et al. 2003
Flow Control Idea

• Prior work shows that suppressing the surface pressure fluctuations is indicative of reattaching flow

Ref: Kumar and Alvi, 2005
Adaptive Disturbance Rejection Algorithm

- ARMARKOV disturbance rejection algorithm is the dynamic controller

\[
J_k = \sum_{i=1}^{p_c} L_i \theta(k - i + 1) R_i \Phi_{uy}(k)
\]

\[
U(k) = \sum_{i=1}^{p_c} L_i \theta(k - i + 1) R_i \Phi_{uy}(k)
\]

\[
\hat{Z}(k) = W_{zw} \Phi_{zw}(k) + B_{zu} \theta(k) \sum_{i=1}^{p_c} L_i R_i \Phi_{uy}(k)
\]

\[
J(k) = \frac{1}{2} \hat{Z}^T(k) \hat{Z}(k) + \frac{1}{2} \hat{U}^T(k) Q \hat{U}(k)
\]

\[
\frac{\partial J(k)}{\partial \theta(k)} = \sum_{i=1}^{p_c} L_i^T B_{zu}^T \hat{Z}(k) \Phi_{uy}^T(k) R_i^T
\]

\[
\theta(k + 1) = \theta(k) - \eta(k) \frac{\partial J(k)}{\partial \theta(k)}
\]

Ref: Venugopal and Bernstein, 2000
ARMARKOV System ID

- ARMARKOV model is extended from ARMA model
- Explicitly includes Markov parameters
- Advantage: good robustness, especially when the signal to noise ratio is poor (Akers and Bernstein, 1997)

\[
G_1(z) = \frac{Y(z)}{U(z)} = \frac{\beta_0 z^n + \beta_1 z^{n-1} + \cdots + \beta_n}{z^n + \alpha_1 z^{n-1} + \cdots + \alpha_n}
\]

\[
G_2(z) = \frac{Y(z)}{U(z)} = \frac{H_{-1} z^{\mu+n-1} + \cdots + H_{\mu-2} z^{n-n} + \beta_{\mu,1} z^{n-1} + \cdots + \beta_{\mu,n}}{z^{\mu+n-1} + \alpha_{\mu,1} z^{n-1} + \cdots + \alpha_{\mu,n}}
\]

where \( H \) are Markov parameters, \( n \) = order of the system
and \( \mu \) = number of Markov parameters
ID/Controller Implementation

[Diagram showing a system with components labeled such as Amplifier, Actuation signal, dSPACE system, Filter/Amplifier, Synthetic jet Actuators, Dynamic pressure transducers, and various labeled parts like A1, A2, A3, A4, S1, S2, S3, S4, S5, S6.]
Dynamic Control Results

- Single input, two outputs

<table>
<thead>
<tr>
<th>Case #</th>
<th>Reference transducer y</th>
<th>Performance transducer z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S1</td>
<td>S1</td>
</tr>
<tr>
<td>2</td>
<td>S6</td>
<td>S6</td>
</tr>
<tr>
<td>3</td>
<td>S1</td>
<td>S6</td>
</tr>
<tr>
<td>4</td>
<td>S6</td>
<td>S1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>n</th>
<th>μ</th>
<th>n_c</th>
<th>μ_c</th>
<th>Fs (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10</td>
<td>2</td>
<td>20</td>
<td>4096</td>
</tr>
</tbody>
</table>

ID  Disturbance rejection $\Theta$
ZNMF actuators create acoustic noise, which means the actuator input has an acoustic path (fast) and a hydrodynamic path (slow).

Need to remove acoustic component and feed back only hydrodynamic path for effective control.

