AERODYNAMIC FLOW CONTROL

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Outline

• Examples of VA Efforts (AIAA Paper 2004-2622)
• What is flow control?
• Low-order model approach (KISS)
  – Pitching airfoil
  – Cavity tone suppression
  – Separation control
• Reduced-order model approach (KIRS)
  – Nonlinear convection
• Summary and future work
Cavity Flow Control

\[ M_\infty \]
\[ U_\infty \]

L
D
W
HIFEX Test at ARA

Objective of Research:
Compare the effectiveness of high- and low-frequency flow control methodologies and applied them to a generic weapons bay

Test Conditions
• Mach 0.85 and 1.19

Devices Tested
• One-Delta “Sawtooth” Spoiler
• Pulse-blowing “Rotary” Actuator
• Power Resonance Tube (PRT) and Splash Jet
• Rod and Rod with Wire

HIFEX Model
• 10% Scale Weapons Bay Model
• Dimensions 20” x 4” x 4”
• L/D = 5
• Attached Doors Positioned at 90°
Results of HIFEX Test

Passive “Zero-Frequency” Actuation

High-Frequency Actuation > 1 kHz

Low-Frequency Actuation < 1 kHz

Frequency Sweep of Device

<table>
<thead>
<tr>
<th></th>
<th>Zero-Frequency</th>
<th>Low-Frequency</th>
<th>High-Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tonal</td>
<td>OASPL</td>
<td>Tonal</td>
</tr>
<tr>
<td>Subsonic</td>
<td>6 dB</td>
<td>3.5 dB</td>
<td>17 dB</td>
</tr>
<tr>
<td>Supersonic</td>
<td>1 dB</td>
<td>2.0 dB</td>
<td>18 dB</td>
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High-Frequency Actuation (PRT/ Splash Jet) Reduces Tonal Peak and OASPL better than any other method tested.
Active Integrated Inlets

- Compact and offset
- Integral to airframe
- Flow-control enabled
- Close-loop controlled
Pulsed Vortex Generator Jets

2-D Low Speed
Separation Control

- M = 0.3 - 0.7
- \( C_{l,\text{max}} \) inc. 21-14%
- L/D inc. up to 35%

3-D Low Speed
Separation Control – Vehicle Control

- M = 0.1 & 0.2
- \( C_{l,\text{max}} \) inc. 7%
- L/D inc. up to 17%
- Prop. roll control

2-D Low Speed
Exploration

\( \delta_{\text{LE}} = 15^\circ \)

\( \delta_{\text{jet}} = 45^\circ \)

Air Force
SBIR/STTR

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Defining Flow Control

Do you know what “control” means?

• Passive flow control
  – Modifications to geometry

• Active flow control
  – Adding/removing mass, momentum, or energy to the flow, e.g. synthetic jets, pulsed vortex generators, mass injection, suction

• Quasi-steady – Slow relative to time scales of fluid
  – Active flow control with monitoring and updating of control input, e.g. performance enhancement

• Feedback flow control
  – Feedback control theory applied to active flow control
  – Time scales for control on order of time scales of the system
Motivation

• Ability of small-scale devices to effect large-scale changes in aerodynamic flows through natural amplification has been demonstrated
  – Open-loop

• Ability to control flow fields by sensing their state then employing these mechanisms is within reach

• Goal — integrate aerodynamic flow control techniques with closed-loop control theory

• Potential applications
  – Replacements for traditional aircraft control surfaces
  – Weapons bay acoustics
  – Drag reduction
Why Is It A Difficult Problem?

- Components of drag
  - Trailing vortices, lift generation
  - Friction
  - Lack of pressure recovery at T.E., wake
  - Separation (makes pressure recovery worse)
  - Wave (shock - transonic and supersonic)
Re-laminarization Reduces Drag

- Friction drag is proportional to velocity gradient at wall: \( \tau_w = \mu \left( \frac{\partial u}{\partial y} \right)_{y=0} \)
- Laminar flow has less mixing of far-field with flow near wall → smaller velocity gradient
Likelihood of Separation Increased

- Adverse pressure gradient retards the flow
- Separation occurs where
- Separation occurs farther downstream in turbulent flow due to increased mixing of high velocity fluid in far-field with low velocity fluid near the surface


from Brown, F.N.M., *See the Wind Blow*, 1971, plate. 42.
Role of Feedback in Flow Control

