AERODYNAMIC FLOW CONTROL

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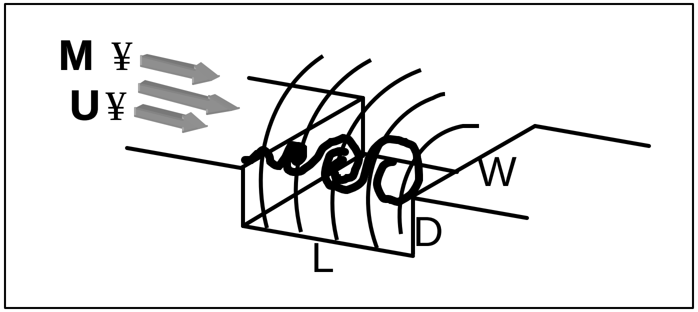
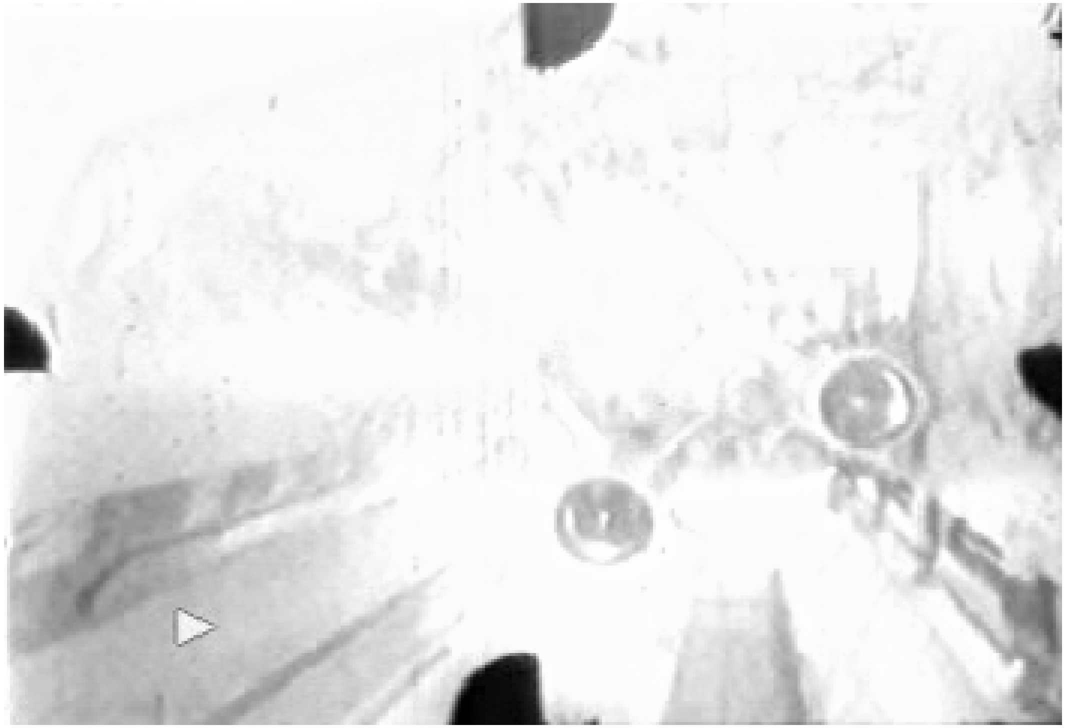
Outline

- 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





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

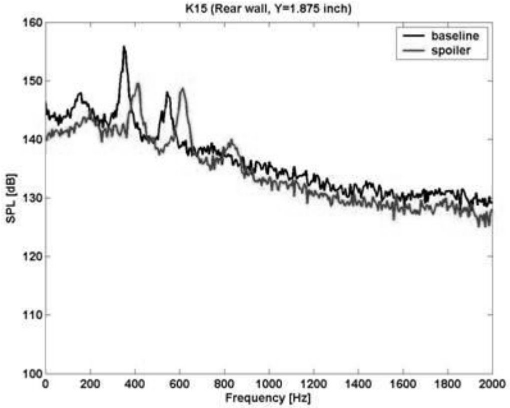
- **One-Delta “Sawtooth” Spoiler**
- **Pulse-blowing “Rotary” Actuator**
- **Power Resonance Tube (PRT) and Splash Jet**
- **Rod and Rod with Wire**

HIFEX Model

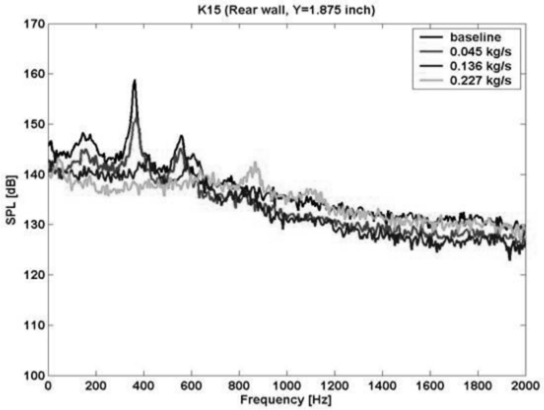
- **10% Scale Weapons Bay Model**
- **Dimensions 20” x 4” x 4”**
- **L/D = 5**
- **Attached Doors Positioned at 90^o**

Results of HIFEX Test

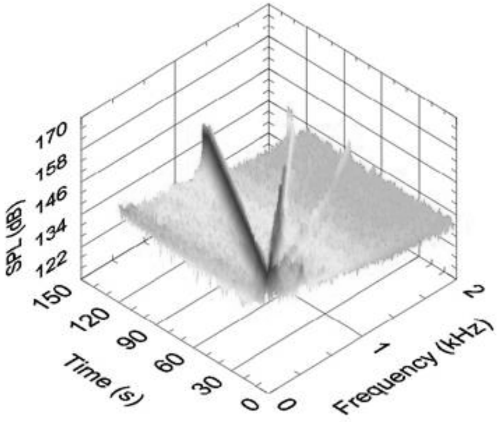
Passive “Zero-Frequency” Actuation



High-Frequency Actuation > 1 kHz



Low-Frequency Actuation < 1 kHz



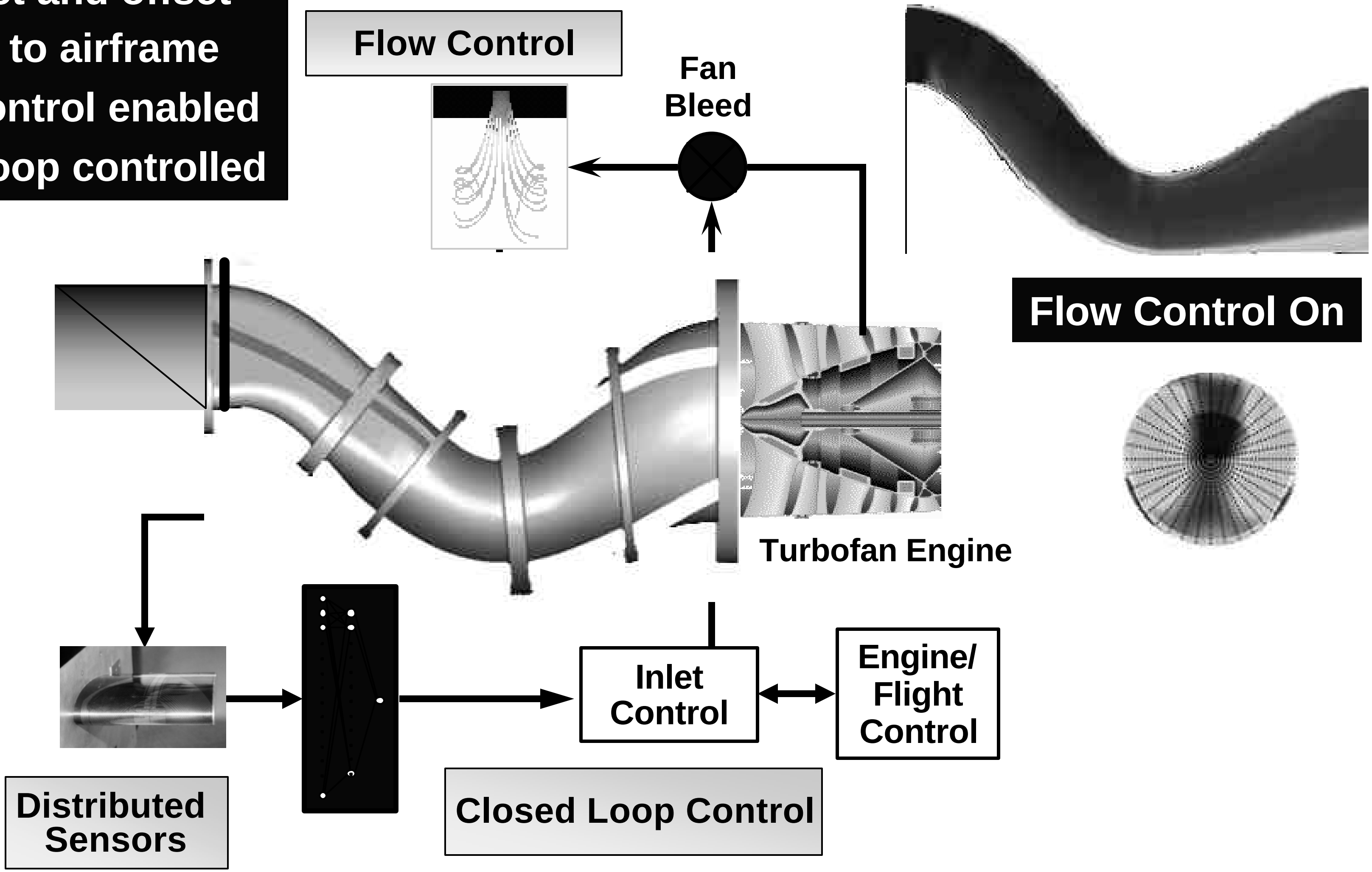
Frequency Sweep of Device

	Zero-Frequency		Low-Frequency		High-Frequency	
	Tonal	OASPL	Tonal	OASPL	Tonal	OASPL
Subsonic	6 dB	3.5 dB	17 dB 14 dB	5 dB 2 dB	34 dB (PRT)	8.5 dB (PRT/S. Jet)
Supersonic	1 dB	2.0 dB	18 dB 19 dB	9 dB 8.5 dB	34 dB (S. Jet)	14 dB (PRT/S. Jet)