Achieved via digital filter to predict and reject the noise component.
Dynamic Control Results

AoA = 12° and Re = 120,000

Time-average $u/U$ velocity contours

PIV

uncontrolled

controlled

Performance Signal

Control Signal

Power spectrum ($V^2$)

Frequency (Hz)
Dynamic Control Results

- Impact on lift-to-drag ratio using actuator 1 and various sensor combinations (typical power < 10 mW)
- Controller is able to maintain partially attached flow as the AoA is slowly increased
- Examination of control input signal reveals strong forcing at frequencies corresponding to wake and shear layer instabilities
- Suggests nonlinear forcing may be more effective

<table>
<thead>
<tr>
<th>Case #</th>
<th>Reference transducer y</th>
<th>Performance transducer z</th>
<th>C_L ( \pm )</th>
<th>C_D ( \pm )</th>
<th>L/D ( \pm )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>-</td>
<td>-</td>
<td>0.21 ( \pm ) 0.02</td>
<td>0.21 ( \pm ) 0.09</td>
<td>1.01 ( \pm ) 0.08</td>
</tr>
<tr>
<td>1</td>
<td>S1</td>
<td>S1</td>
<td>0.84 ( \pm ) 0.01</td>
<td>0.12 ( \pm ) 0.01</td>
<td>6.97 ( \pm ) 0.37</td>
</tr>
<tr>
<td>2</td>
<td>S6</td>
<td>S6</td>
<td>0.83 ( \pm ) 0.01</td>
<td>0.12 ( \pm ) 0.01</td>
<td>7.21 ( \pm ) 0.46</td>
</tr>
<tr>
<td>3</td>
<td>S1</td>
<td>S6</td>
<td>0.84 ( \pm ) 0.01</td>
<td>0.12 ( \pm ) 0.01</td>
<td>7.11 ( \pm ) 0.40</td>
</tr>
<tr>
<td>4</td>
<td>S6</td>
<td>S1</td>
<td>0.84 ( \pm ) 0.01</td>
<td>0.12 ( \pm ) 0.01</td>
<td>7.09 ( \pm ) 0.43</td>
</tr>
</tbody>
</table>
Nonlinear Interactions

\[ \text{Re}_c = 10^5, \alpha = 20^\circ \]

Higher-order spectrum quantifies nonlinear interactions between wake and shear layer instabilities.

\[ \mathbb{S}\{E[x(t)x(t+\beta)x(t+\phi)]\} \]
Part 2: Quasi-Static Control

Flow Control Approaches

- Passive Control: No energy added
  - Manually adjust excitation

- Active Control
  - Open-Loop
  - Closed-Loop
    - Energy added via:
      - Steady blowing
      - Steady suction
      - Periodic excitation
    - Use feedback to improve performance
    - Advantages:
      - Save energy
      - Adaptivity
      - Search large design space

Quasi-static
- Works on time scale of mean flow

Dynamic
- Works on time scale of flow dynamics
Quasi-Static Control Approach

- Use multi-frequency waveforms to drive actuator
- Use lift-to-drag ratio as cost function
- Adjust waveform parameters iteratively to minimize drag/lift in a time-averaged sense using optimization algorithm
- Constrain actuator input $C_\mu$ or electrical power = const
Dilemma: ZNMF Actuator Output

- Actuators are nonlinear and only effective over a narrow bandwidth, so how do we force the low-frequency wake instability?

Helmholtz freq. ~ 1200 Hz

![Graph showing the relationship between F (Hz) and U_rms/N for different voltages (30 Vpp, 40 Vpp, 50 Vpp). The graph indicates that the maximum U_rms/N occurs near 1200 Hz for all voltages, with a peak value of 0.01 m/s/V for 30 Vpp.]
Nonlinear Forcing Strategy

- Use multi-frequency waveforms to force nonlinear interactions
- Use feedback control to optimize waveform parameters

\[ e(t) = A \sin\left(2\pi f_c t\right) \cdot \sin\left(2\pi f_m t\right) \]

AM

Burst Modulation (BM)

Pulse Modulation (PM)

- Less electrical power \(\rightarrow\) lower cost!
- Effectiveness?
Optimization Algorithms

- **Optimization algorithms**
  - Extremum-Seeking Control
  - Downhill simplex algorithm
    - Evaluate cost function at initial simplex
    - Use the lowest value as reference and search for lower value of cost function
    - Only moves in downhill direction
    - Multi-dimensional space
  - Finds local minimum → repeat w/ various ICs
Constrained Control