- General role of feedback
  - Stabilization
  - Tracking in presence of uncertainty

- Necessary components for model-based approaches
  - Model that captures dynamics of relationships between inputs (actuators), outputs (variables to be controlled)
  - Definition of states (not trivial in flow control)
  - Quantified control objective (not trivial)
Technical Challenges/Approaches

• Technical Challenges
  – Actuation devices and power
  – Feedback sensing
  – Flow physics
  – Order reduction for models
  – Control law design
  – Order reduction of control

• Approaches
  – “Experimental” data collection with low-order model → Control design
  – Simulation and reduction of model order → Control design
  – Control of PDE → Order reduction
Air Vehicle Applications for Flow Control

- Vehicle control
- Separation control
- Aero-acoustic fatigue
- Skin friction reduction
- Thermal control
- Plasma / MHD
- Fluidic shape change
- Virtual area nozzle
- Fluidic thrust vectoring
- Mixing enhancement
- Noise attenuation
- Buffet alleviation
- Pressure distortion
- Compressor, turbine, combustor control

Which applications will benefit from order reduction and feedback control?
Actuators & Sensors

- Many choices for actuators and sensors
  - Actuators – must be amenable to simulation/modeling
    - Synthetic jets (MEMS and non-MEMS)
    - Pulsed vortex generator jets
    - Deployable vortex generators
    - Pulsed/steady blowing/suction
- Sensors

Which actuators are relevant for order reduction and control law design?
Ranges of Actuators

Macros Devices
- Passive
  - Macro Vanes
  - Fluidic Shape Change
  - Mechanical Deployable: VGs, roughness, bubbles

Active
  - Mechanical Deployables: VGs, roughness, bubbles
  - Pulsed Injection & VG Jets

Micro Devices
- Passive
  - Sub Boundary Layer VGs

Active
  - Oscillatory Zero Net Mass Flux
  - Synthetic/Micro Jets
  - Open-Loop Near Wall
  - Reactive Near Wall
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Control of Wing Attitude with Synthetic Jets

• Goal: Vehicle control without hinged moving surfaces

• Objective: Develop feedback flow control methods for vehicle control

• Technical Challenges:
  – Modeling of input/output relationships
    ▪ Must be amenable to control law design
    ▪ Must be valid for wide range of operating conditions
  – Control law design
    ▪ Nonlinearities in system
    ▪ Imperfect models
  – Efficient actuators with sufficient control authority over wide operating range

• Approach: Develop system for pitching/plunging 2D airfoil in wind tunnel with low-order models
Leading Edge Control with Flow Separation

- Control of the forces/moments possible at high angle of attack by controlling separation
  - Array of six piston/cylinder synthetic jets near leading edge
  - Good control authority above stall (17 deg angle of attack)
  - Nonlinear relationship between synthetic jet frequency, angle of attack, and lift and pitching moment

\[\alpha \text{ (deg)} \quad C_L \quad C_m\]
Demonstration of Pitch Control via Feedback Flow Control

- Control law tested in simulation
- Feedback control of angle of attack demonstrated in wind tunnel
  - Via control of reattachment of separated flow

Simulation Results

Experimental Results
Trailing Edge Control for Low Angles of Attack

- Good control authority
- Linear!
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Experimental Arrangement
Response Modes

![Graph showing response modes vs. Mach number with lines for 1st, 2nd, 3rd, and 4th Rossiter modes and markers for dominant and secondary peaks.](image)
Changing Response w/ Mach

Cavity floor spectrum at Mach 0.25

SPL (dB)

frequency (Hz)
Nonlinearities Lead to Mode-Switching

- Forcing at Frequencies Ranging from 1 kHz to 6 kHz) for Mach 0.30
- Unforced flow exhibits single dominant Rossiter mode
Proportional-Proportional Control

Mach 0.30 flow

2\textsuperscript{nd} Rossiter mode reinforced
Proportional-Proportional Control

Mach 0.30 flow
Proportional + delayed feedback control
(2 feedback loops out of phase)

Dynamic feedback suppresses resonance
Benefit of Feedback Control
Robustness

FEEDBACK PRODUCES SUPERIOR RESULTS AT OFF-DESIGN CONDITIONS

Open-loop Control
Optimized for Mach 0.3

Feedback Flow Control
P-P control (P1 leads P2 by 260 ms, gain 10)