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



Flow Control

Fan Bleed

Flow Control On

Turbofan Engine

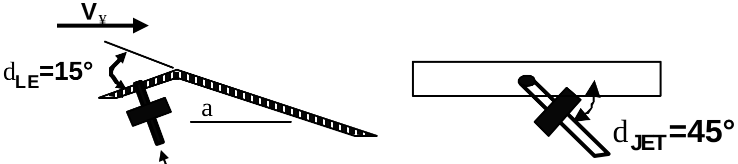
Distributed Sensors

Inlet Control

Engine/ Flight Control

Closed Loop Control

Pulsed Vortex Generator Jets

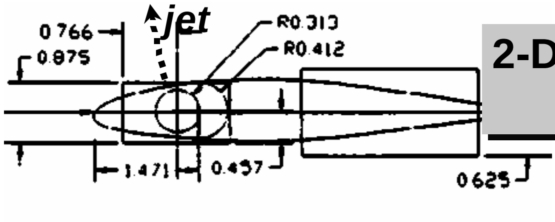


Side View

Front View

2-D Low Speed Exploration

2-D Low Speed Separation Control

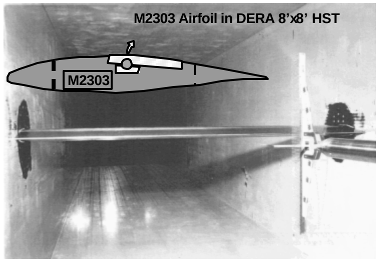


2-D Compressible Validation

- M=.3-.7
- $C_{l,max}$ inc. 21-14%
- L/D inc. up to 35%

3-D Low Speed Separation Control –Vehicle Control

- M=.1&.2
- $C_{L,max}$ inc. 7%
- L/D inc. up to 17%
- Prop. roll control



- M=0.67- 0.71
- Re_c=19x10^6
- $F^+ = f\,(x_{te}-x_{jet})\,/\,V_{¥}$ » 0.6-0.8
- Overall L/D increase over high-a range

McManus, et al,.AFRL-VA-TR-1998-3028, AIAA-97-1971, AIAA-96-1948, AIAA-96-0442, AIAA-95-2187
Tilmann, C.P., "Enhancement of Transonic Airfoil Performance Using Pulsed Jets for Separation Control," AIAA-2001-0731

Outline

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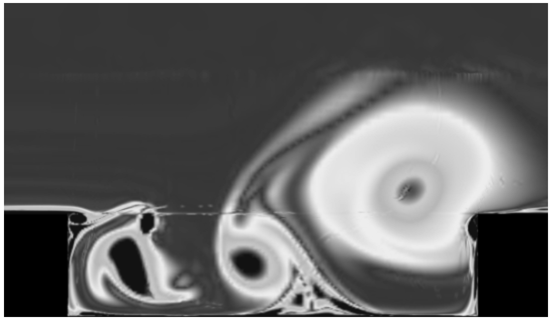
Defining Flow Control

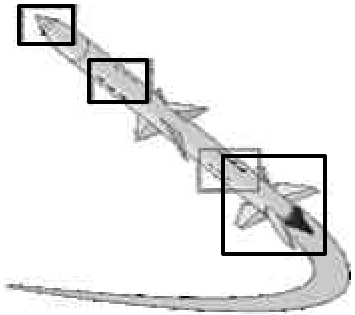


Do you know what "control" means?

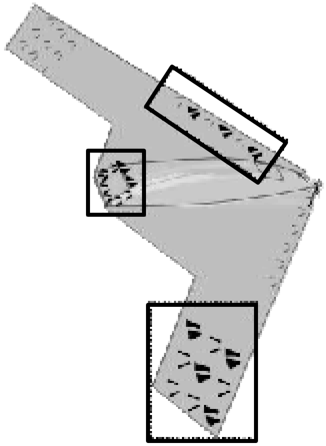
- **Passive flow control**
  - **Modifications to geometry**
- **Active flow control**
  - **Adding/removing mass, momentum, or energy to the flow, *e.g.* synthetic jets, pulsed vortex generators, mass injection, suction**
- **Quasi-steady – Slow relative to time scales of fluid**
  - **Active flow control 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

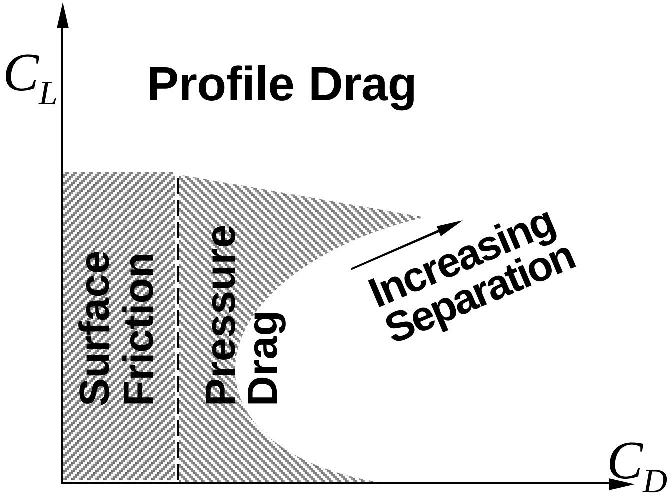


- Ability to control flow fields by sensing their state the employing these mechanisms is within reach
- Goal — integrate aerodynamic flow control techniques with closed-loop control theory
- Potential applications
  - Replacements for traditional aircraft control surfaces
  - Weapons bay acoustics
  - Drag reduction

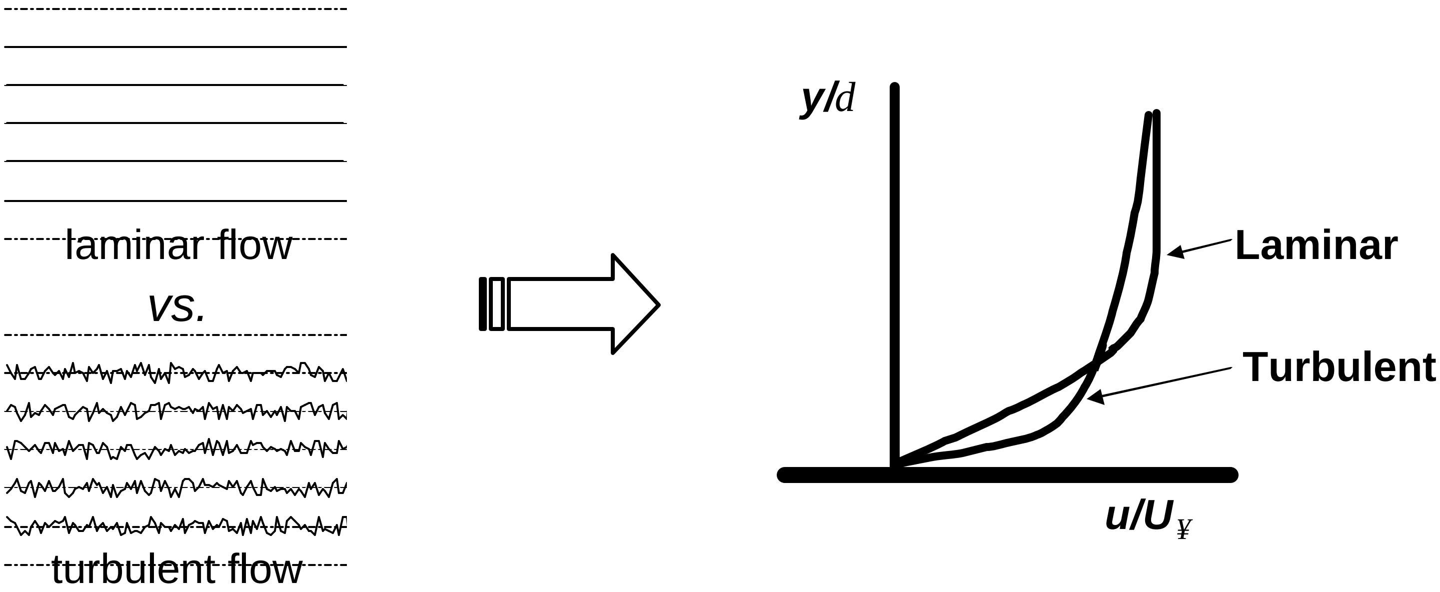


Why Is It A Difficult Problem?

- 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)



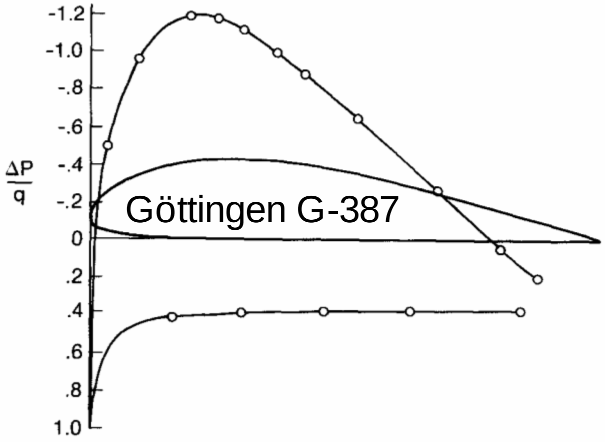
Re-laminarization Reduces Drag



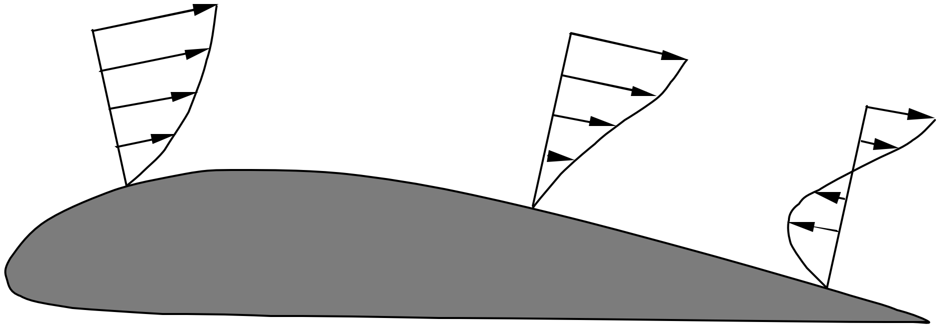
- **Friction drag is proportional to velocity gradient at wall:** $\tau_w = \mu \left(\frac{\partial u}{\partial y} \right)_{y=0}$
- **Laminar flow has less mixing of far-field with flow near wall**
  ➔ smaller velocity gradient

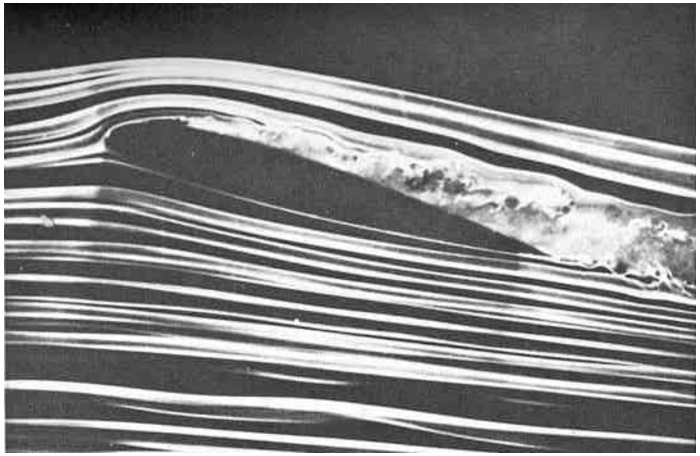
Likelihood of Separation Increased

- **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 Jones, Robert T., *Wing Theory*, Princeton University Press, Princeton, NJ, p. 36.

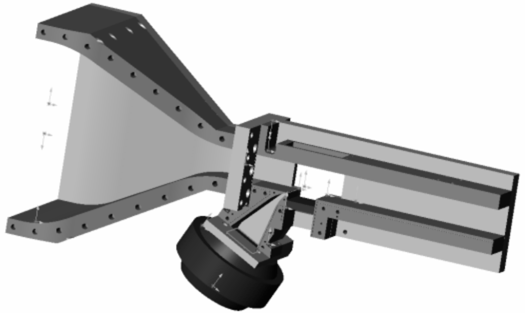


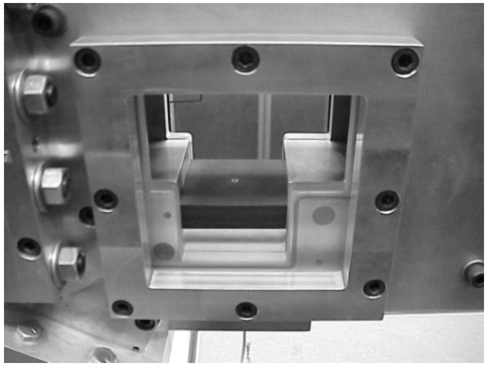


from Brown, F.N.M., *See the Wind Blow*, 1971, plate. 42.

