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Recent Advances of Flow Control on Compressible Flow Applications Using Microjets

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- ONR
- Boeing
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Outlines

- Compressible Flow Control Issues
  - Inherent noises and flow robustness
  - Relevant control parameters and flow physics
- Sample Applications
  - Supersonic Impinging Jets
  - Compressible Dynamic Stall
  - Supersonic Cavity Flow

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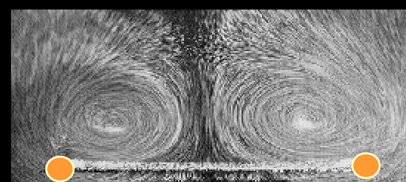
Effective Flow Control

Flow Amplifier

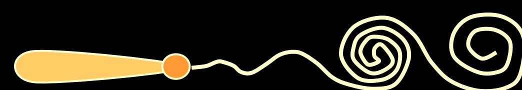
ε → **1**

Separation



Vortex dominated flow

Instability



Enhance mixing

Resonance

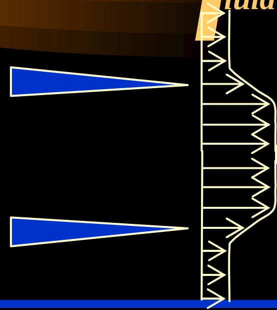
Feedback-driven

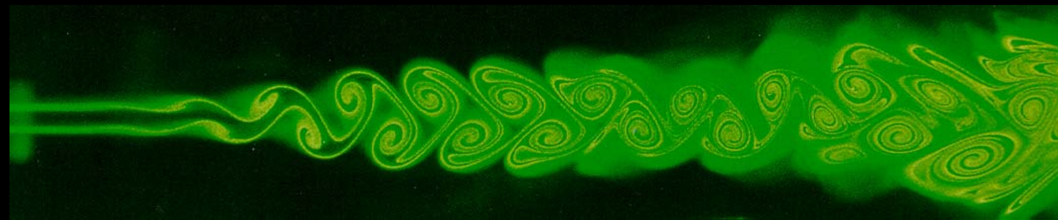
Vibration/noise control

Origin : sensitive position

***Perceive* - sensor, signal acquisition**
***Think* - flow physics ⇨ control strategies**
***Act* - actuator, amplitude, frequency, phase**

Free Shear Layers



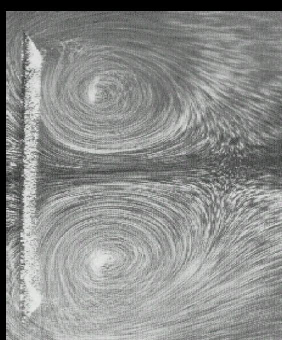


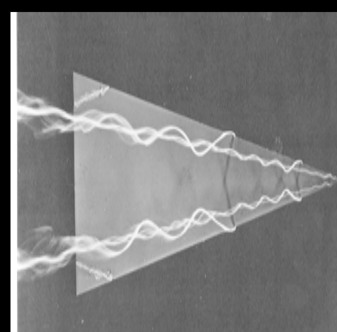
Kelvin-Helmholtz Instability
- high gain amplifier

Sensitive to initial perturbations

- **Frequencies - subharmonics**
- **Amplitude - background noise**

- Ho and Huang 1982





Vorticity dominated flow

- **Instabilities lead to the formation of vortex**
- **Vortex-induced interactions**

