Recent Advances of MEMS Applications In Flow Control

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Cms Center for Micro Systems

fmrl fluid mechanics research laboratory

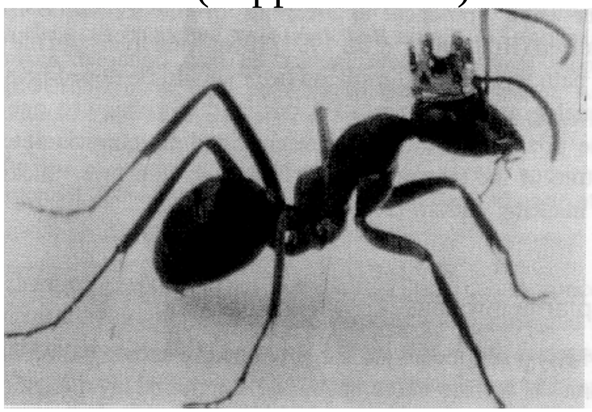
Outline

- Micro Electro Mechanical System
  - What is MEMS?
  - Why MEMS?
- Flow Control Issues
  - Physical parameters: Scale, Amplitude, Phase, Location ...
  - Relevant Flow Physics
- Sample Flow Control Applications

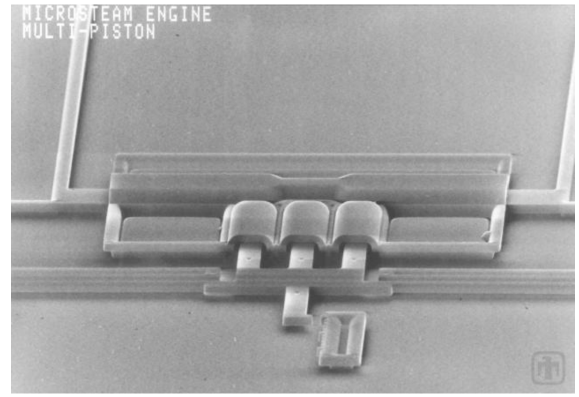
Micro Electro Mechanical System (MEMS)

Miniaturized

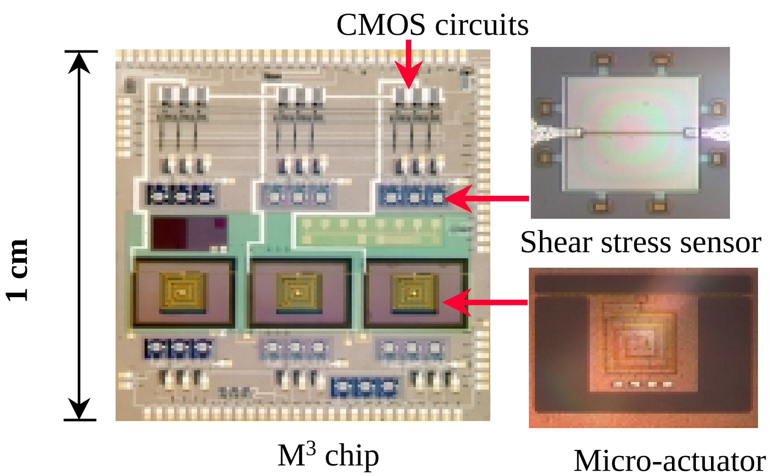
A crown on an ant’s head
(Nippon Denso)



World’s Smallest Steam Engine
(Sandia Lab)

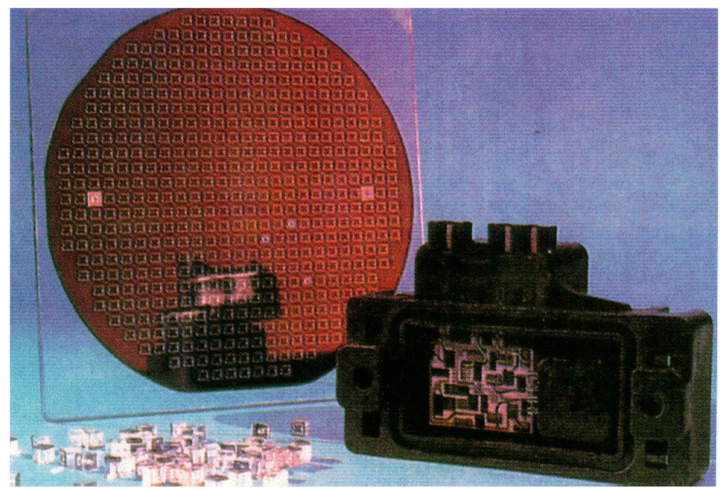


Integration



UCLA/Caltech

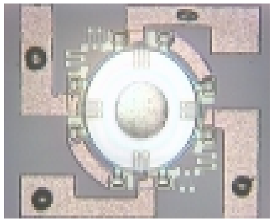
Batch Fabrication



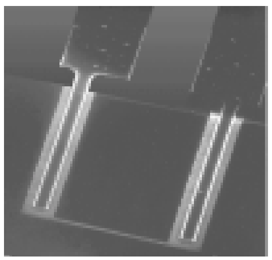
General Motor’s MAP sensors

MEMS Sensors

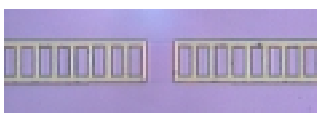
Whole-field sensing
Spatial-temporal evolution



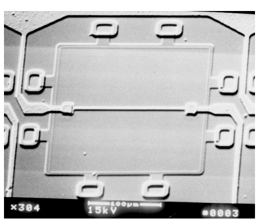
Pressure sensor



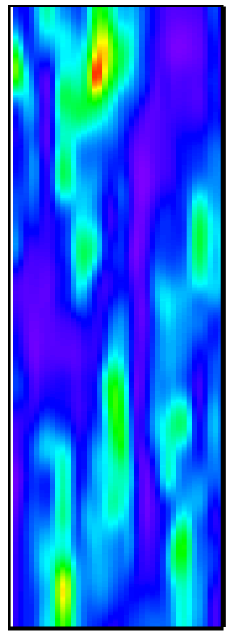
1 M Hz Hot-wire
⇒ Velocity

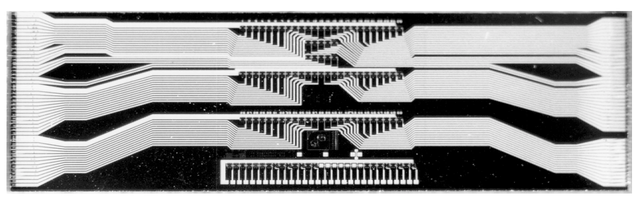


0.02ºC Temp. sensor

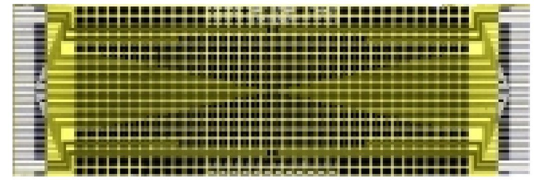


Shear stress sensor

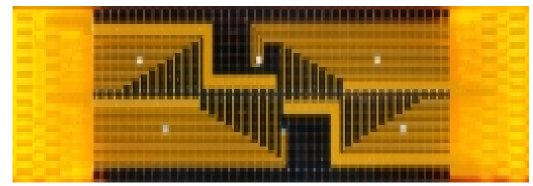




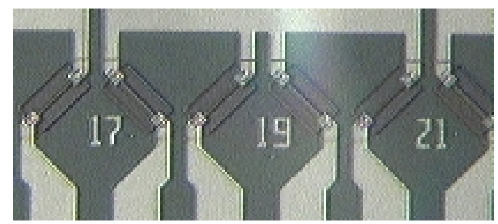
Shear stress sensor array



Shear stress sensor skin



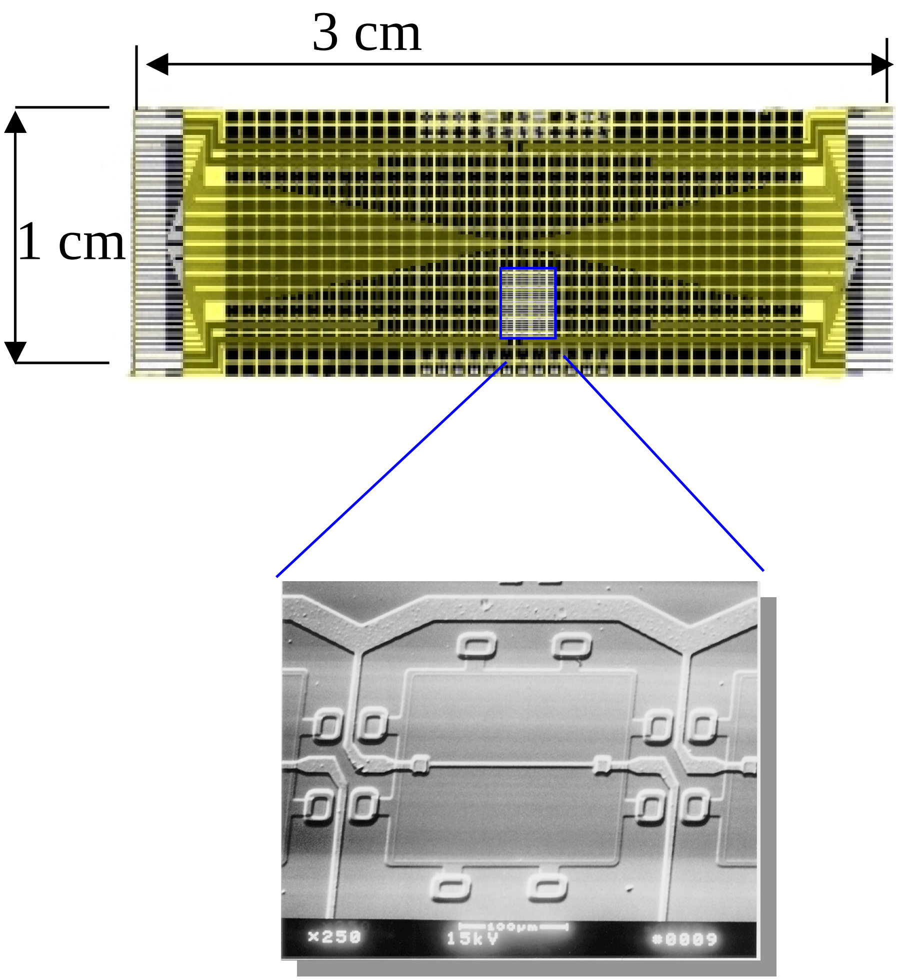
Backside contact sensor skin



V-shape
shear stress sensor array

Sensor array

Flexible skin with sensor array

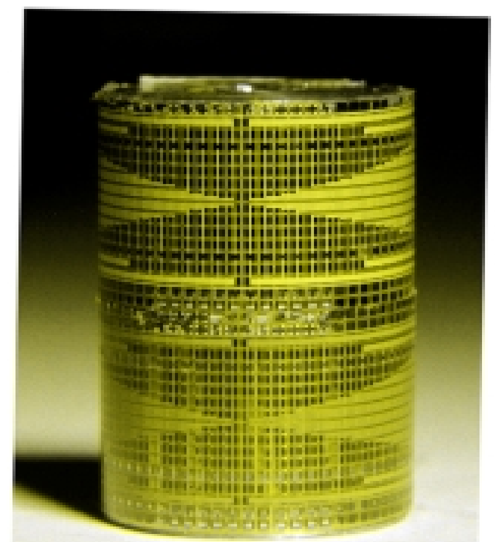


200 x 200 μm^2

* 72 sensors in 1x3 cm^2 area.