Role of Feedback in Flow Control

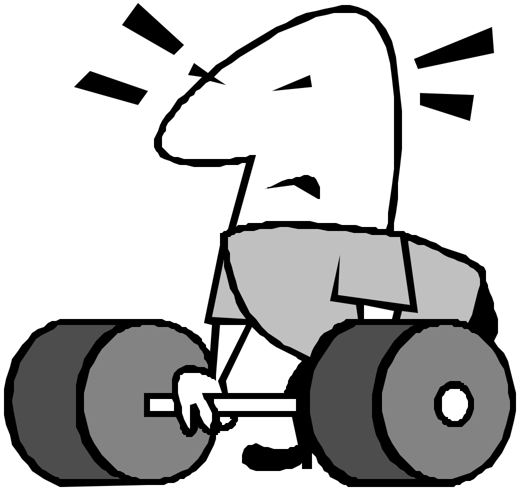
- General role of feedback
  - Stabilization
  - Tracking in presence of uncertainty
- Necessary components for model-based approaches
  - Model that captures dynamics of relationships between inputs (actuators), outputs (variables to be controlled)
  - Definition of states (not trivial in flow control)
  - Quantified control objective (not trivial)



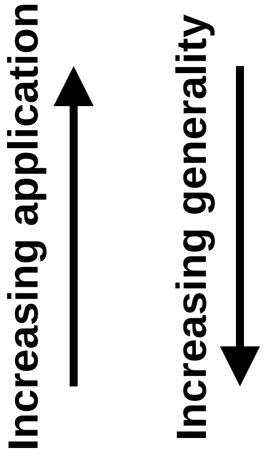


Technical Challenges/Approaches

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



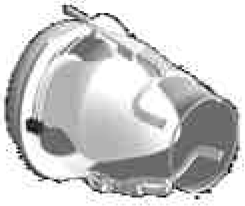
- **Approaches**
  - **“Experimental” data collection with low-order model → Control design**
  - **Simulation and reduction of model order → Control design**
  - Control of PDE → Order reduction

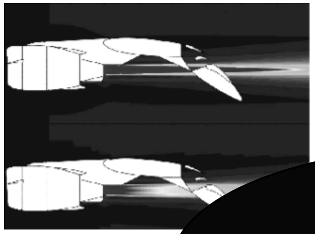


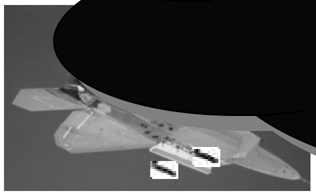
Increasing application

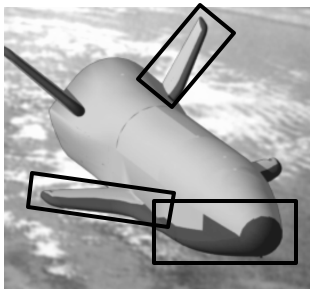
Increasing generality

Air Vehicle Applications for Flow Control

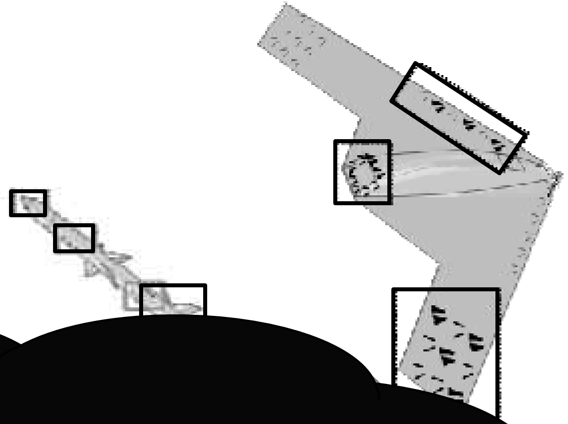




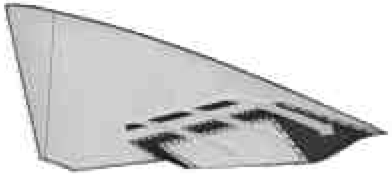




- **Vehicle control**
- **Separation control**
- **Aero-acoustic fatigue**
- Skin friction reduction
- Therma
- Noise atten
- Buffet alleviation
- Pressure distortion
- Compressor, turbine, combustor control

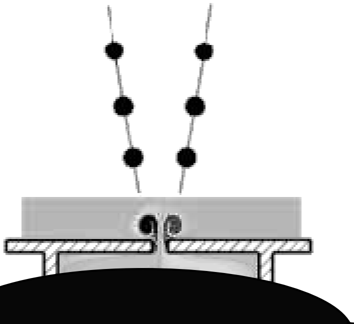


Which applications will benefit from order reduction and feedback control?

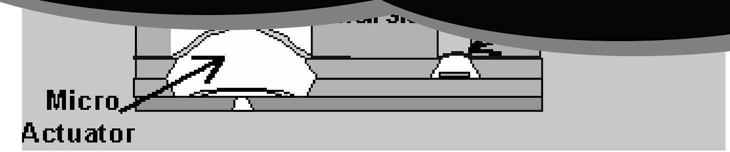


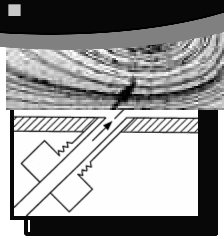
Actuators & Sensors

- 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

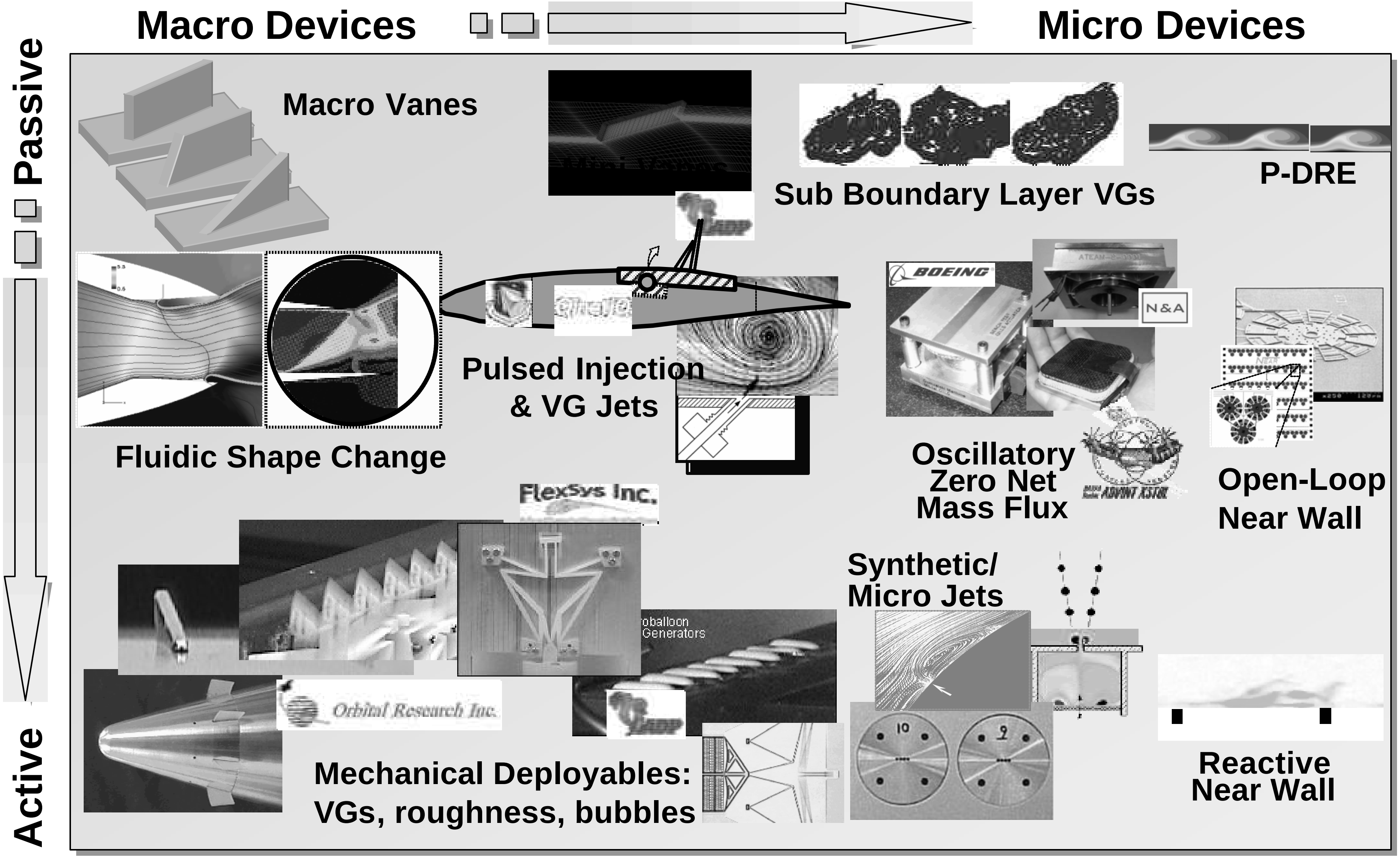


Which actuators are relevant for order reduction and control law design?