Resonance

- **Strong coupling mechanism**
- **Insensitive to extrinsic perturbations**

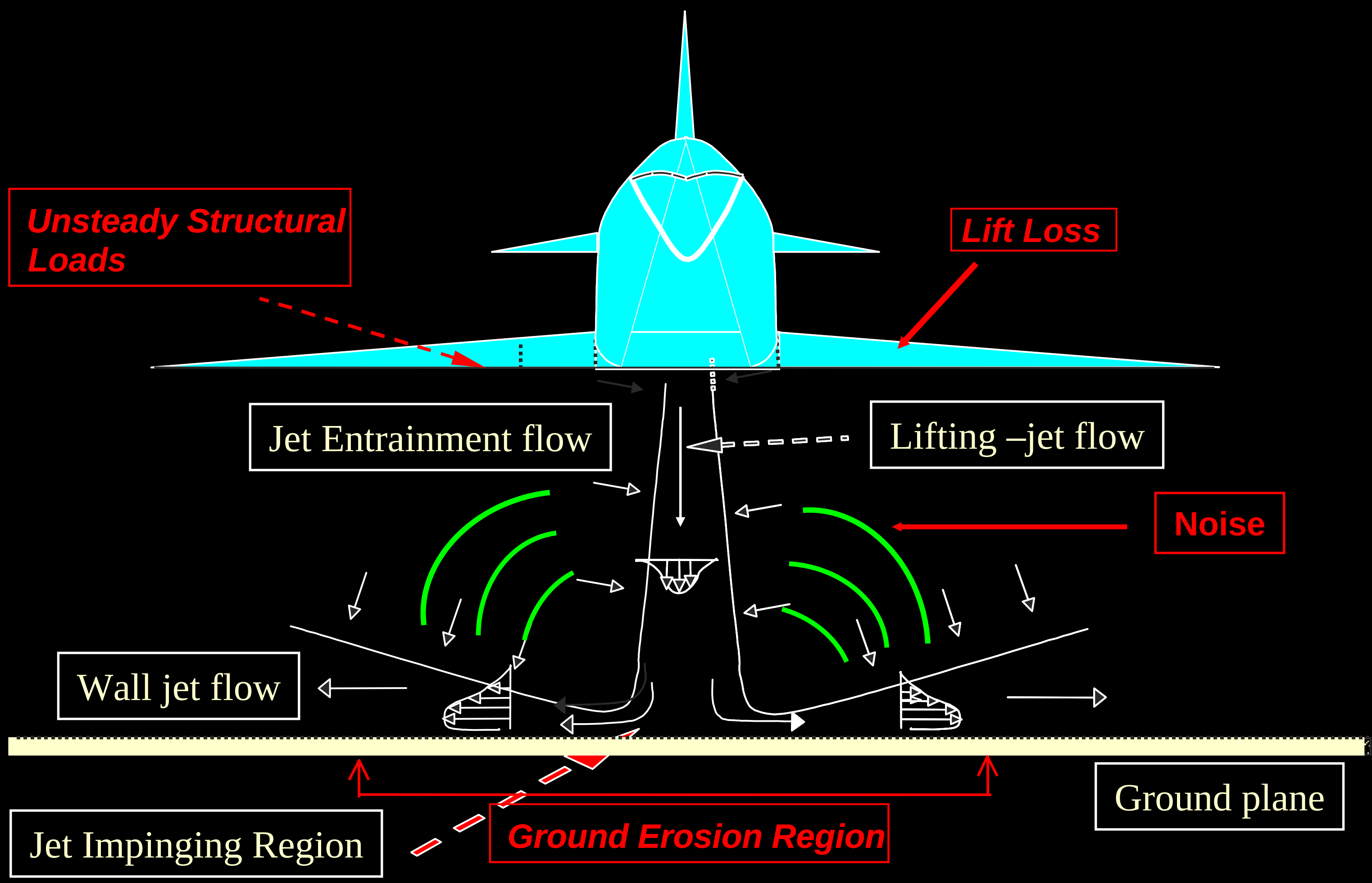
Microjet Array as the Flow Control Mechanism

- A distributed actuation system; could be placed at strategic locations
- Readily controllable: on-demand activation with varying amplitude, orientation, phase, etc..
- Relatively economical: high pressure system available on most aerodynamic systems
- Robust: without delicate mechanical structures for high speed flow control, non-intrusive