* Frequency response: 10 kHz

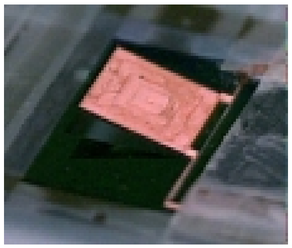
* Thickness: 80 µm

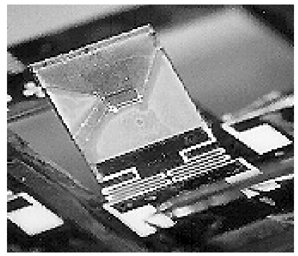


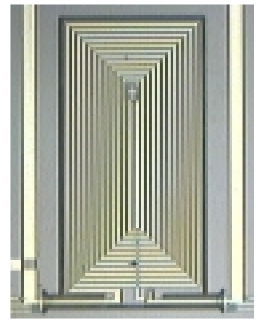
Sensor Skin

MEMS off-plane actuator

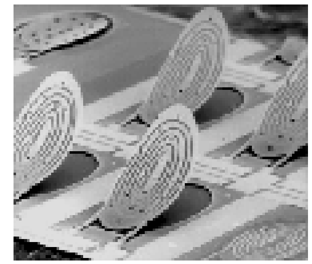
Flap actuator





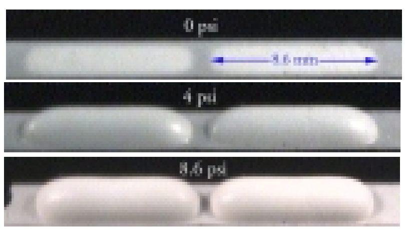


4 kHz

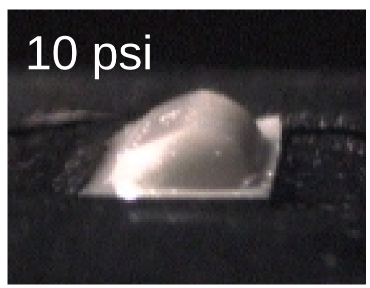


Array

Balloon actuator

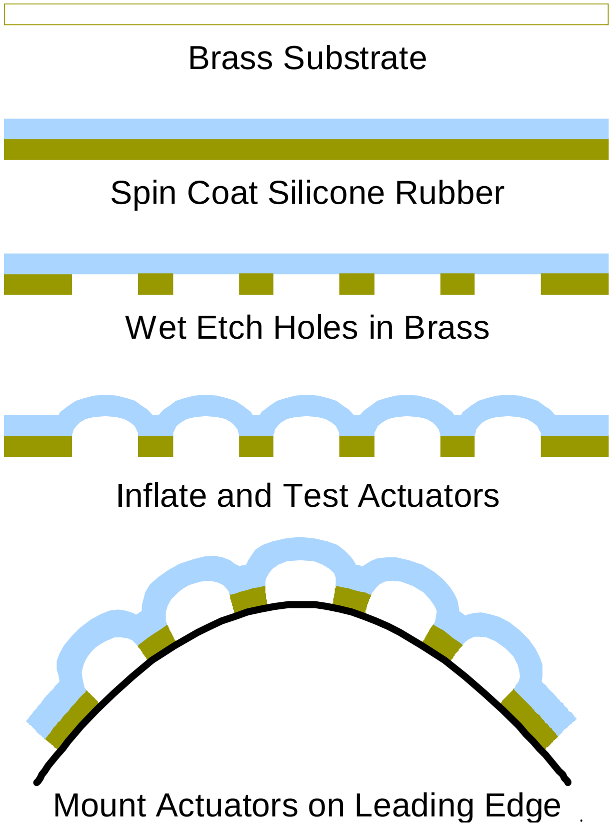


symmetric

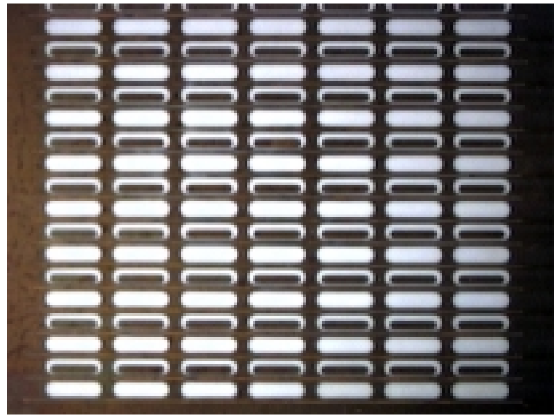


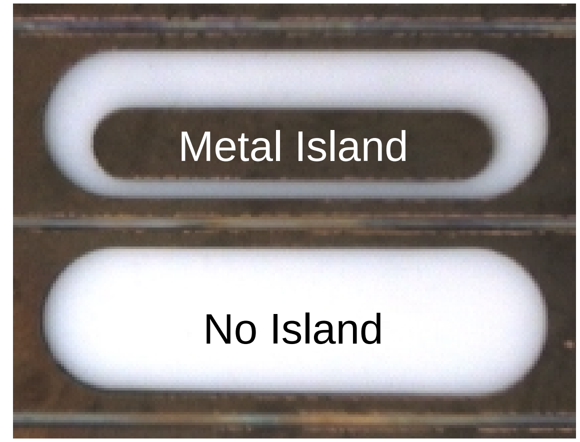
asymmetric

Array on the LE

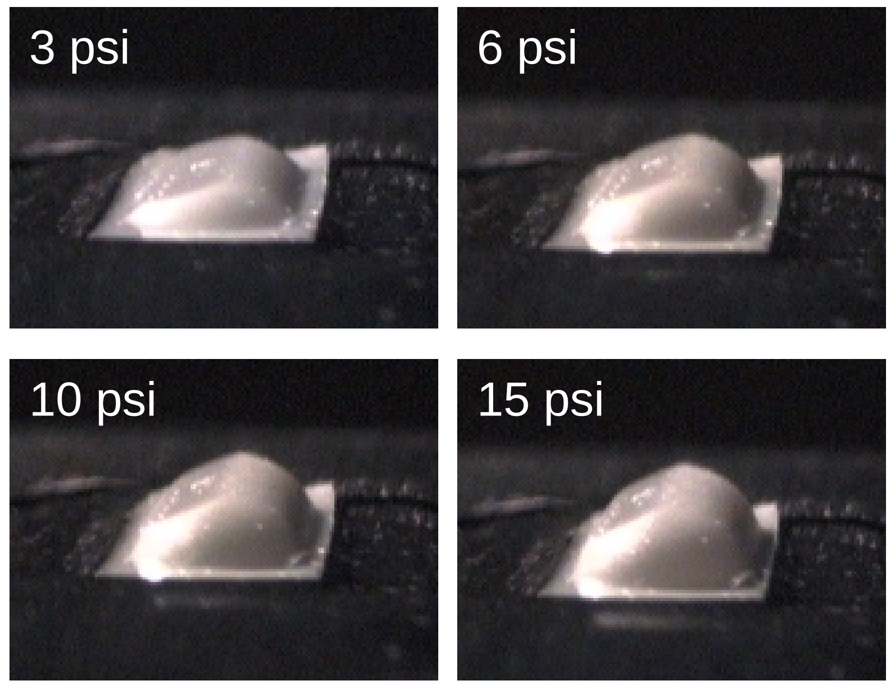


- Square Substrate
- No Alignment
- Arbitrary Island Shape
- Simple Etching Step





Metal Actuator Skin



Asymmetric Balloon Actuation

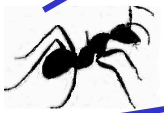
MEMS in Flow Control

System – Sensors IC Actuators

Perceiving Decision Action

1 / ε control

O (1)



O (ε)

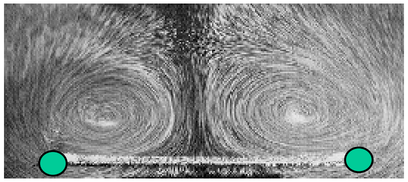
Understand Flow Physics

Capability to Perform Real-time Distributed Sensing and Control

Flow Amplifier

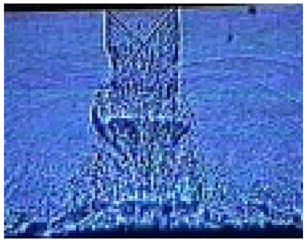
ε ⟶ **1**

Separation



Vortex control
UAV maneuvering

Instability



Impinging Jet
Feedback loop
attenuation

Transition

Boundary layer:
laminar-turbulent

Drag Reduction

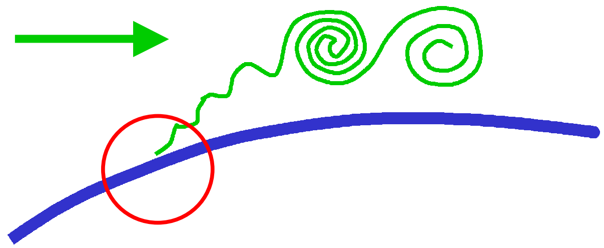
Origin : sensitive position

Perceive* - *sensor, signal acquisition
Think* - *flow physics, simple & definitive
Act* - *actuator, amplitude, frequency,phase

Sample MEMS Application I

- Aerodynamic Delta Wing Flow Control
  - ⇨ Scale matching: $O(\varepsilon) \Rightarrow O(1)$
  - ⇨ Leading-edge vortex manipulation for UAV maneuver

Flow Separation



After separation
Wake formation

Before separation
Boundary layer is
thin, thickness δ

$$\frac{\partial P}{\partial s} > 0 \Rightarrow \text{Separation, Instabilities \& Stall}$$

$\Rightarrow$ Eruption of large vorticity flux

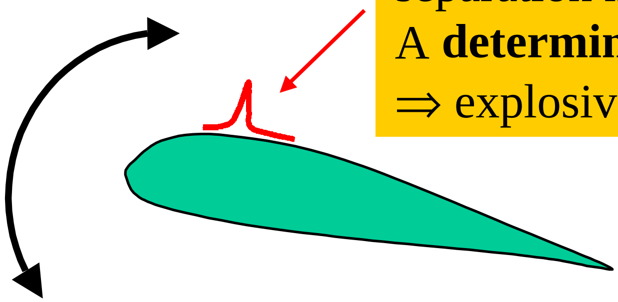
from the surface at the separation point

- Sensitive to local curvature variation: $\frac{\partial P}{\partial s}$
- Scale matches micro devices: $\delta \sim O(\varepsilon)$
- Intrinsic flow amplifier:

$O(\varepsilon)$ perturbation $\Rightarrow O(1)$ effect

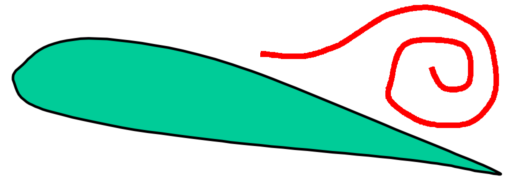
Dynamic Stall Vortex Control

Van Dommelen & Shen unsteady separation model:
A **deterministic** particle collision process
⇒ explosive vorticity eruption

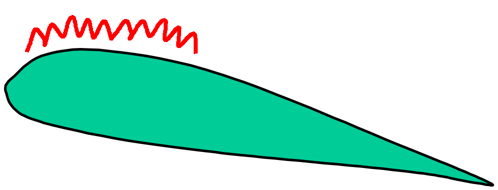


Pitching airfoil, ex: helicopter rotor blade

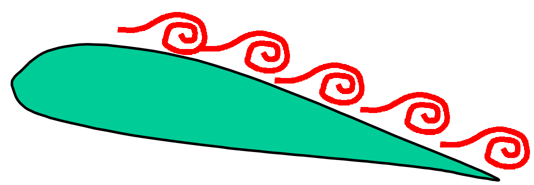
Leads to the formation of a dynamic stall vortex
⇒ catastrophic breakdown



Controlled, distributed ejection of surface vorticity ⇒ **redistribution** of the vorticity ejection