No Control - Mach 0.3

Mach 0.27
Mach 0.30
Mach 0.32
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Separation Control on NACA 4412

- Water tunnel
  - Laminar flow
  - Simulations for POD model calculation

- Wind tunnel
  - Turbulent flow
  - PIV for POD mode calculation
  - 87% of K.E. captured in 50 states
  - mLSM predicts flow separation with 11 surface-mounted pressure sensors
Demonstration of Feedback Control

NACA 4412 in wind tunnel
Benefit of Feedback
Reduced Power

• Constant pitch rate from 12° to 17° of angle of attack
• Incipient separation at 15°
• Proportional feedback on 1st POD mode which correlates directly to degree of separation

34% power savings with feedback control
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Simulation-Based Feedback Flow Control

Benefits:
- Control design and verification before hardware
- Optimal actuator and sensor placement
- Fast investigation of different control formulations

Challenges:
- Simulation time requirements
- Huge system dimension
- CFD and control design often incompatible
- Experimental validation
Design/Reduce: PDE Feedback Control Design? Discretize

Issues:
- Systematic control formulation (+)
- Control developed with infinite-dimensional model (+)
- Commercial software (+)
- Many open questions for highly nonlinear systems (-)
- Prohibitively expensive gain computation (-)

63,179 Cells
~10^8 Riccati unknowns

System Structure Can Reduce Computational Expense  (AIAA-2004-2411)
Reduce/Design: System Model Reduction? Feedback Control Design

Issues:
- Low-dimensional system model (+)
- Fast gain calculation (+)
- Difficult model development (-)
- Potentially expensive snapshot generation (-)
- Potential omission of important dynamics (-)
- Snapshot control inputs based on intuition (-)

Potential for Tractable Systematic Feedback Flow Control
Proper Orthogonal Decomposition

POD developed primarily as a simulation tool. Can it be used to develop feedback control laws?

Necessary Pieces

Control-Oriented POD Model
Control Objective (Full and Reduced)
Full Simulation Validation

Critical Capability: POD Boundary Feedback Control/Verification
Nonlinear Convection
Over an Obstacle

Goal: Boundary Tracking Feedback Control

Governing Equation:

Specify multiple boundary inputs in snapshot ensemble

\[
u_B(t) = N \sin(0.25t^2) \quad u_T(t) = 0
\]

\[
u_B(t) = 0 \quad u_T(t) = N \sin(0.25t^2)
\]

\[
u_B(t) = N \sin(0.25t^2) \quad u_T(t) = N \sin(0.25t^2)
\]

\[N = -3, -2, -1\]

First 9 POD Modes
Validate Model

Comparison of POD and Full Order Models

Open-Loop Test

First 5 temporal coefficients
Validate Control Law

Design Control From 25 Modes

Reference Function

Controlled POD Model

Controlled Full Order System

Effective Reduced Control (2005 GNC)
Extension to Navier-Stokes

AVUS Flow Solver
• finite-volume, cell centered
• 2nd order accurate in space/time
• CS CoE consultation

Mesh Parameters
• 63,179 Cells
• 43 Cells within boundary layer
• Cavity Resolution
  - 251 streamwise nodes
  - 77 normal nodes
Reduce/Design Conclusions

- POD Potential for Systematic Boundary Feedback Flow Control

Techniques Developed to Address Critical Issues
- POD basis suitable for range of input conditions
- Reduced models amenable to boundary feedback design
- Control objective for full and reduced systems
- Control-oriented model fidelity
- Full order validation

- Methods Tested and Effective
  - Heat conduction on cavity geometry
  - Nonlinear convection on obstacle geometry

- Extending Techniques to Cavity Flow
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Summary & Future Work

• Three-pronged approach
  – Experiment → Low-Order Model → Control
  – Simulation → Order Reduction → Control
  – Control → Order Reduction → Experiment

• Demonstration of feedback flow control
  – Pitch control of 2-D wing in wind tunnel
  – Subsonic cavity

• Expanding complexity/relevance of problem and robustness/mathematical rigor/generality of solution

• Future work
  – Dynamic pitch/plunge demonstration, flight test
  – Application to N-S equations – in-house
  – Trade study and flight demonstration
    • FY2005 SBIR