Ranges of Actuators



Macro Devices → **Micro Devices**

Passive → **Active**

Macro Vanes

Sub Boundary Layer VGs

P-DRE

Fluidic Shape Change

Pulsed Injection & VG Jets

Oscillatory Zero Net Mass Flux

Open-Loop Near Wall

Synthetic/ Micro Jets

Mechanical Deployables: VGs, roughness, bubbles

Reactive Near Wall

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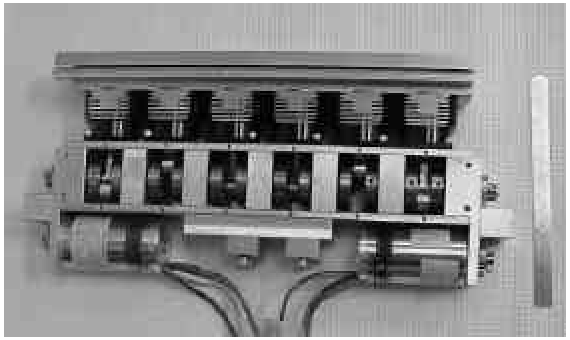
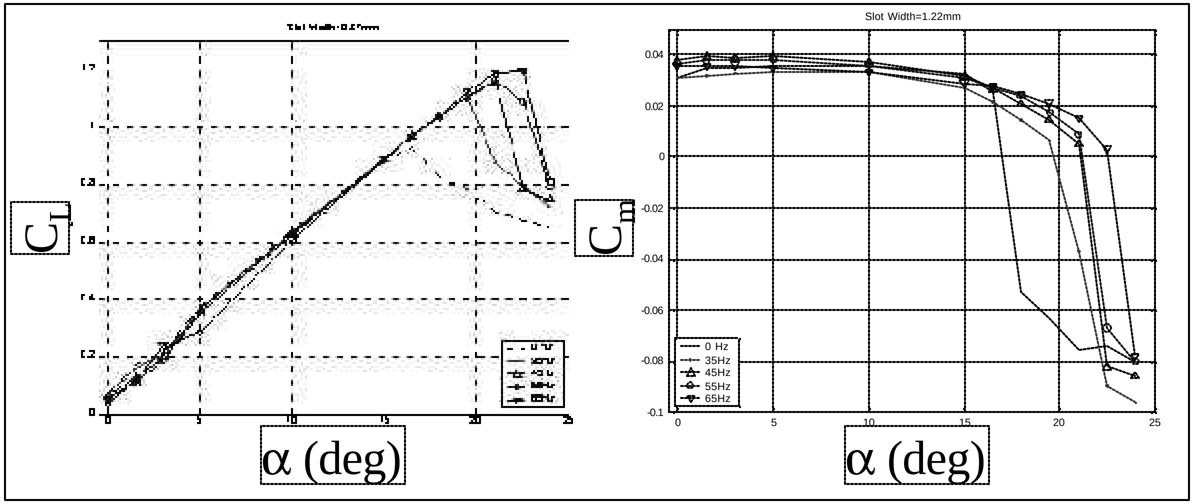
Control of Wing Attitude with Synthetic Jets

- **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

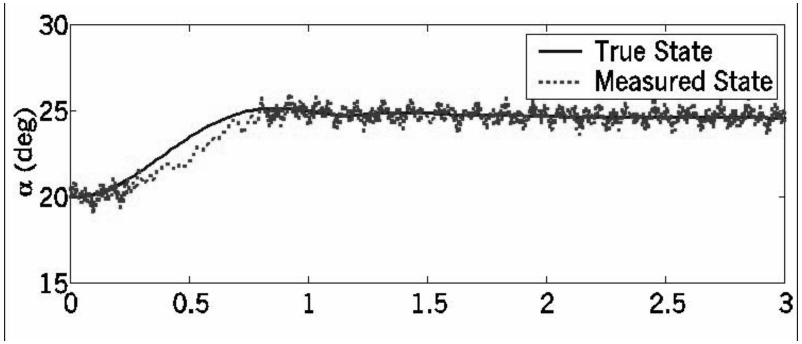
- Control of the forces/moments possible at high angle of attack by controlling separation
  - Array of six piston/cylinder synthetic jets near leading edge
  - Good control authority above stall (17 deg angle of attack)
  - Nonlinear relationship between synthetic jet frequency, angle of attack, and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



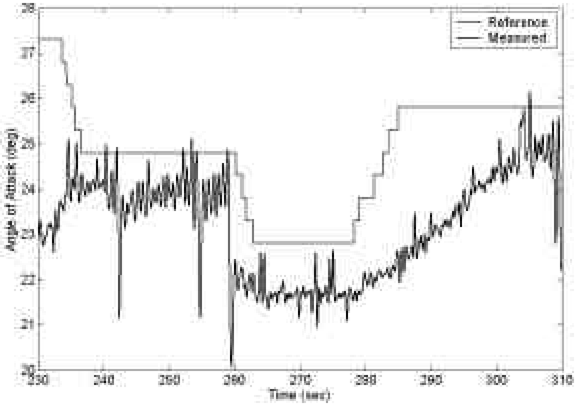


Demonstration of Pitch Control via Feedback Flow Control

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



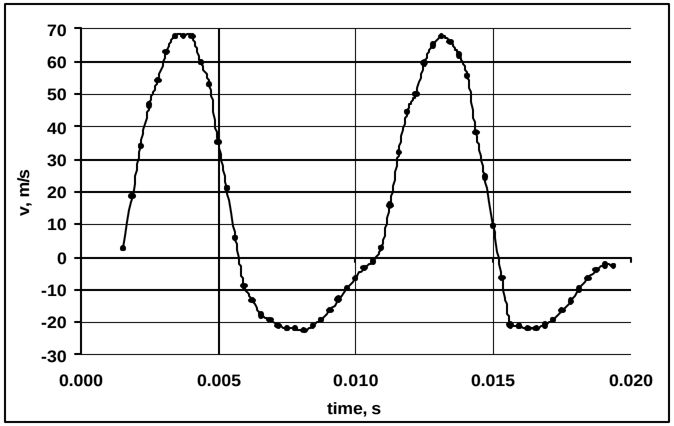
Simulation Results

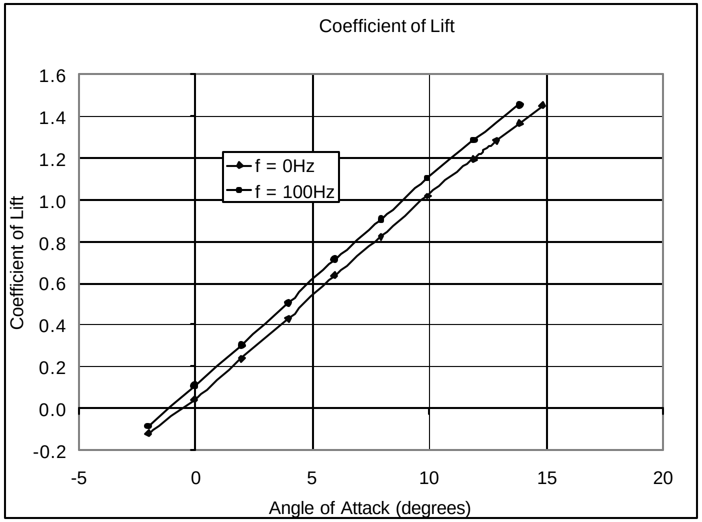


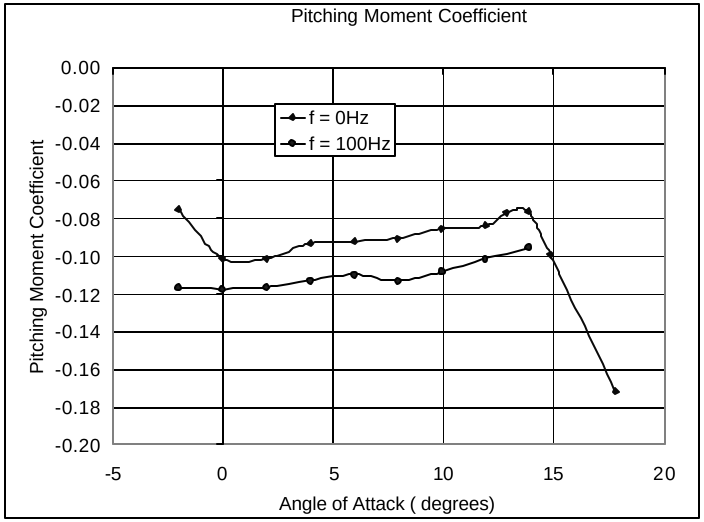
Experimental Results

Trailing Edge Control for Low Angles of Attack

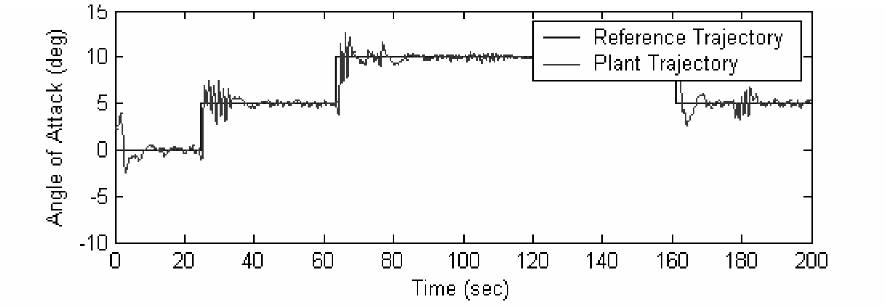
- **Good control authority**
- **Linear !**