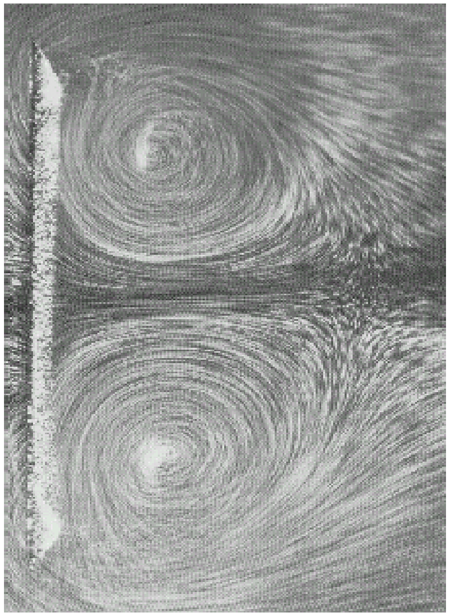


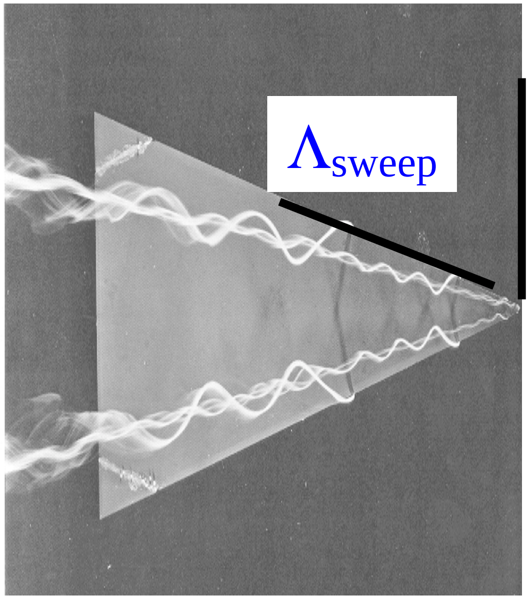
More manageable breakdown process



- **Timely (phase detection by sensors) control is critical**

Aerodynamic Control of a Delta Wing



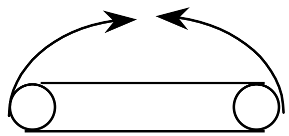


Werle [1963]

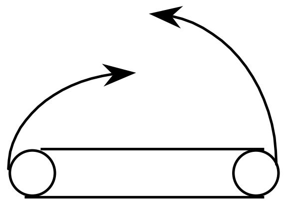
- Leading-edge vortices contribute a significant portion of total lift
- Vortex lift : 40 % of total lift (at Λ_{sweep}=56.5° , AOA=30°)

Symmetry breaking ==> Aerodynamic torque

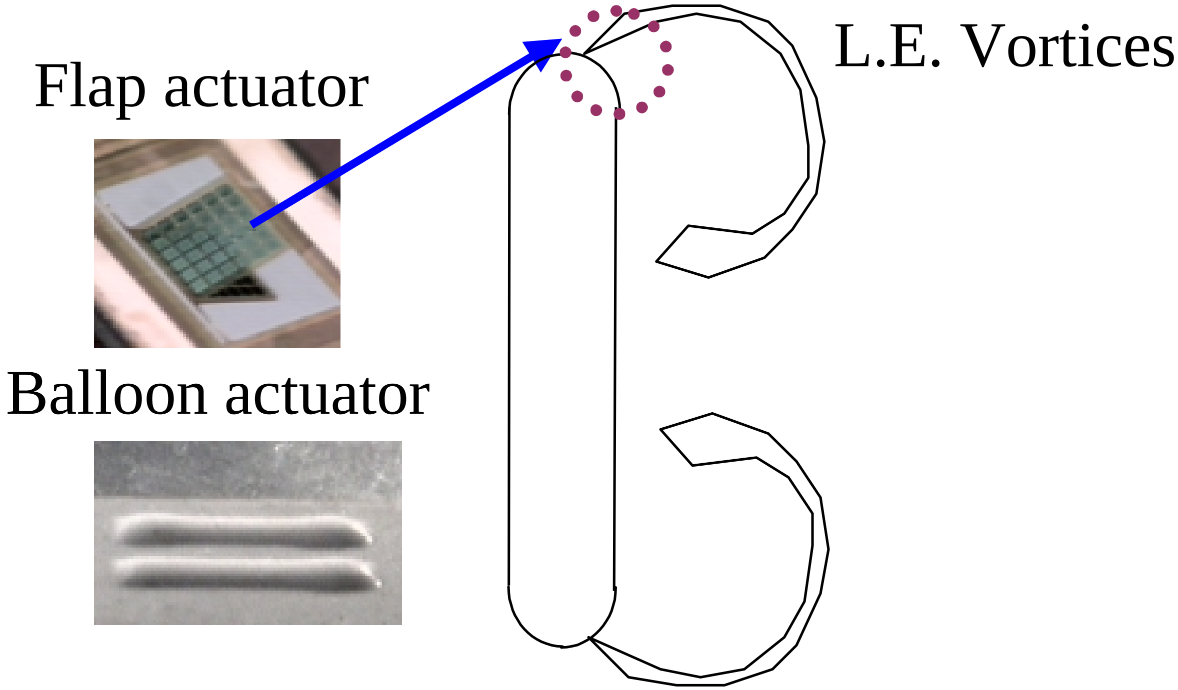
Strategy



w/o actuation



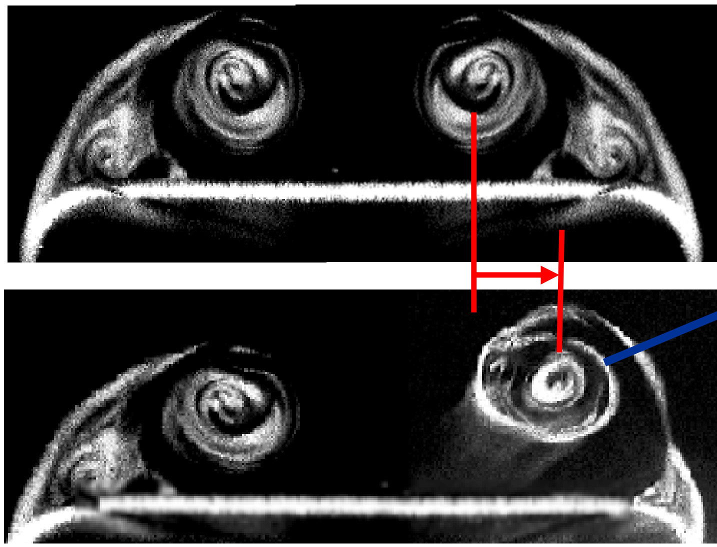
w/ actuation

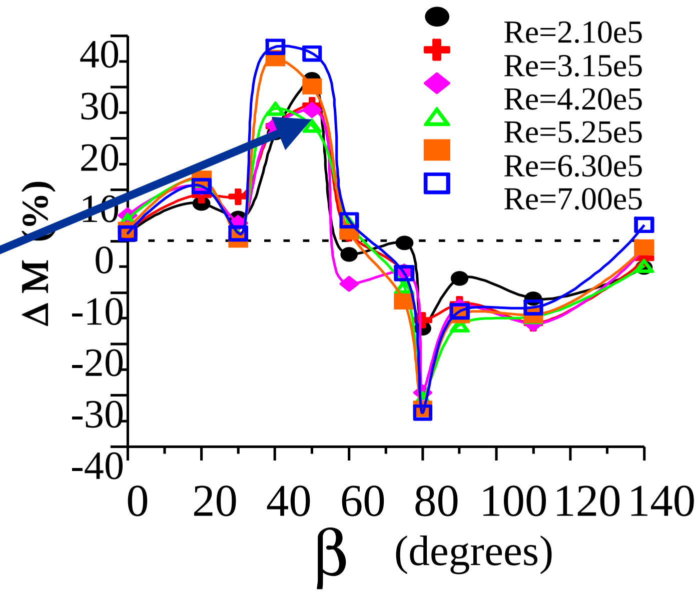


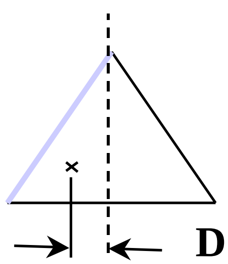
- Boundary layer thickness ~ *O*(mm) => Length Scale Coupling
- Shear stress sensor array => Separation line detection
- Use micro actuators to control the separation => Symmetry breaking
- Vortex Control instead of camber control

Micro-scale Perturbation ==> Macro-scale Modification

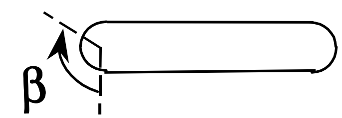
Positive Rolling Moment





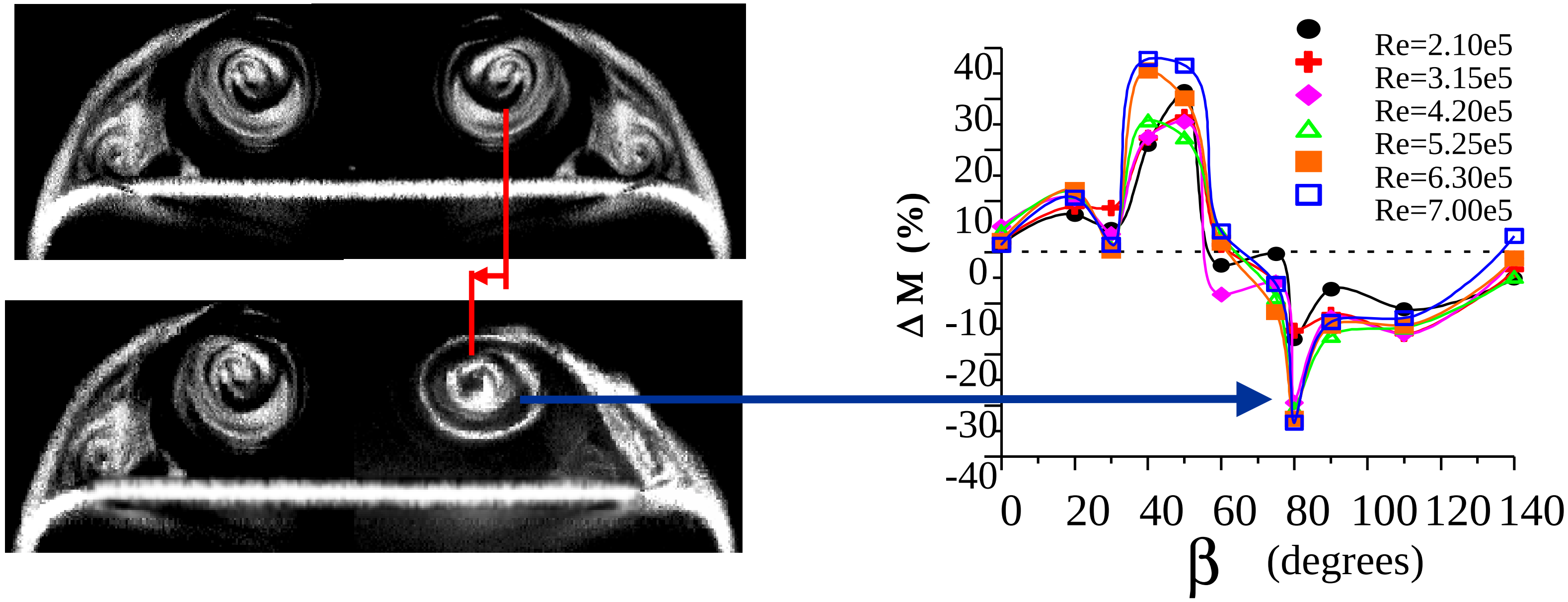


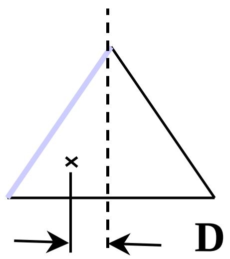
$$\Delta M\ (\%) = \frac{\Delta Mr}{\frac{1}{2} \times Lift_{vortex} \times D}$$