- Goal is to “remove” influence of actuator dynamics
- Extensive calibrations performed to estimate $C_\mu$ & electrical power as a function of waveform parameters ($A, f_m, f_c$)
- Constrain the optimization to fix $C_\mu$ or power
Experimental Implementation

- Dual-timing control architecture
  - Real-time loop controls actuators \( \rightarrow \) runs at synchronous rate \( O(40 \text{ kHz}) \)
  - Supervisory-control loop averages balance output and performs optimization \( \rightarrow \) runs at \( O(\text{Hz}) \) asynchronous rate
Quasi-Static Controller Results

- Identical performance as dynamic controller at AoA = 12°
- AoA = 20° and Re = 120,000
- Baseline L/D = 1.1; L/D=1.76 for F+=15 and Cµ=3.2E-4

<table>
<thead>
<tr>
<th>Signal type</th>
<th>Constraint</th>
<th>Converged f_m (Hz)</th>
<th>Converged f_c (Hz)</th>
<th>Converged L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM: Case (a)</td>
<td>C_µ = 7.15 x 10^{-6}</td>
<td>61</td>
<td>2405</td>
<td>2.18 ± 0.07</td>
</tr>
<tr>
<td>BM: Case (a)</td>
<td>C_µ = 7.15 x 10^{-6}</td>
<td>55</td>
<td>1979</td>
<td>1.95 ± 0.05</td>
</tr>
<tr>
<td>PM: Case (a)</td>
<td>C_µ = 7.15 x 10^{-6}</td>
<td>16</td>
<td>NA</td>
<td>1.49 ± 0.04</td>
</tr>
</tbody>
</table>

- Examination of velocity statistics via PIV shows unsteady / incipient separation for high AoA cases

12°, just above S6

20°, just above S6
Summary & Future Plans

• Have demonstrated linear adaptive feedback control of separated flow with very low actuator input power on an airfoil model using only surface $p/\xi$ measurements
  — reveals the promise of adaptive feedback flow control in practical flow control problems
  — highlights the importance of understanding and leveraging nonlinear interactions in control of separated flows

• Have demonstrated static (dc) nonlinear feedback control of separated flow using multi-frequency excitation

• Future work will focus on nonlinear dynamical approaches and implementation with MEMS floating element shear stress sensors on this and more complex configurations
  — Control of 3-D separation
Sample Publications


Questions?
What is a Zero-Net Mass Flux Jet?

- Separation of oscillatory driven flow in an orifice leads to the generation of vortex rings, as seen using (a) steady and (b) stroboscopic illumination
  - Ingard and Labate, 1950

\[ F = 234 \text{ Hz} \]
Multiple frequency scales exist in a separated flow

\[ f_{\text{sep}} \sim U_\infty / L_{\text{sep}} \]  
Separation bubble frequency

\[ f_{\text{SL}} \sim U_\infty / \theta_{BL} \]  
Shear layer frequency (Ho & Huerre 1984)

\[ f_{\text{wake}} \sim U_\infty / W_{\text{wake}} \]  
Wake frequency (Roshko 1954)

Goal is to enhance nonlinear interactions between these phenomenon to control the separated flow
System Identification

- Experimental approach to system modeling
  - Various Model Structures
- Adapted via programmable training process
- Amenable to real-time process
  - RLS or LMS algorithms

System ID using Adaptive Filter

Input $u$ → Unknown System → Adaptive Filter → Desired Output $d$

Error $e$ → Summation $\Sigma$ → Filter Output $y$ → Adaptive Filter

Diagram showing the system ID using an adaptive filter with input $u$, adaptive filter, and desired output $d$ connected through a summation and filter output $y$ to an error $e$.
**Actuation Waveform: AM**

- **Amplitude Modulation**

\[
e(t) = A \sin(2\pi f_c t) \cdot \sin(2\pi f_m t)
\]

\[
= \frac{A}{2} \left\{ \cos(2\pi (f_c - f_m) t) - \cos(2\pi (f_c + f_m) t) \right\}
\]

\[
f_c = 1180 \text{ Hz}, \ f_m = 50 \text{ Hz}
\]