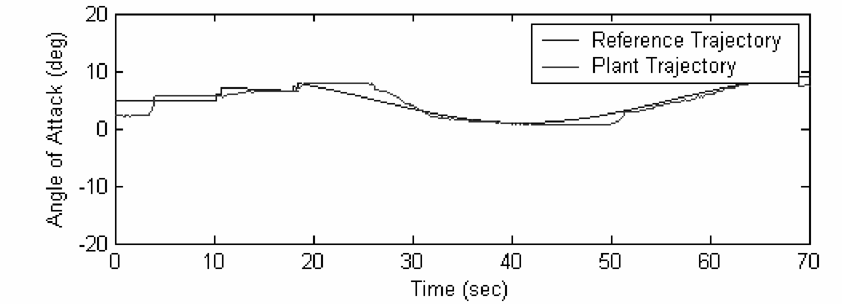


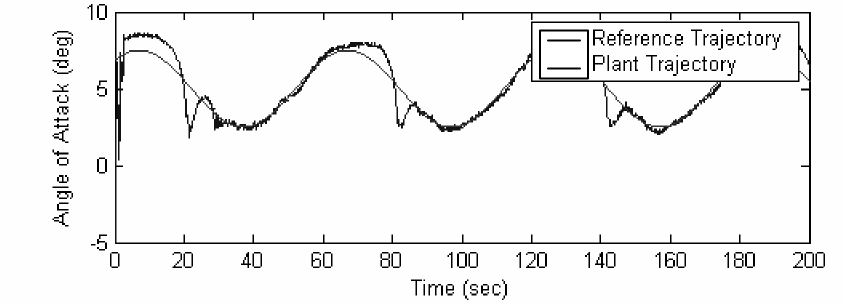




Demonstration of Pitch Control via Feedback Flow Control







Demonstration of Pitch Control via Feedback Flow Control

AEROPROBE CORPORATION

ATM

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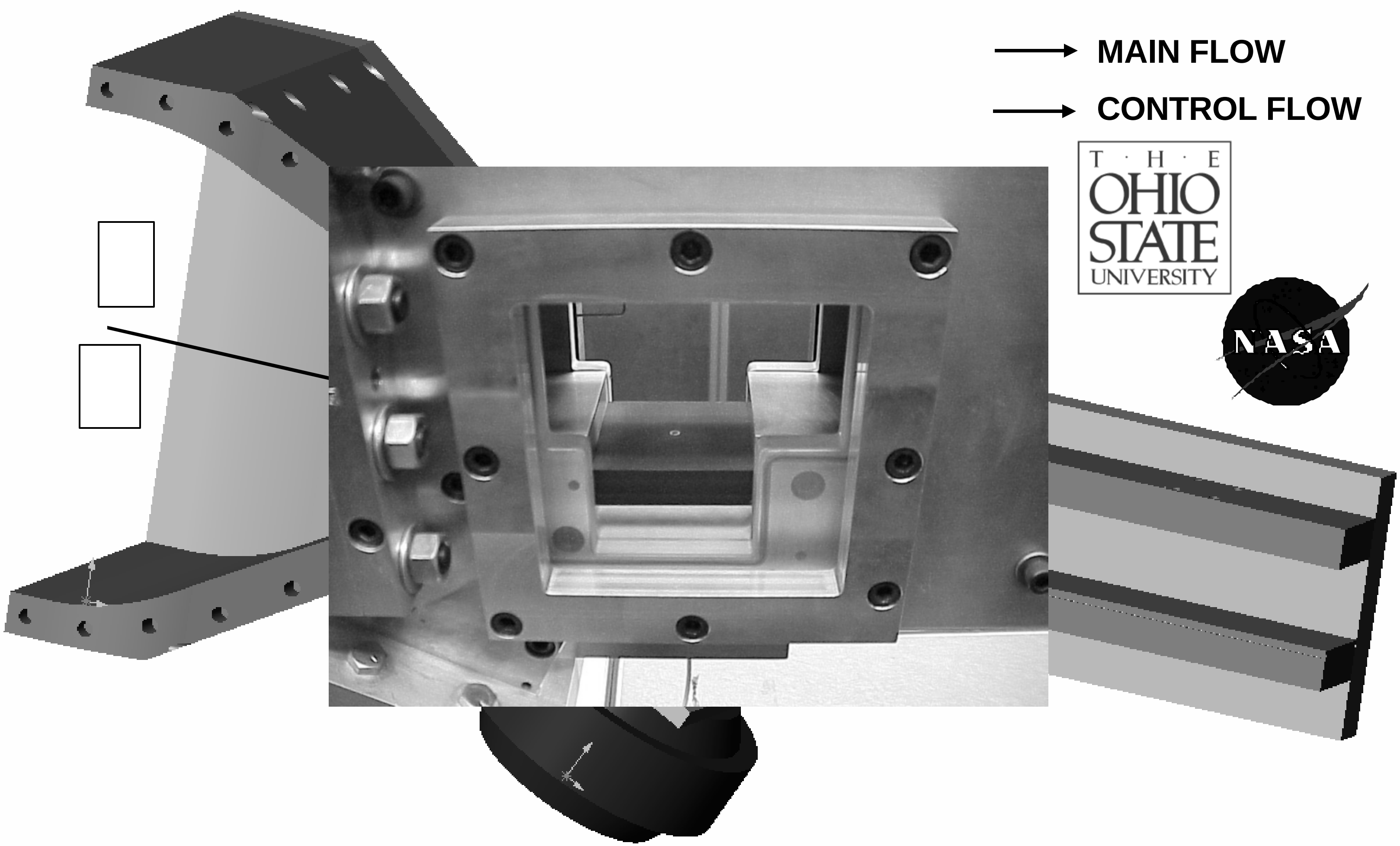
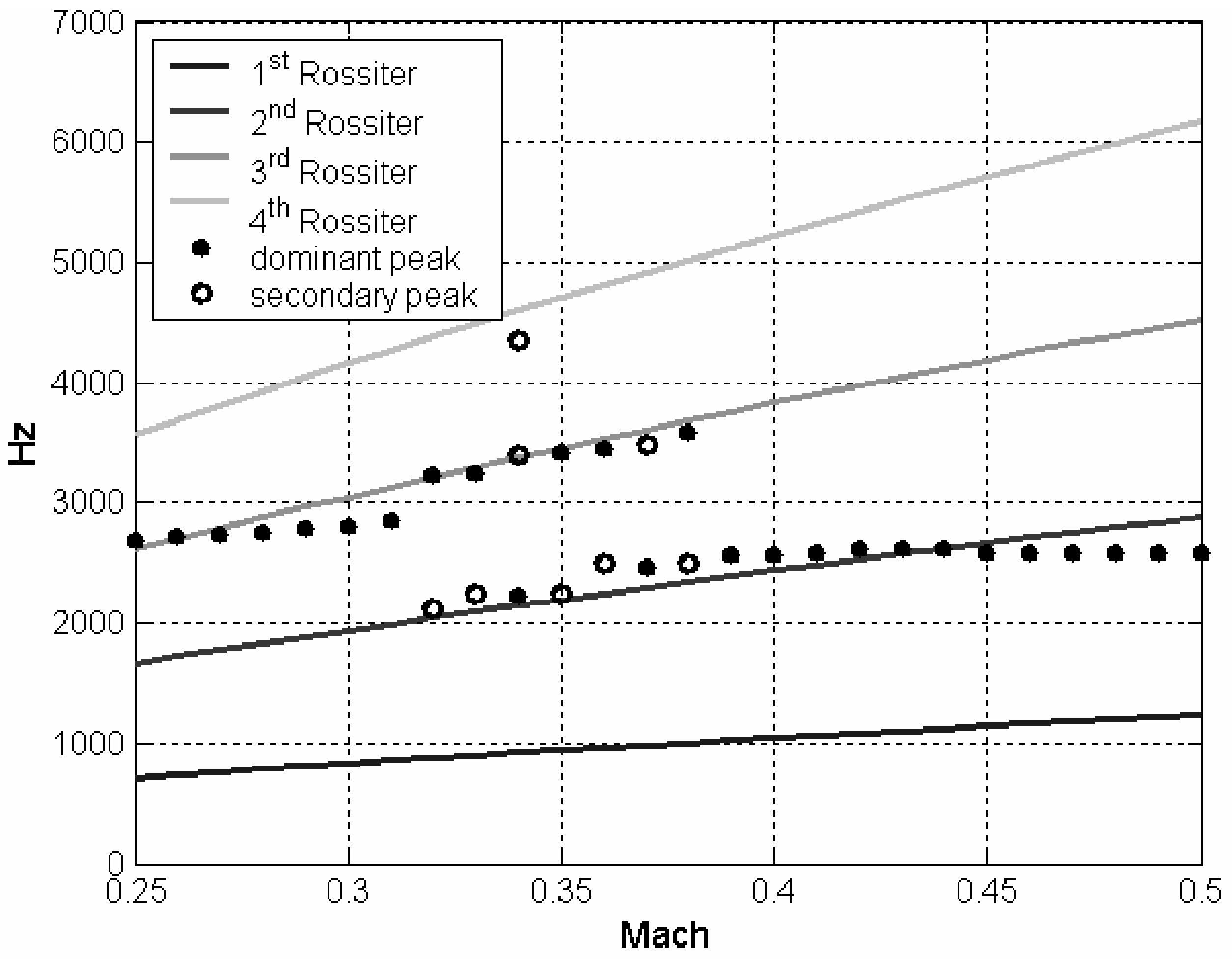
Experimental Arrangement