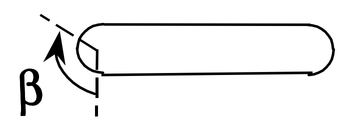
Actuation upstream of the separation line

Negative Rolling moment





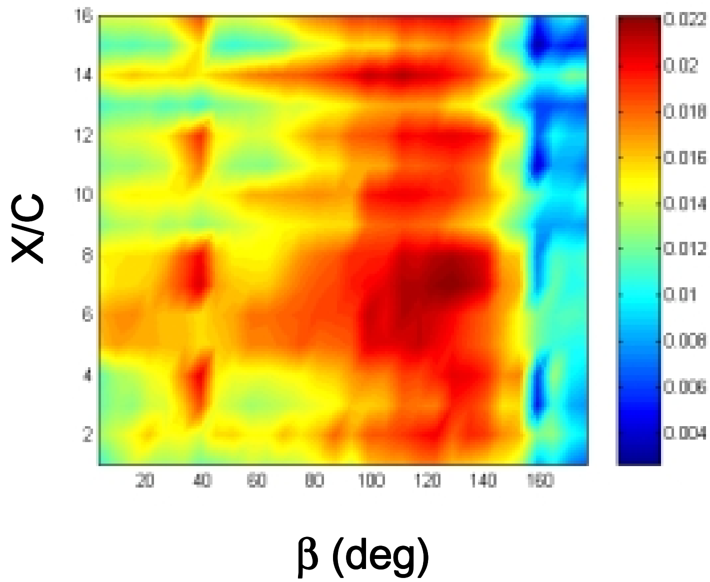
$$\Delta M\ (\%) = \frac{\Delta Mr}{\frac{1}{2} \times Lift_{vortex} \times D}$$



Actuation downstream of the separation line

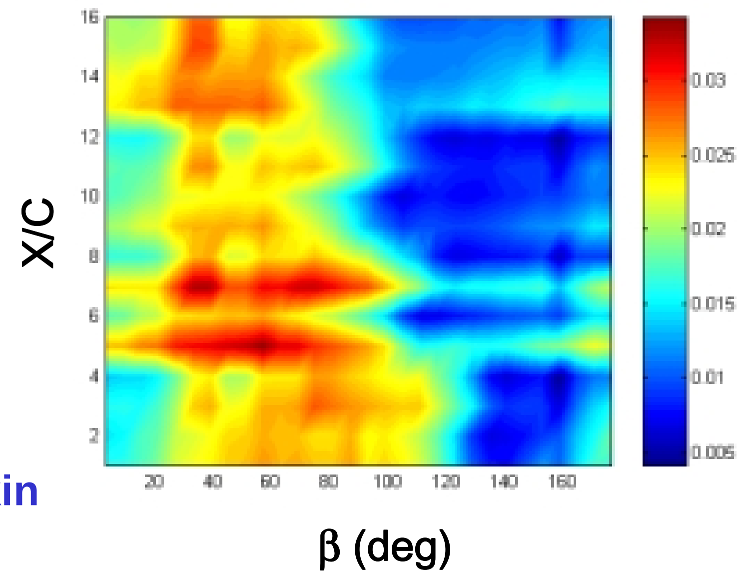
Shear Stress Level

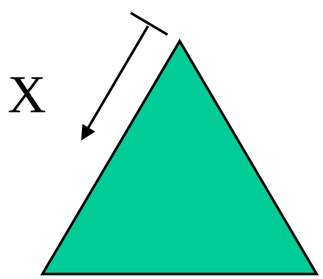
AoA=5

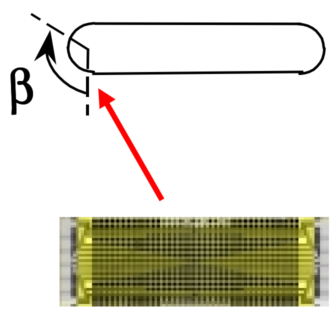


- Separation line moves w.r.t. AoA
- Strongly curved at high AoA
- Distributed sensing & control necessary

AoA=25





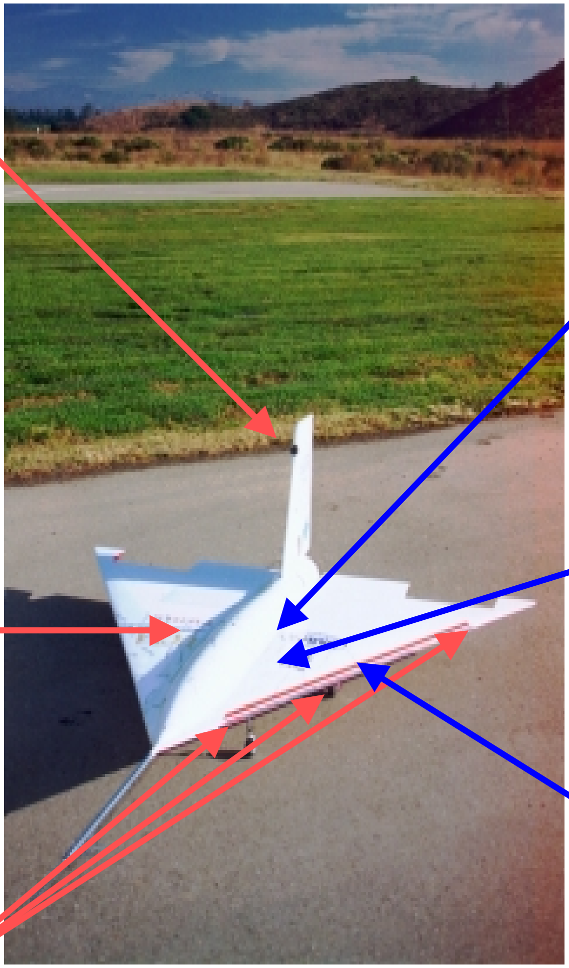


Shear stress sensor skin

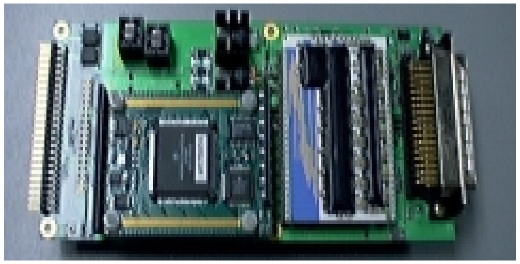
GRYPHON - A MEMS-UAV

Color CCD Camera with real-time down-link.

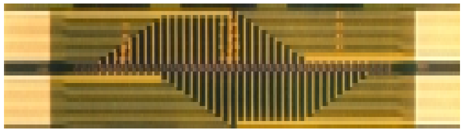
4 On-board Linear Accelerometers
2 Pitch and Yaw Rate Gyroscopes
2 Roll angle and rate Sensors
Nose boom with pressure, AOA, and Side-slip sensors



Main Flight CPU



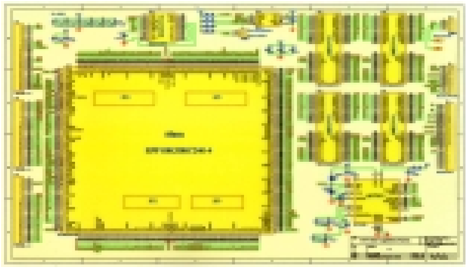
High Sensitivity Flexible Shear Sensors



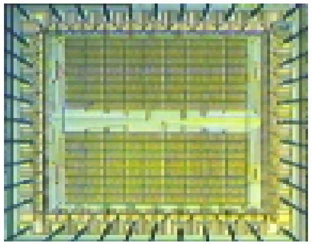
6 mm

30 mm

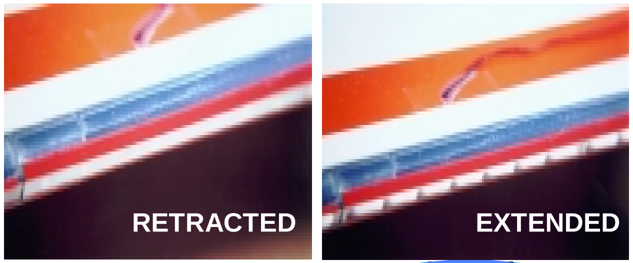
Sensors/Actuators Controller



Shear Stress Sensor Drivers



Bubble Actuators



C ms Center for Micro Systems

DARPA

ETO MEMS

Advantages of MEMS-based Flow Control

Weight reduction

- High frequency response
- Better spatial resolution
- No traditional control device

Low radar visibility

- Smaller size
- Absence of sharp corners

Capability of integration

- Smart transducer
- Distributed flow control

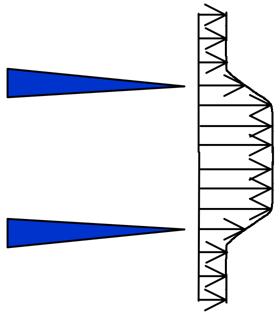
Accomplishments

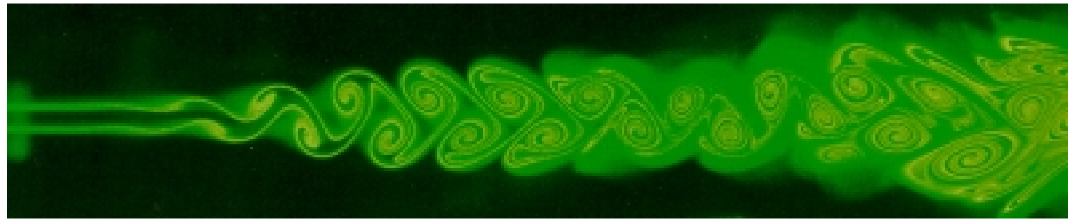
- ❑ New Aerodynamic Control Concept
  - ⇨ Vortex control instead of camber control
- ❑ Large Torque Generated by Micro System
- ❑ Independent control of Rolling, Pitching, and Yawing moments for Flight Maneuver
- ❑ M^3 - Micro-Sensor, Control, Actuator System

Sample MEMS Application II

- Control of Supersonic Impinging Jets
  - Feedback loop attenuation
  - Adaptive control

Free Shear Layers





Kelvin-Helmholtz Instability
- high gain amplifier

Sensitive to initial perturbations

- Frequencies - most amplified
- Amplitude - background noise

- Ho and Huang 1982

Convective and Absolute Instabilities

- Velocity field near the origin
- Globally influenced
- Amplifier or oscillator

- Huerre and Monkewitz 1985

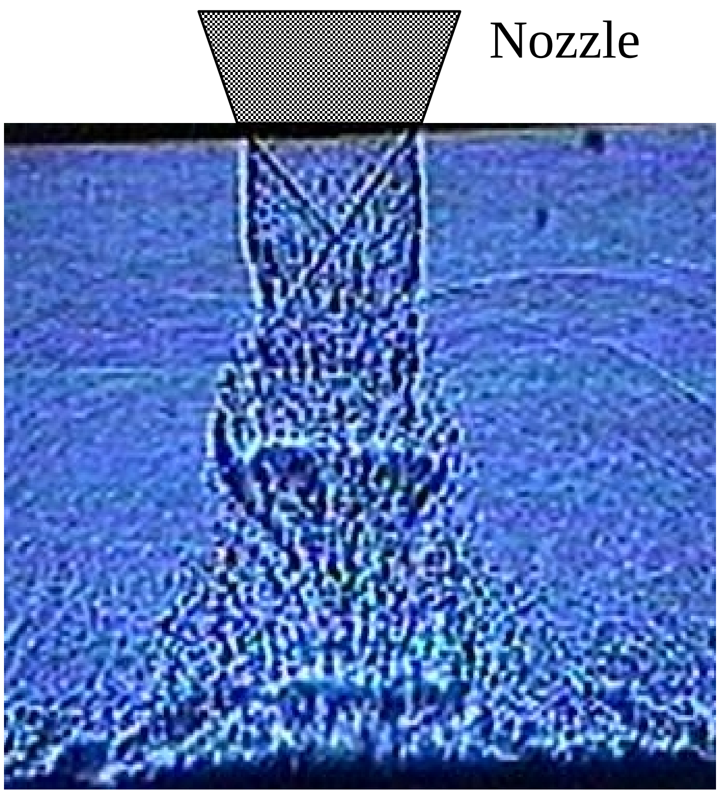
Conditions at Origin

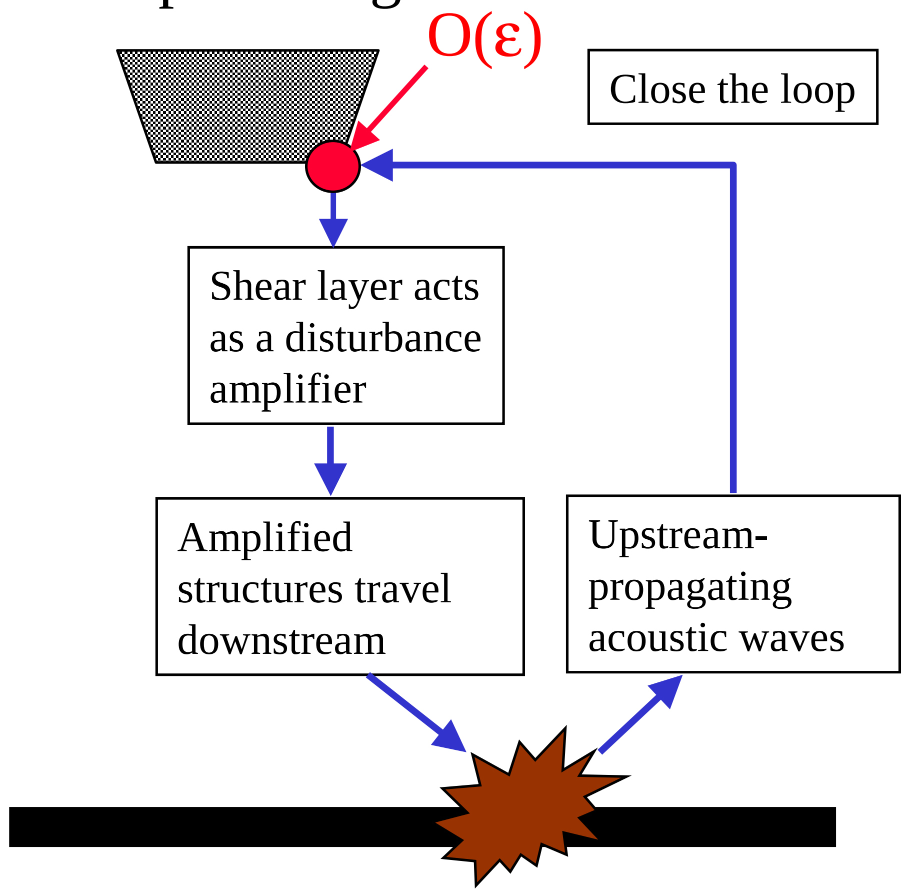
- ***thin shear region - coupling for actuation***
- ***sensitive to perturbations***

Resonance Conditions

• Feedback loop driven flow configurations: Impinging tones, screech tones, cavity flows ….

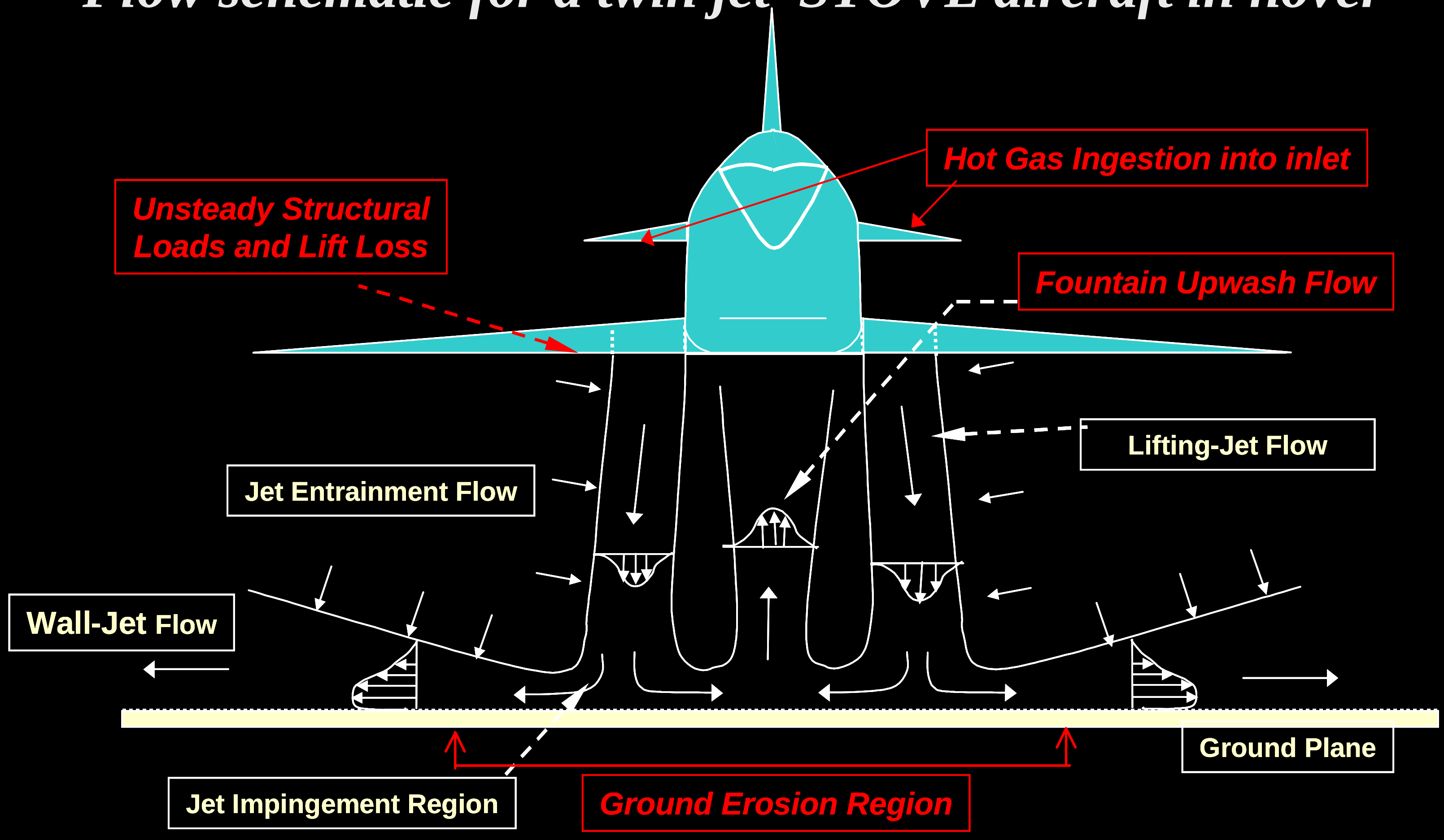
• Effective control can be achieved by disrupting the coherence of the loop at its most susceptible region.





Motivation

Flow schematic for a twin jet STOVL aircraft in hover

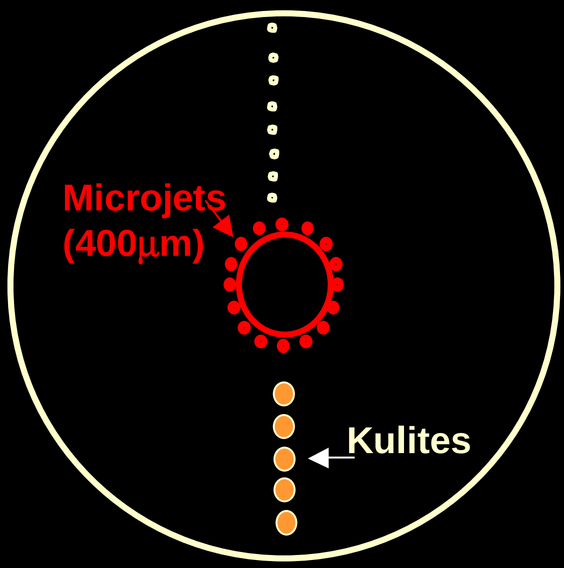


fmrl

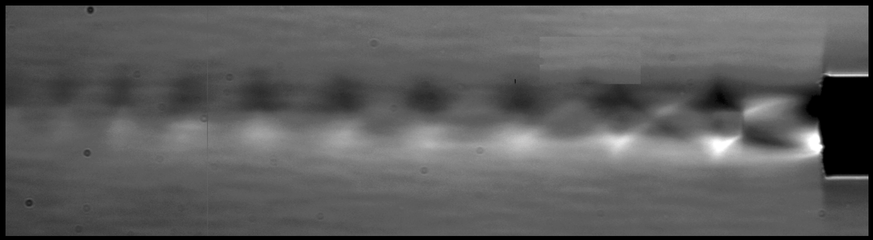
fluid mechanics research laboratory

Micro Jet Details

- **Microjet diameter – 400 μm**
- **Operating pressure – 80- 120 psi**
- **Mass flow (total) ~ 0.4% – 0.7 % of main jet**
- **Operating gas – Air**
- **Microjet inclination angle ~20^0**



200 μm



400 μm

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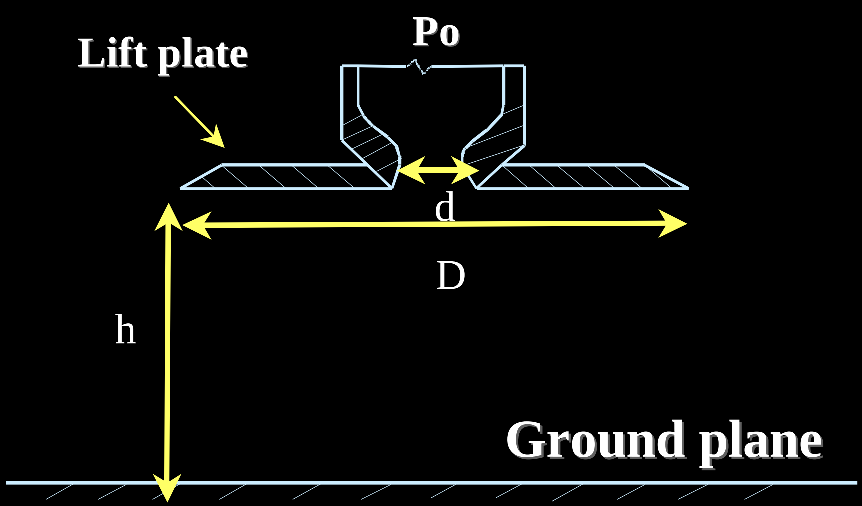
Experimental Hardware



Parametric Space

NPR (Po/Pa)	**= 3.7 & 5.0**
h/d	**= 2.0 - 60**
Nozzle	**= Mach 1.5**
Microjet Press.	**= 80 - 120 psi**

DIAGNOSTICS:

- **Unsteady Pressures**
  - **Ground & Lift Planes**
- **Acoustic.**
- **Mean Pressures**
  - **Ground & Lift Planes**
- **Flow visualization**
  - **Shadowgraph**
- **PIV**