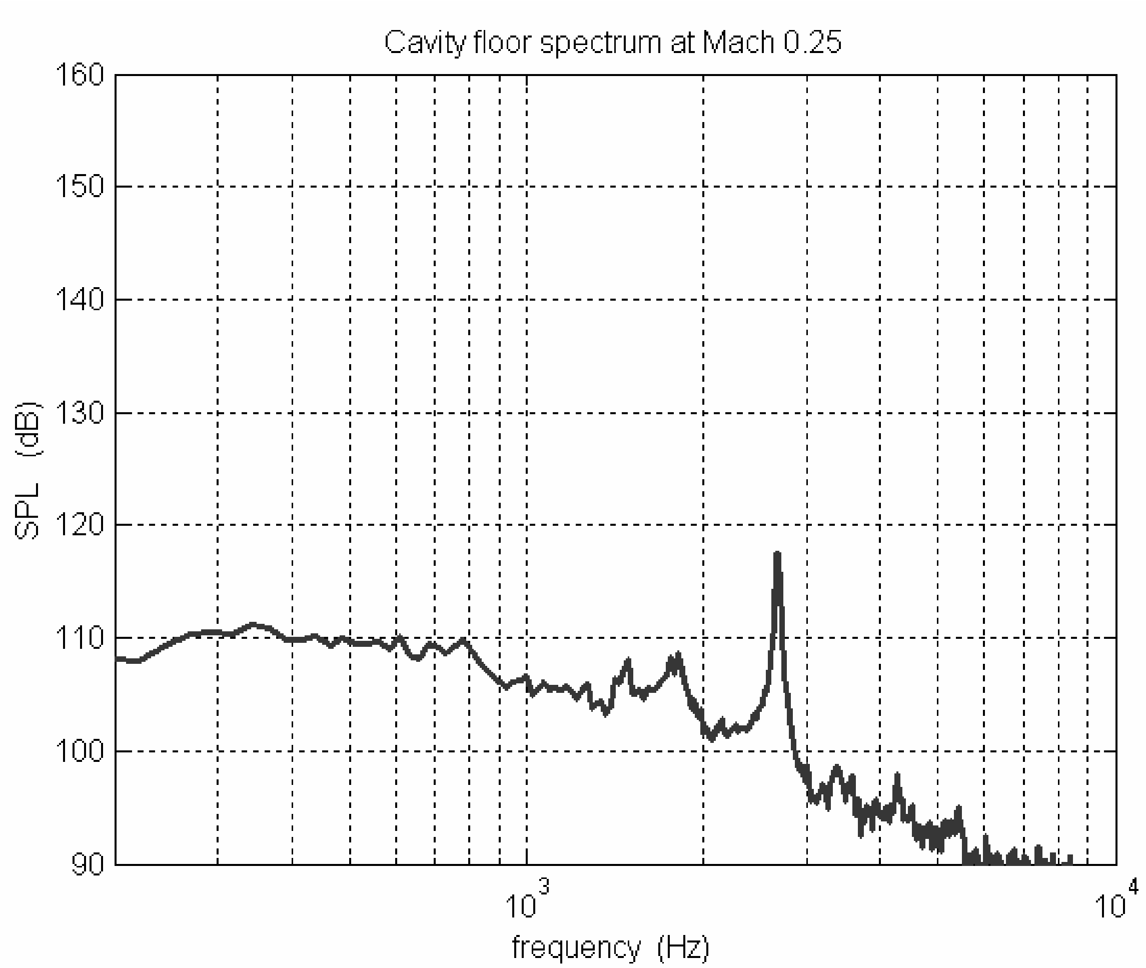
→ **MAIN FLOW**

→ **CONTROL FLOW**

Response Modes

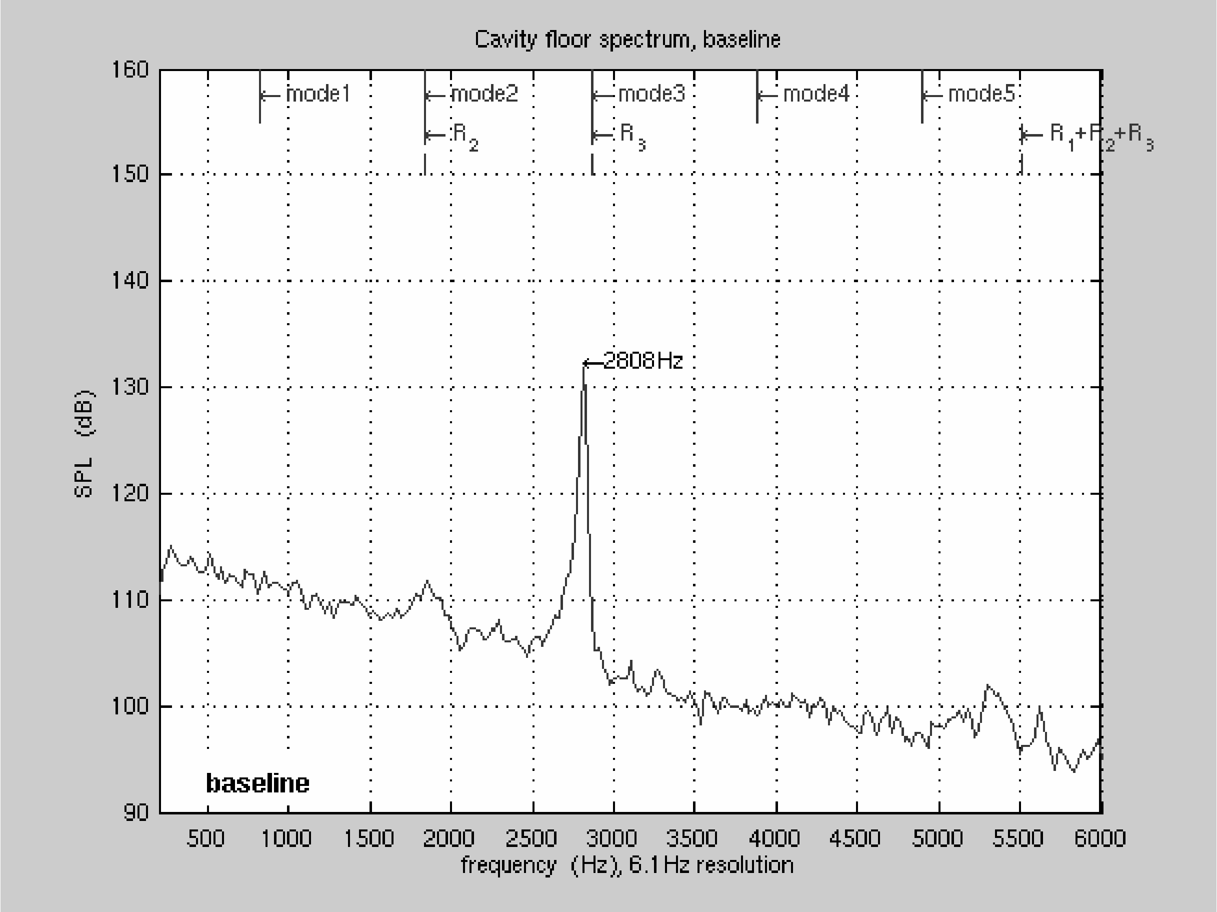


Changing Response w/ Mach



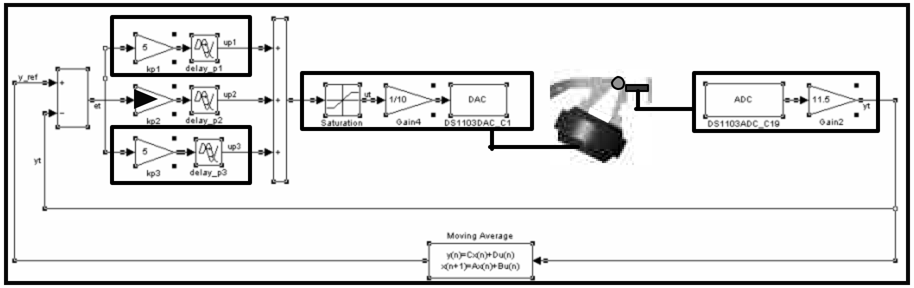
Nonlinearities Lead to Mode-Switching

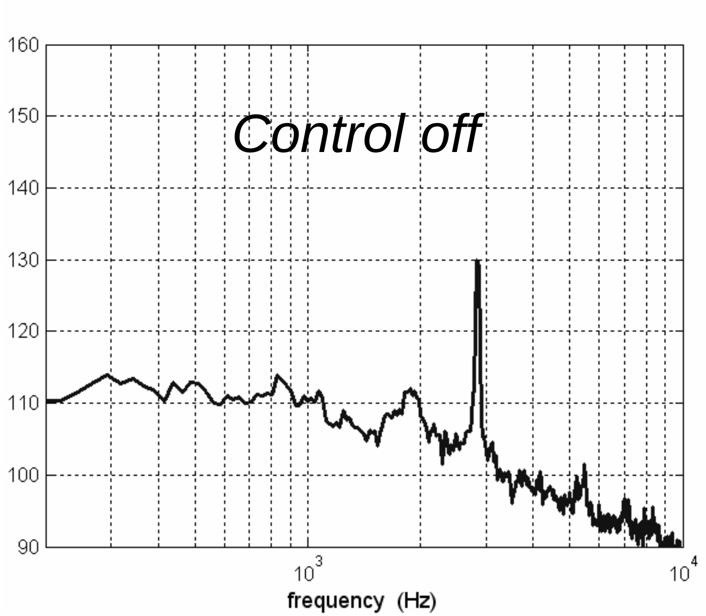
- **Forcing at Frequencies Ranging from 1 kHz to 6 kHz) for Mach 0.30**
- **Unforced flow exhibits single dominant Rossiter mode**