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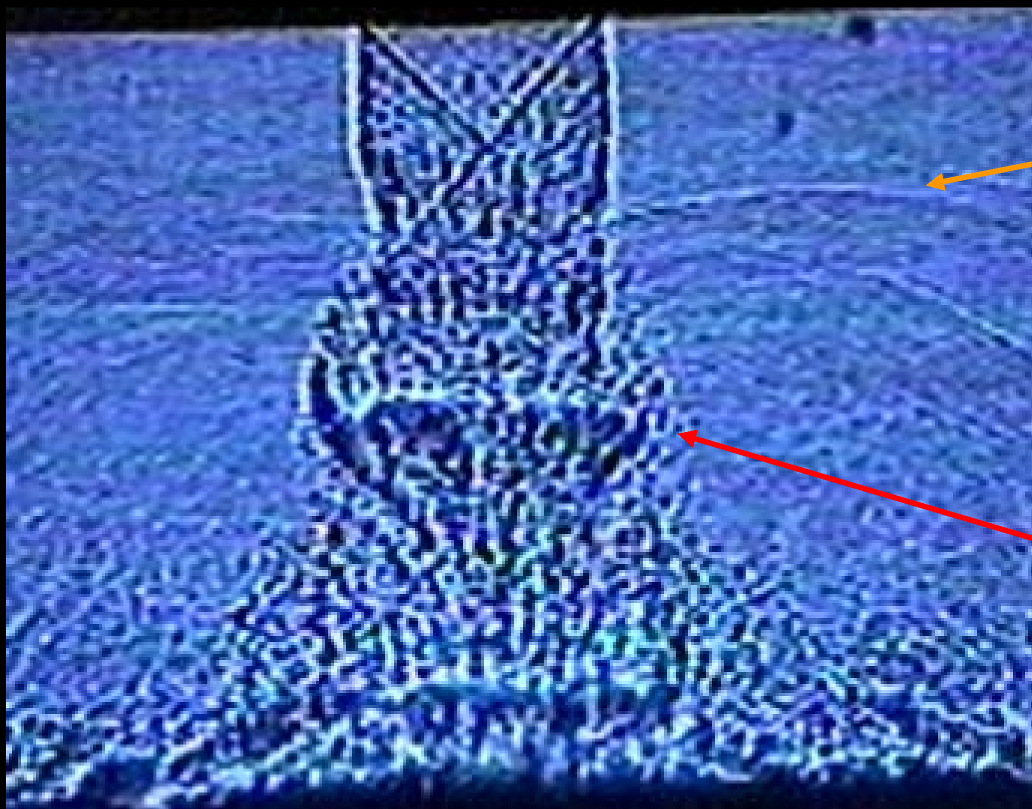
Experimental Results
Instantaneous Shadowgraphs



Upstream-propagating acoustic waves

Downstream-travelling instability structure

NPR=3.7, h/d=4, No Control

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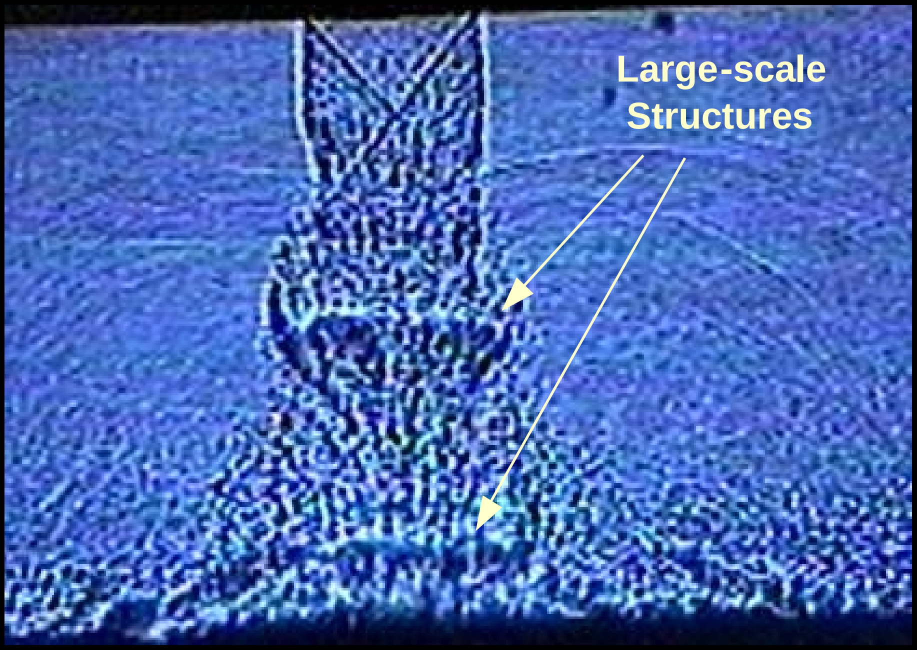
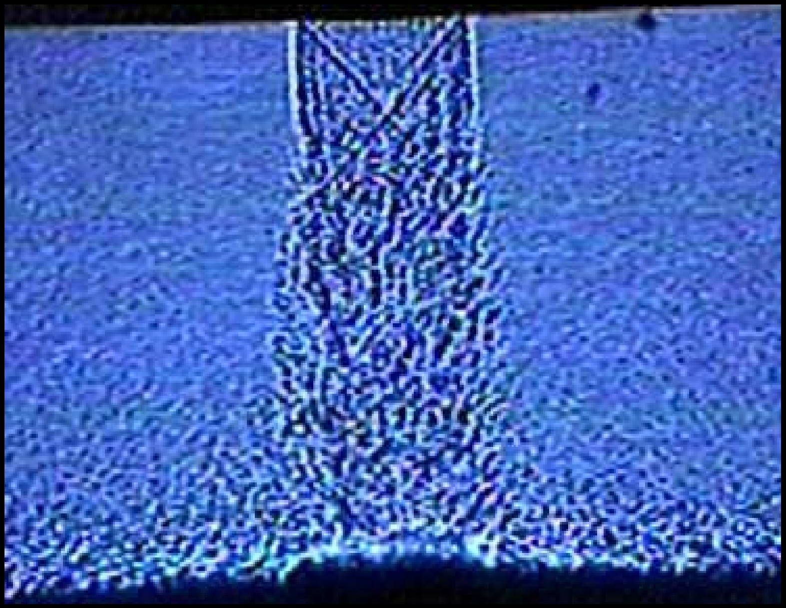
Experimental Results
Instantaneous Shadowgraphs



NPR=3.7, h/d=4, No Control



With Control
Absence of large scale structures

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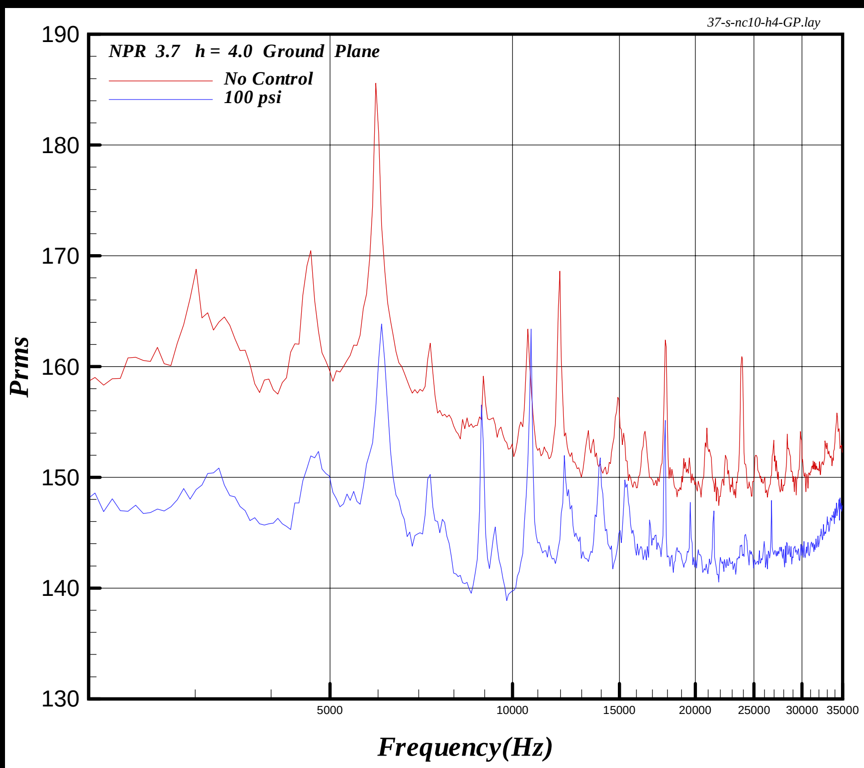
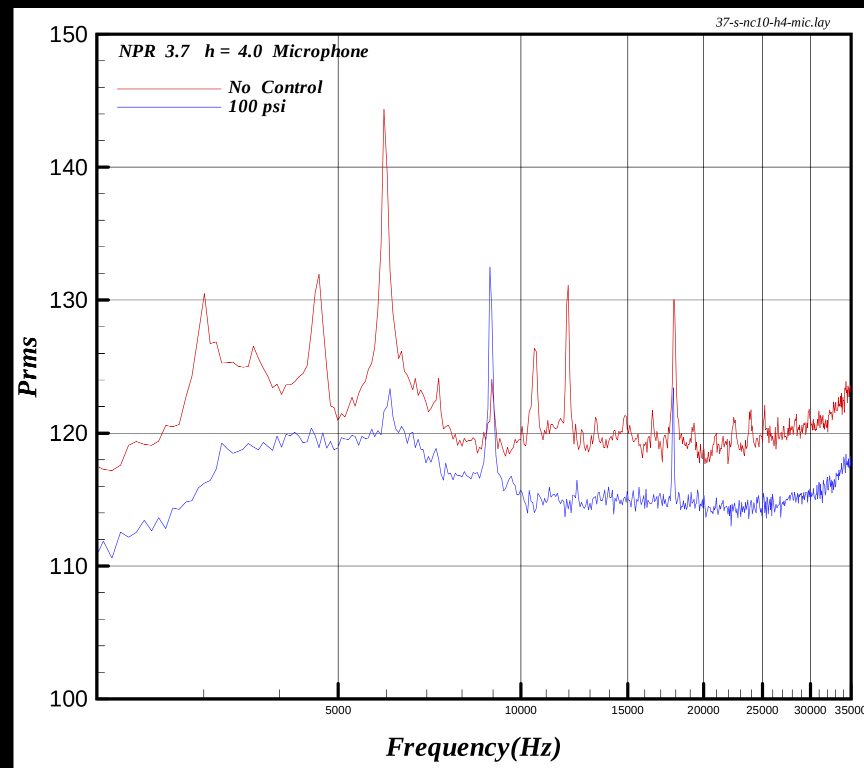
Experimental Results
Noise and Unsteady Pressure Spectra

NPR 3.7, h/d=4.0



Ground Plane



Microphone

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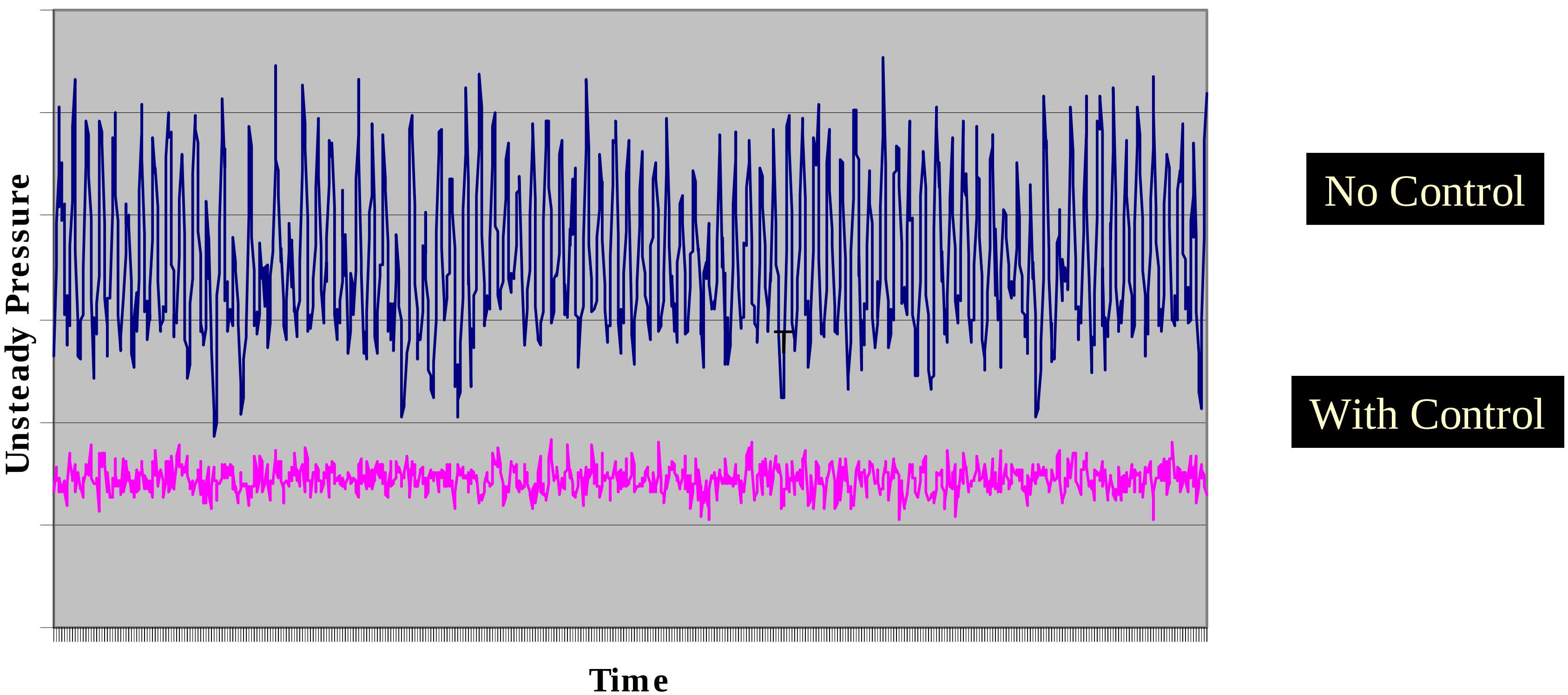
Pressure Fluctuations on Ground Plane, NPR=3.7, h/D=4
With and Without Control



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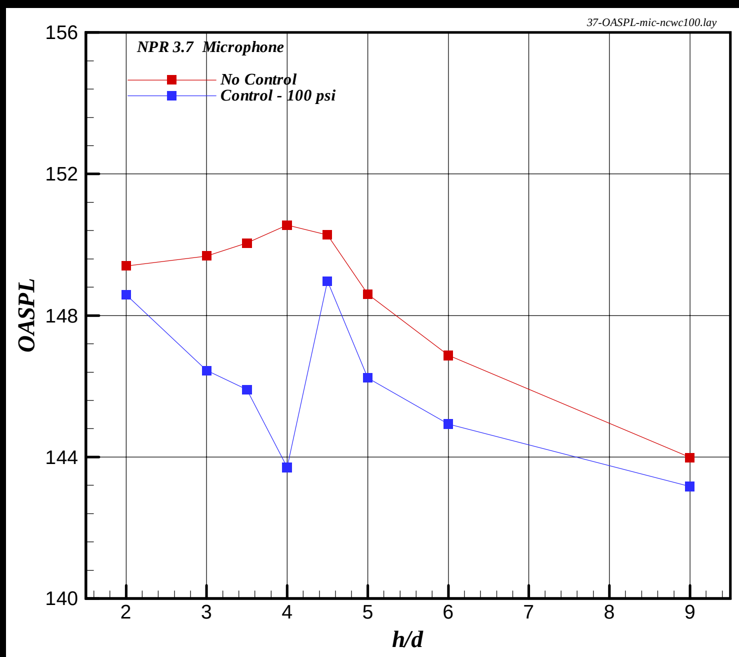
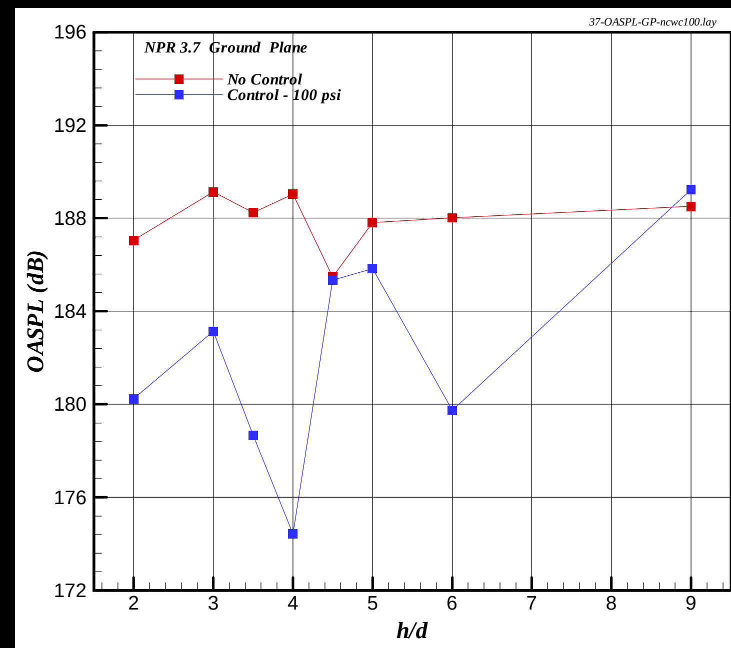
Experimental Results OASPL



NPR 3.7



Microphone

Ground Plane

- **Performance gains not uniform over the entire operating range.**
- **Adaptive control is needed.**

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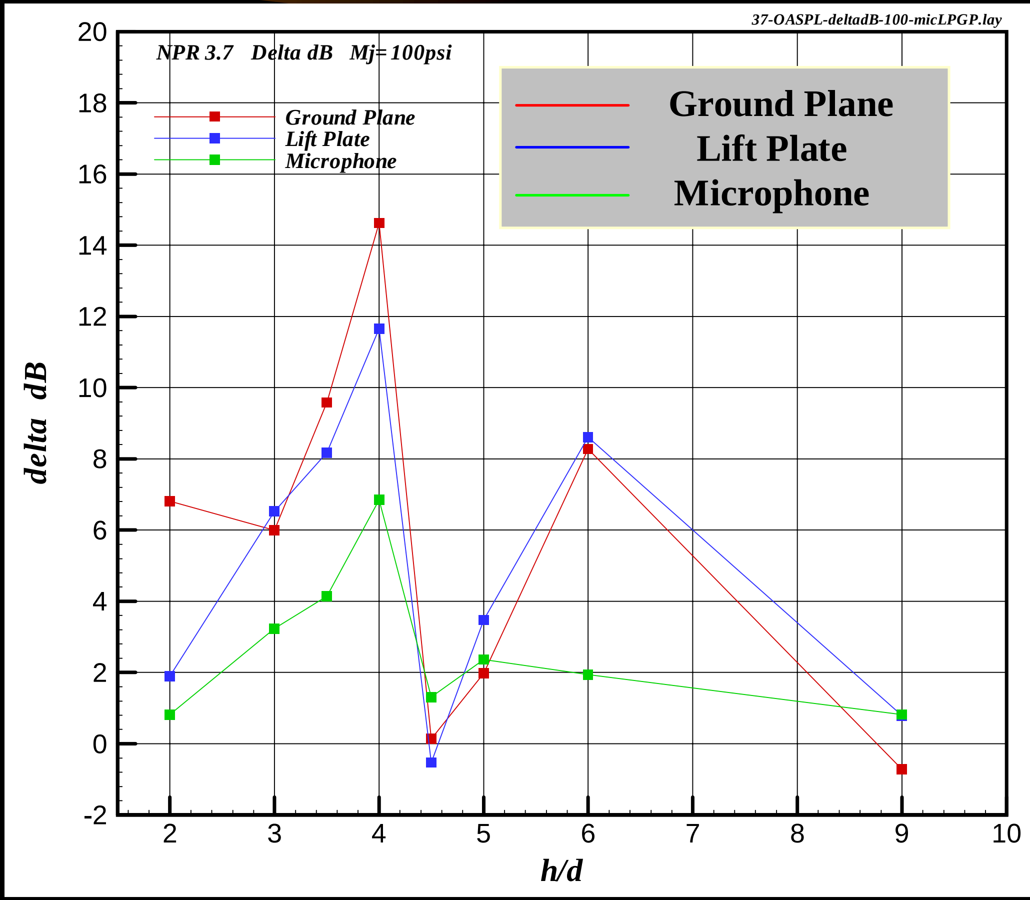
Experimental Results
OASPL reduction

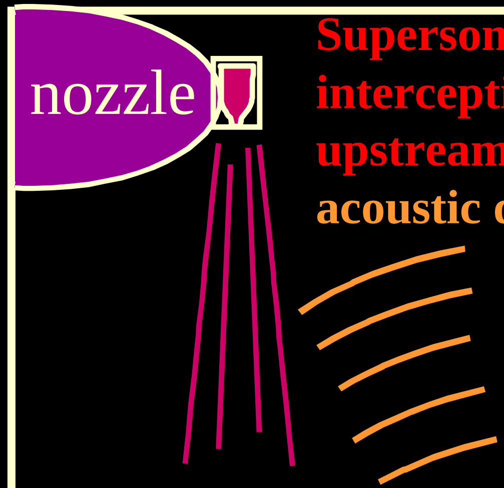


NPR 3.7

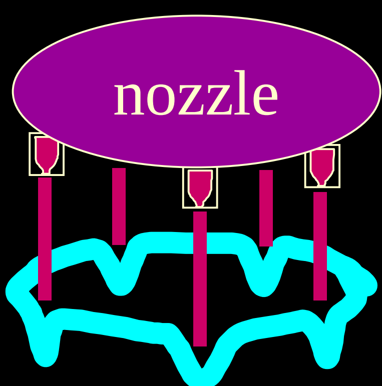
- **Microjet Pressure ~ 100 psia**
- **OASPL reduction up to 14 dB for h/d=4**
- **Almost no reduction for h/d=4.5**
- **Extremely sensitive to h/d, therefore, real-time sensing is critical**

Active Control Strategy

High-frequency pulsed jets thicken the nozzle shear layer, decreasing its receptivity to acoustic disturbances.



Supersonic microjets intercepting the upstream-propagating acoustic disturbances.



Microjets perturb the downstream-propagating instability waves, disrupting its coherent coupling with the acoustic waves.