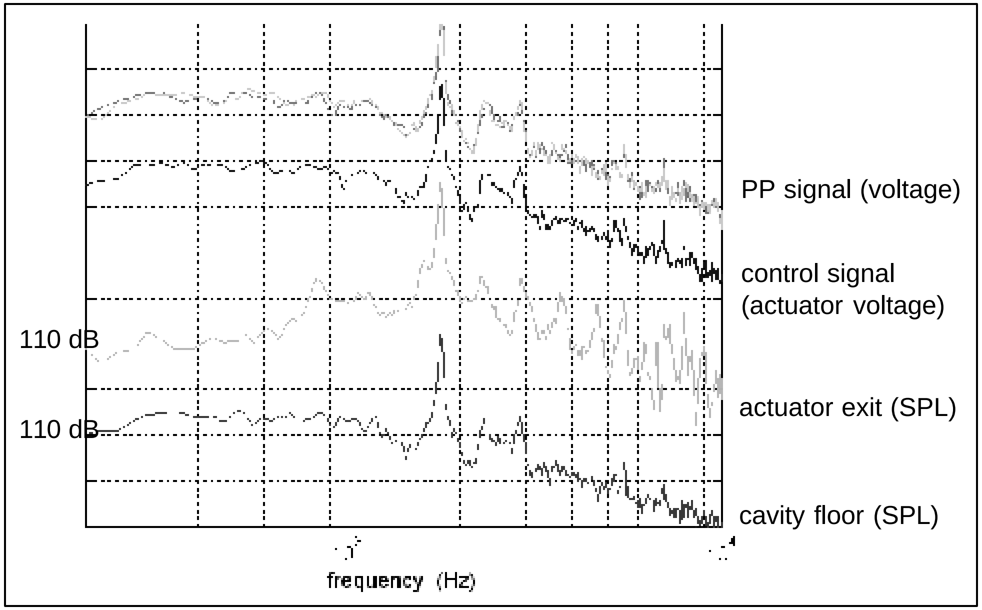


Proportional-Proportional Control

Mach 0.30 flow

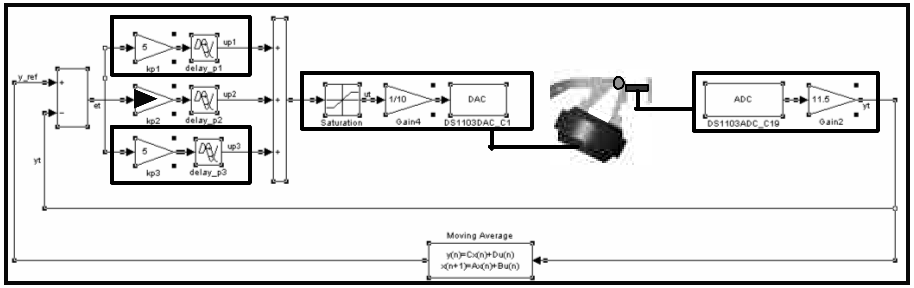






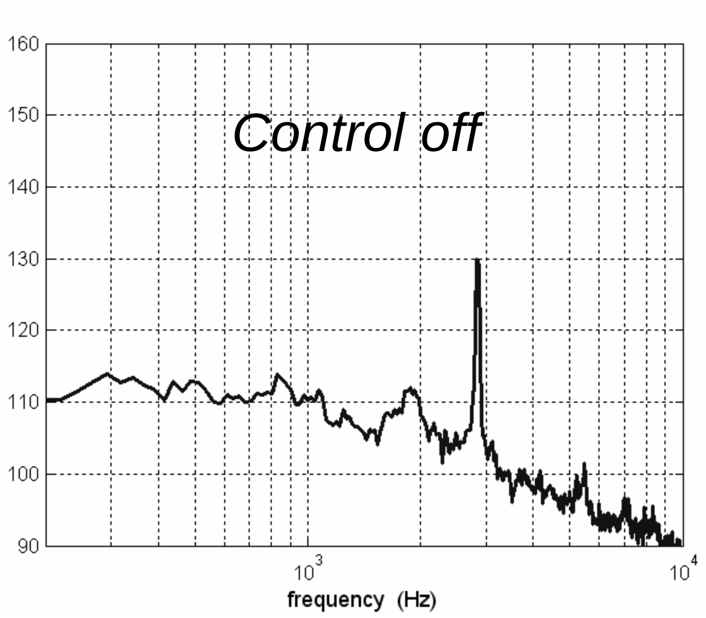
2nd Rossiter mode reinforced

Proportional-Proportional Control

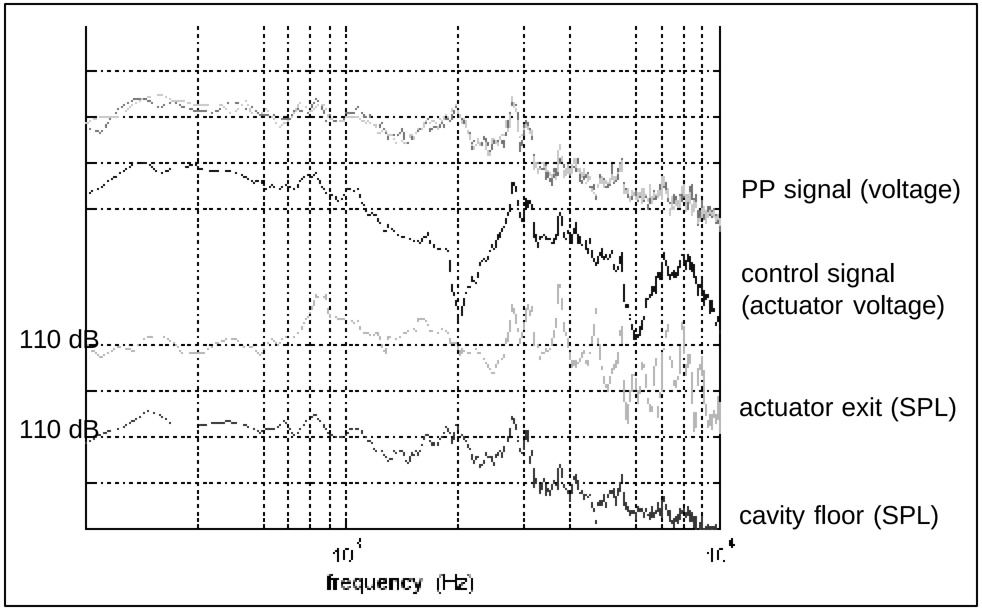


Mach 0.30 flow

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



Control off

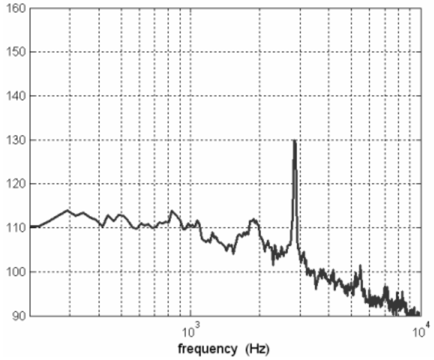


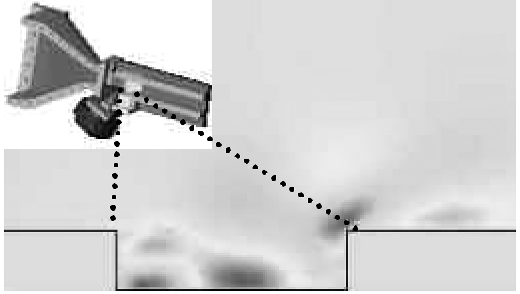
Dynamic feedback suppresses resonance

Benefit of Feedback Control
Robustness

FEEDBACK PRODUCES SUPERIOR RESULTS AT OFF-DESIGN CONDITIONS

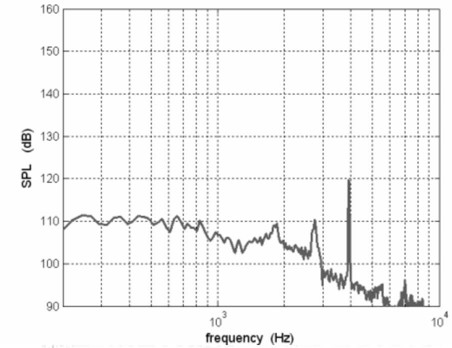
No Control - Mach 0.3

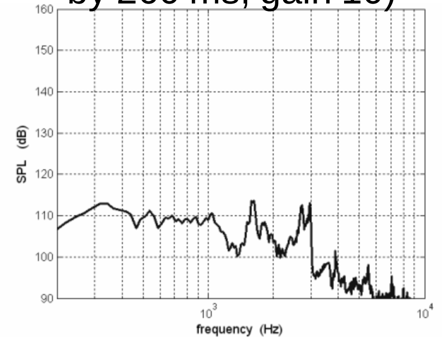




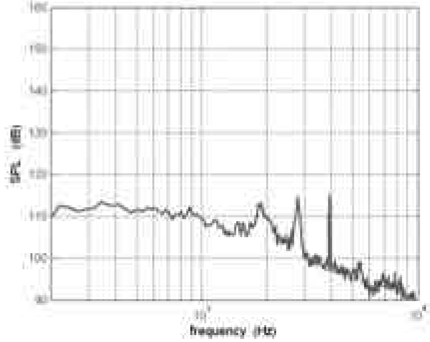
Open-loop Control
Optimized for Mach 0.3

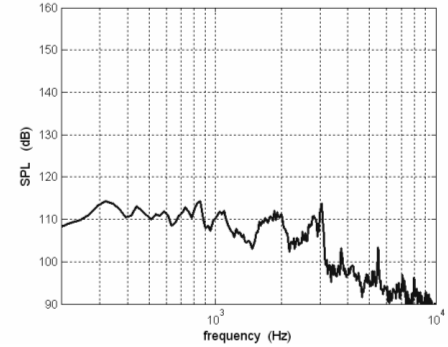
Feedback Flow Control
P-P control (P1 leads P2 by 260 ms, gain 10)



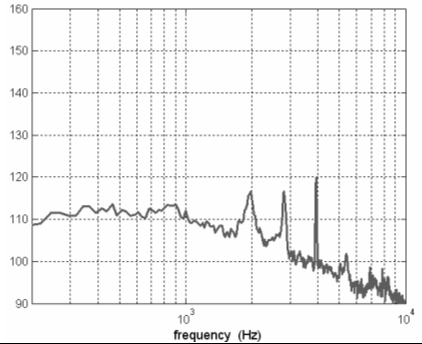


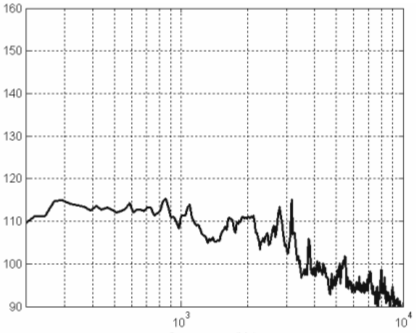
Mach 0.27





Mach 0.30





Mach 0.32

Outline

- Examples of VA Efforts
- 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

Separation Control on NACA 4412

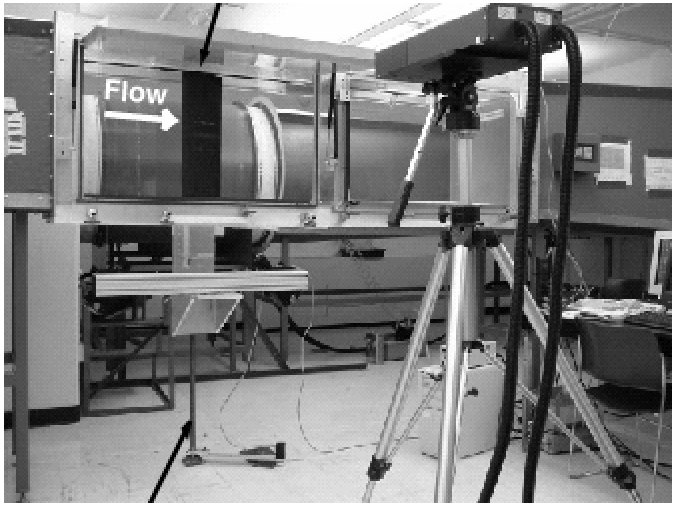
Clear Science Corp.

syracuse UNIVERSITY

Air Force SBIR/STTR

- 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

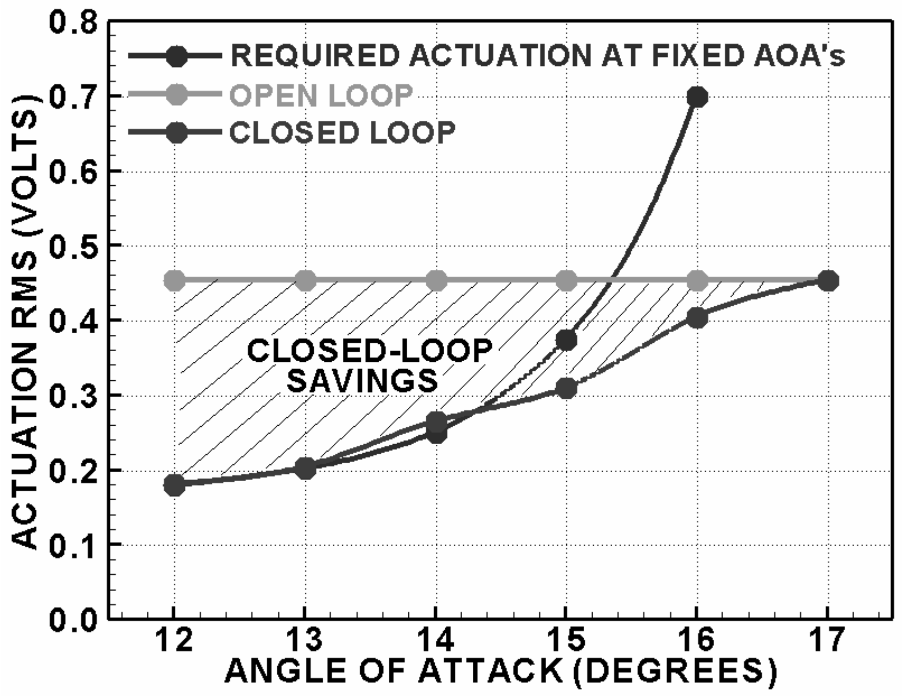


Demonstration of Feedback Control

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

Outline

- **Examples of VA Efforts**
- **What is flow control?**
- **Low-order model approach (KISS)**
  - **Pitching airfoil**
  - **Cavity tone suppression**
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  - **Nonlinear convection**
- **Summary and future work**

Simulation-Based Feedback Flow Control

Benefits:

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

Challenges:

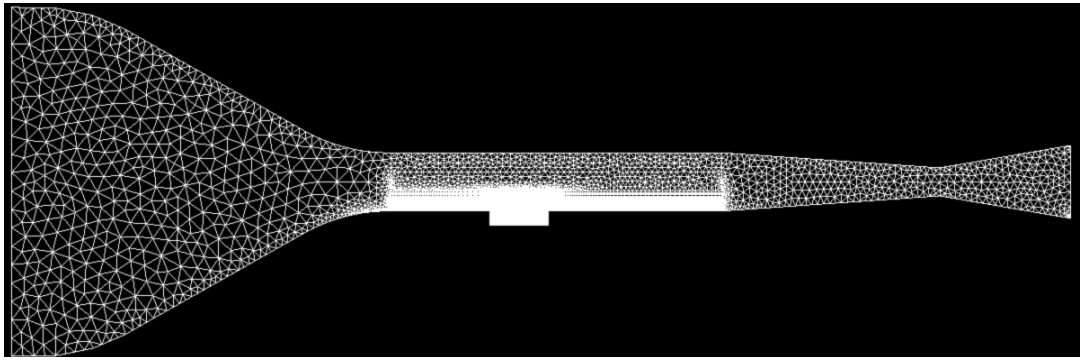
- Simulation time requirements
- Huge system dimension
- CFD and control design often incompatible
- Experimental validation

Design/Reduce

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

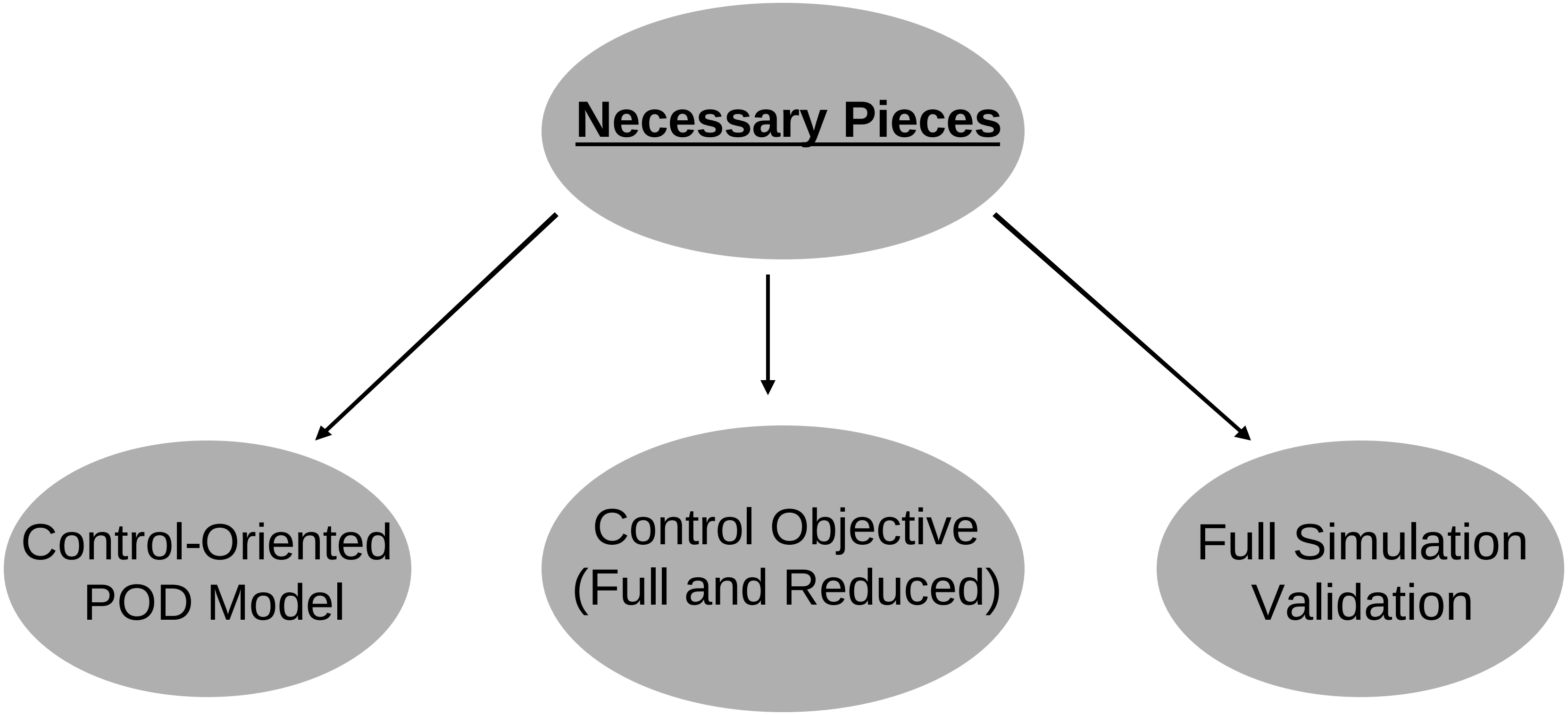
Reduce/Design: System Model Reduction? Feedback Control Design