Accomplishments

- ❑ Disruption of feedback loop using supersonic microjets

- ❑ Attenuate tones as well as unsteady pressure fluctuations - reduction of OASPL can be more than 10 dB for selected configurations

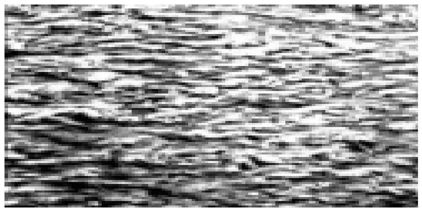
- ❑ Control on demand - no performance degradation in off-position

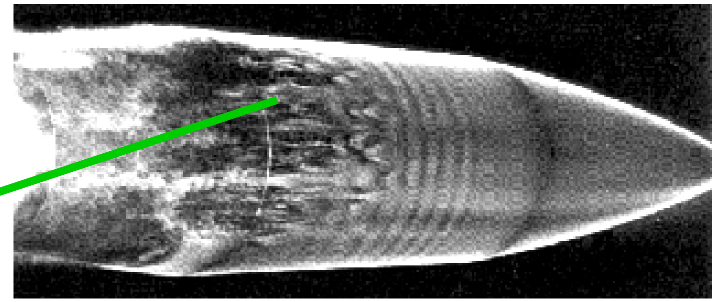
Sample MEMS Application III

- Turbulent Boundary Layer Control
  - Distributed sensing/control
  - Integrated M^3 system for drag reduction

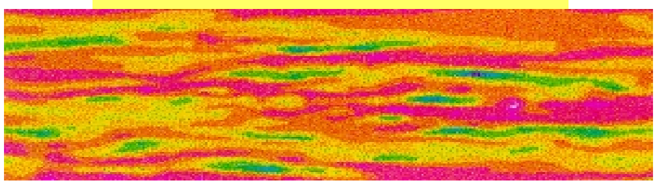
Near-Wall Streaks in Turbulent Boundary Layers

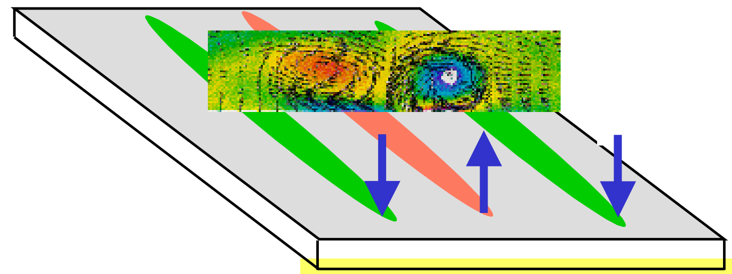
Randomly distributed
Short-life





Numerical Simulation of surface stress





Streamwise vortices

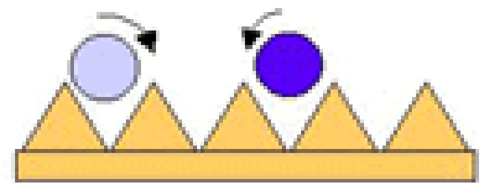
Laboratory condition
streak width < 1 mm
streak length ~ 1 cm
life time ~ 1 msec

Re dependent
Highly unsteady

Real-time Distributed sensing and control

Drag reduction through structure manipulation

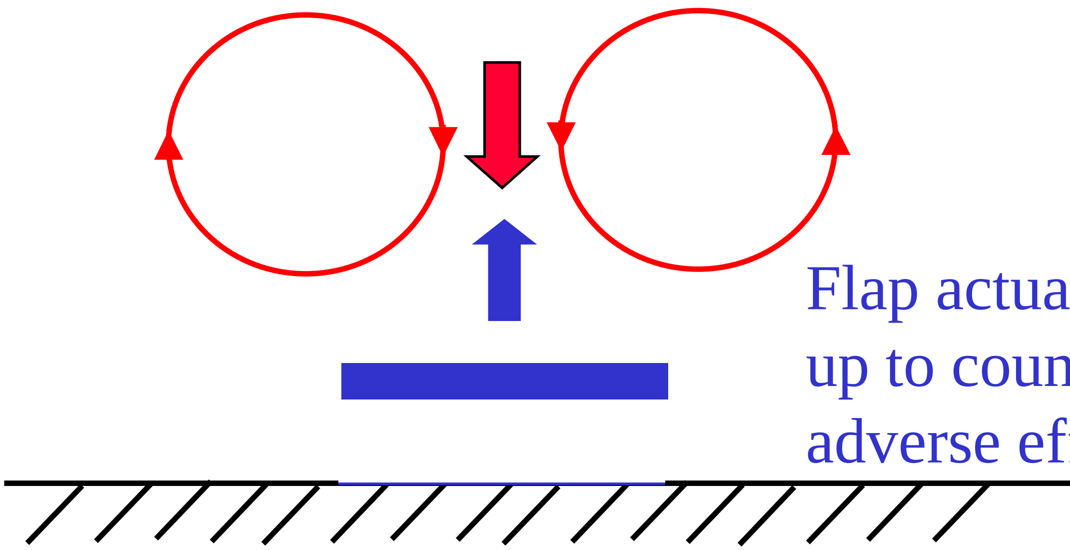
Passive devices : riblets
•less than 8 % drag reduction
•sensitive to Reynolds number change



Active schemes : interactive control
•high drag reduction (~20%)
•insensitive to Reynolds number change
•needs real-time control
•requires small and fast devices, **MEMS !**

Control Strategy

Counter-rotating vortex pair brings high-speed fluid down - Increase frictional drag

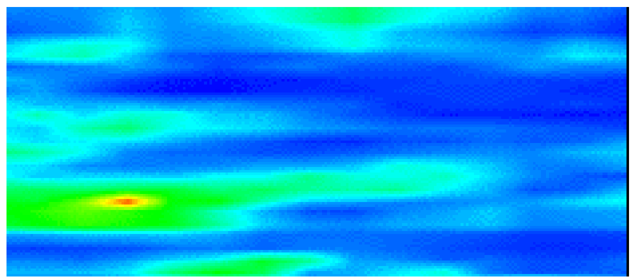


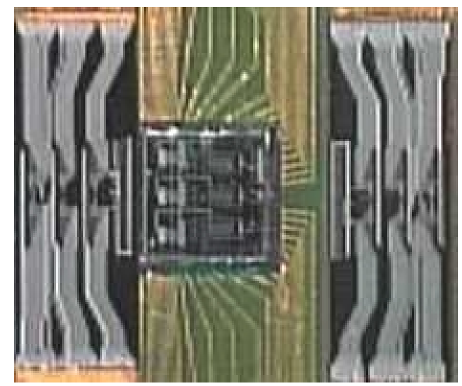
Flap actuator pumps fluid up to counteract this adverse effect

Real-Time Control Experiment Setup

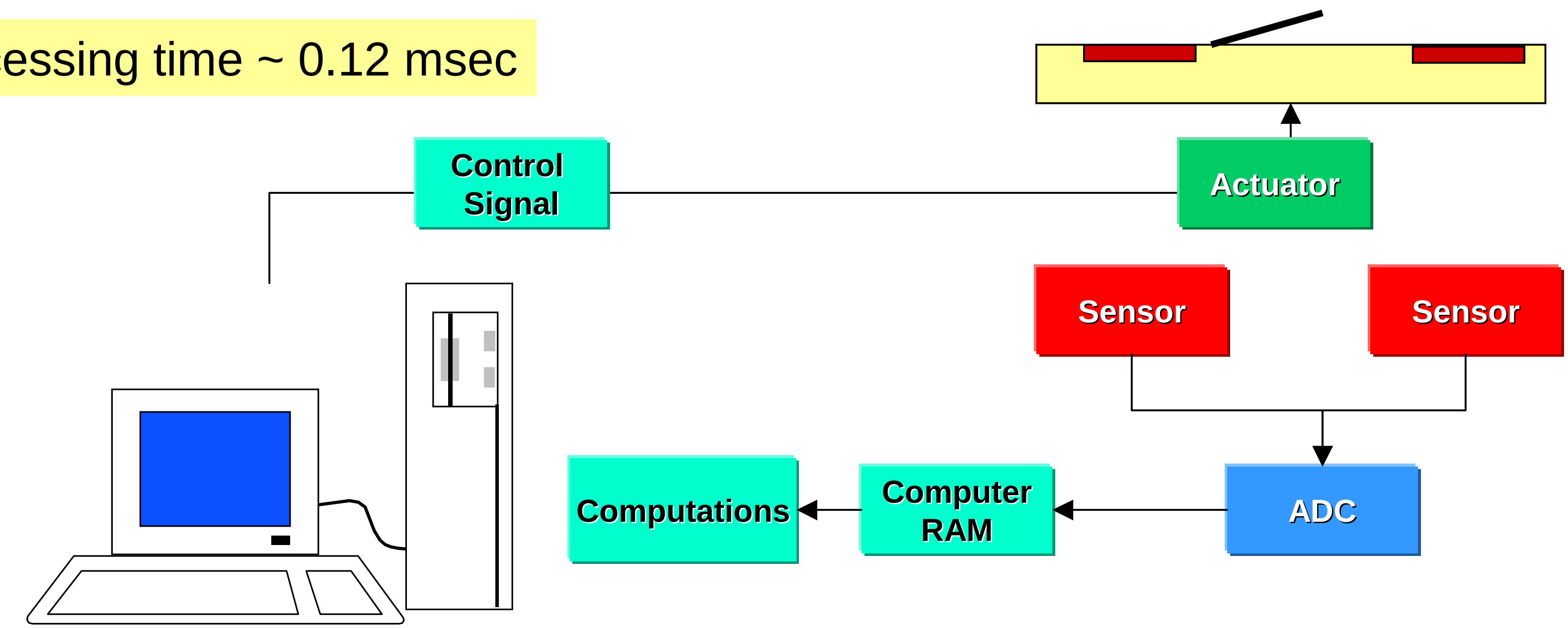
Flow

length ~ 1 cm
lifetime ~ 1 msec

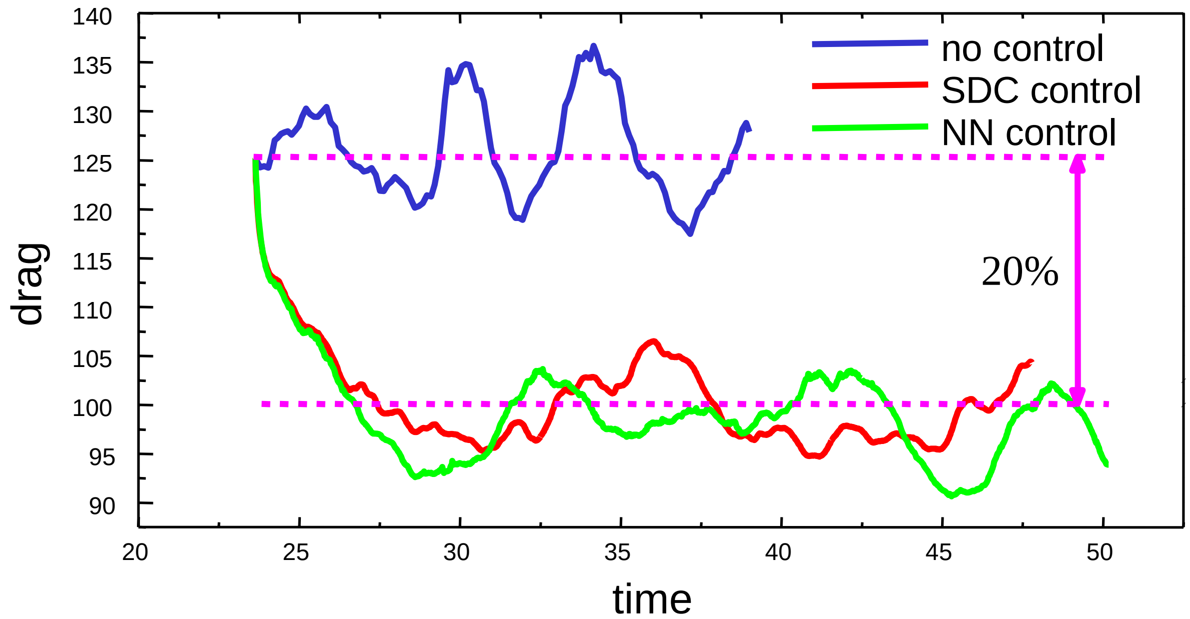




processing time ~ 0.12 msec



Drag History of NN Controlled Flow



Off-line training: input weights converge,
18% drag reduction

On-line training: input weights converge,
20% drag reduction

Accomplishments

- ❑ Drag reduction of a turbulent boundary layer can be achieved under laboratory condition

- ❑ Control scheme can be adjusted according to different flow conditions.

- ❑ Real-time sensing and control (M^3) system developed

SUMMARY

- Effective flow control on macro scale system can be achieved using micro devices
  - Better understanding of flow physics is needed.

- Integration of micro-sensor, micro-control logic and micro-actuator (a M^3 system) is the key for the future development of active flow control applications.