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

<u>Goal</u>: Boundary Tracking Feedback Control

<u>Governing Equation</u>:

Specify multiple boundary inputs in snapshot ensemble

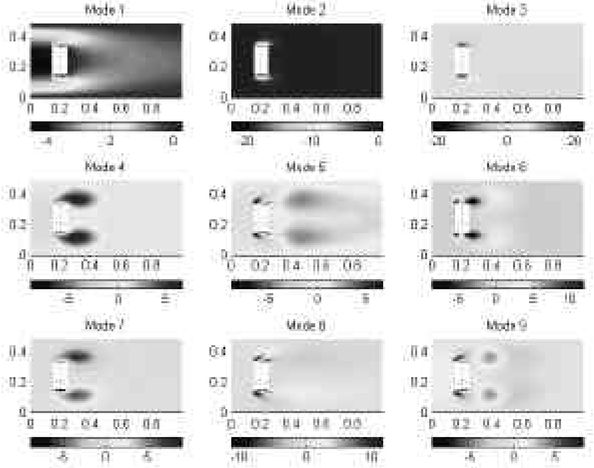
$$u_B(t) = N\sin(0.25t^2) \quad u_T(t) = 0$$

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

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

N = -3, -2, -1

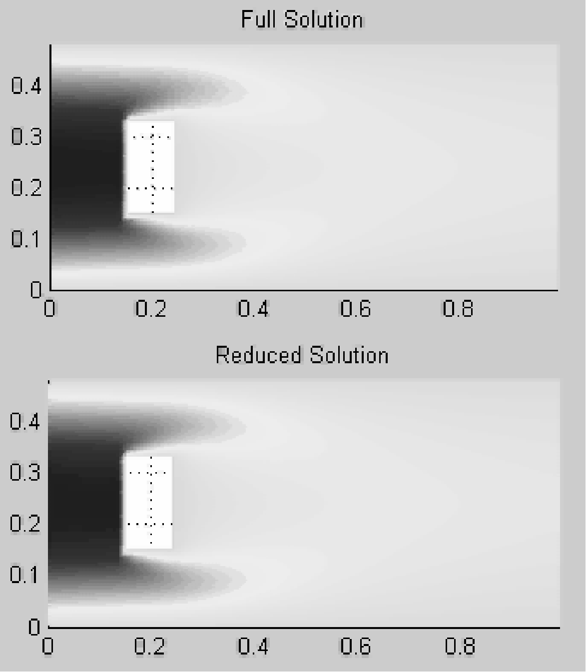
First 9 POD Modes



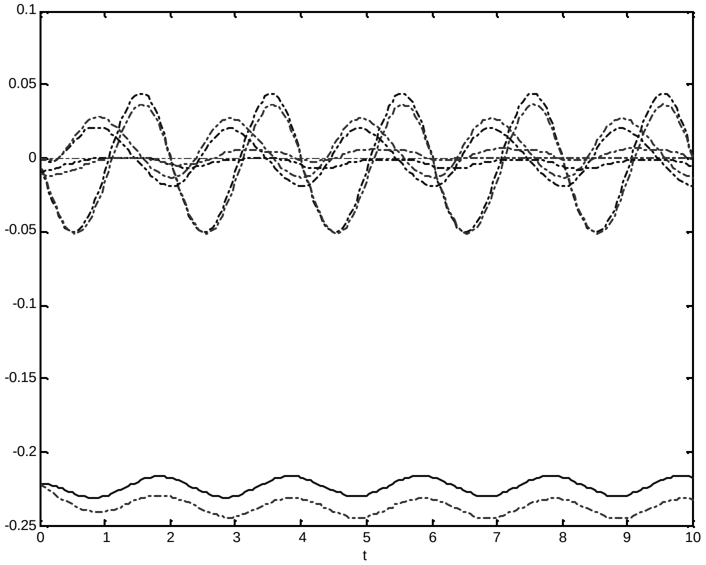
Validate Model

Comparison of POD and Full Order Models

Open-Loop Test



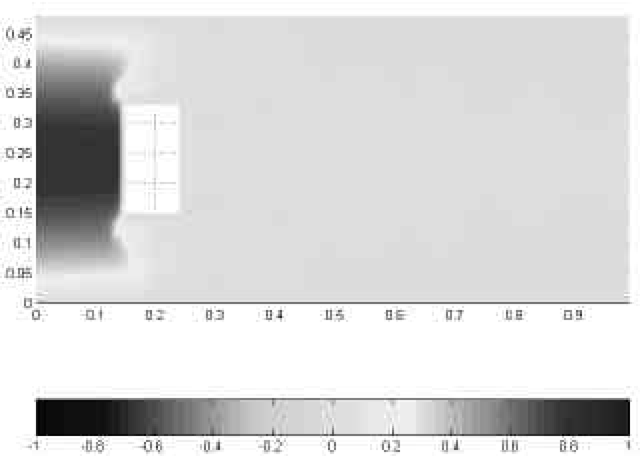
First 5 temporal coefficients



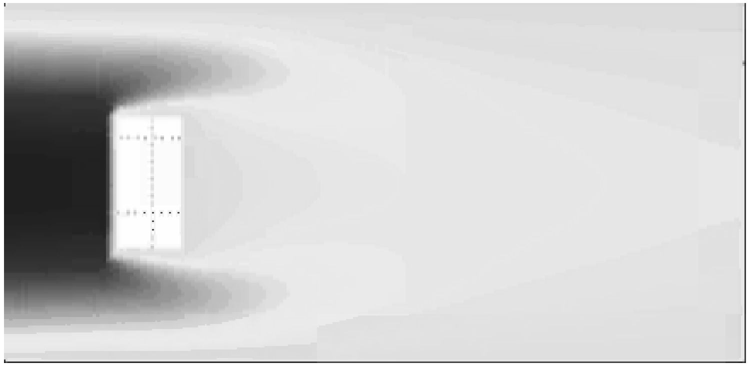
Validate Control Law

Design Control From 25 Modes

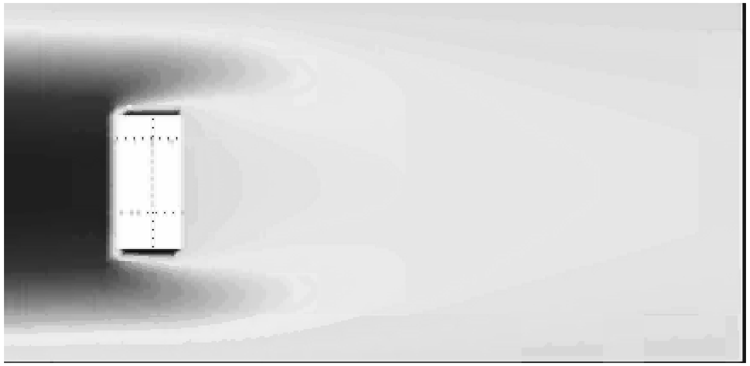
Reference Function



Controlled POD Model

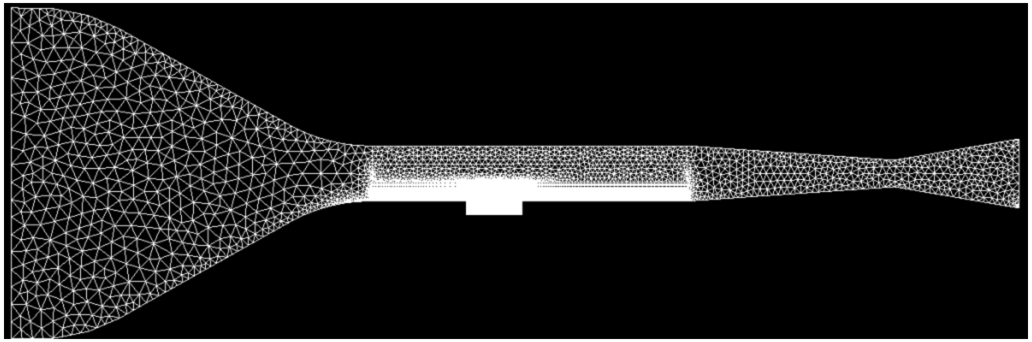


Controlled Full Order System



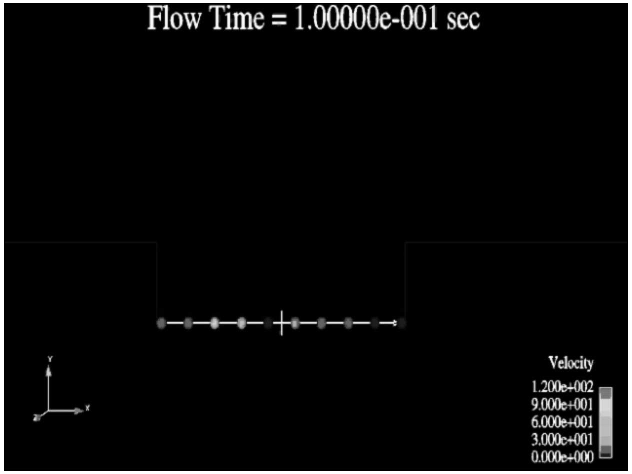
Effective Reduced Control (2005 GNC)

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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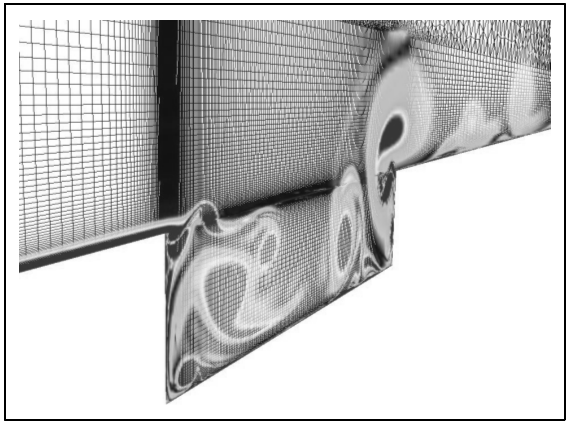
Summary & Future Work

- **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**