1. Control of Supersonic Impinging Jets

Motivation

Flow schematic for a jet STOVL aircraft in hover



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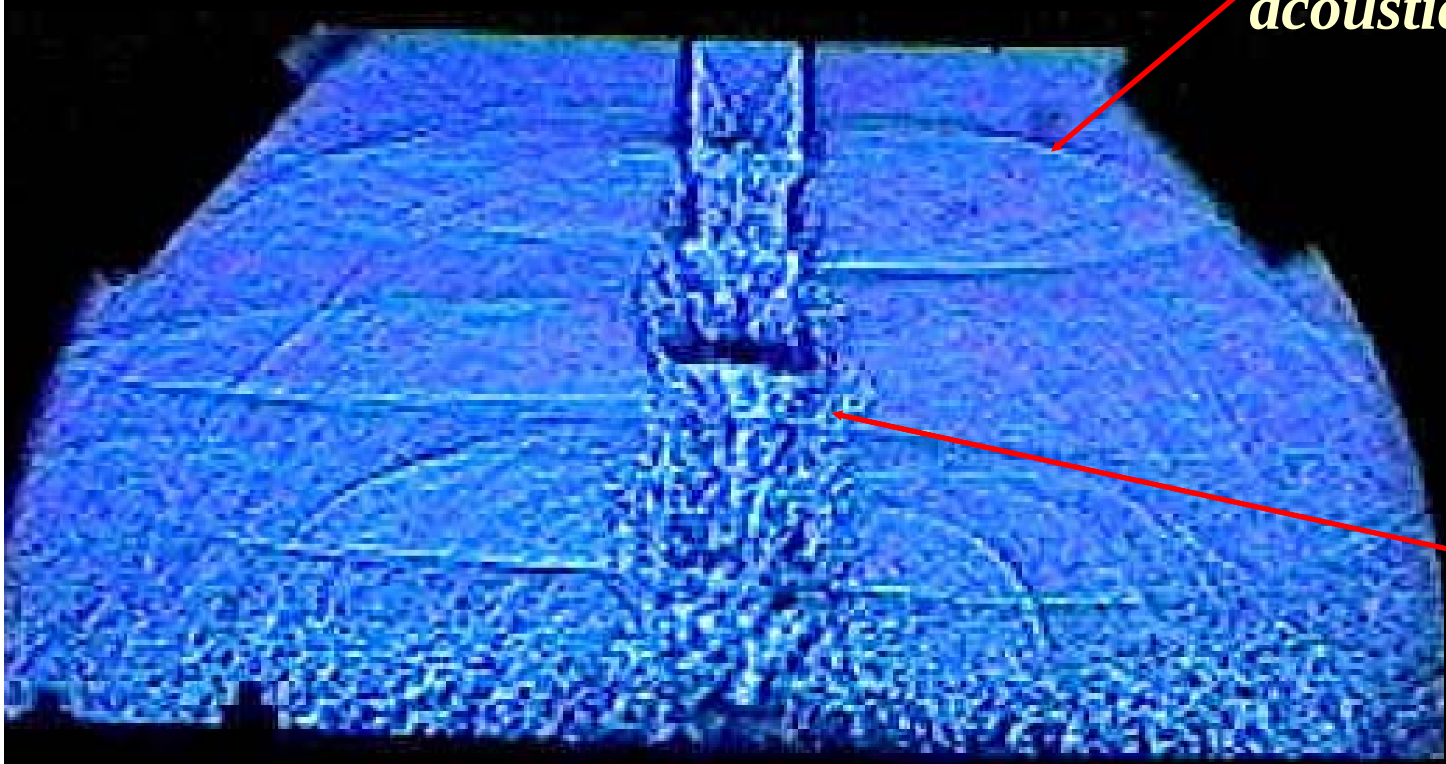
Mechanism

Feedback loop

Upstream propagating acoustic waves



Larger Scale Structures

Powell, Karamcheti, Tam & Ahuja, Krothapalli et al.

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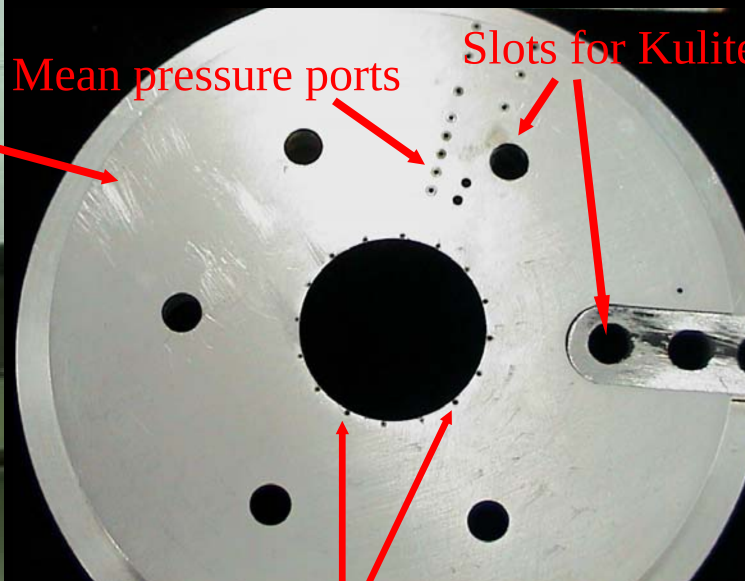
Test Model and Facility

Lift plate



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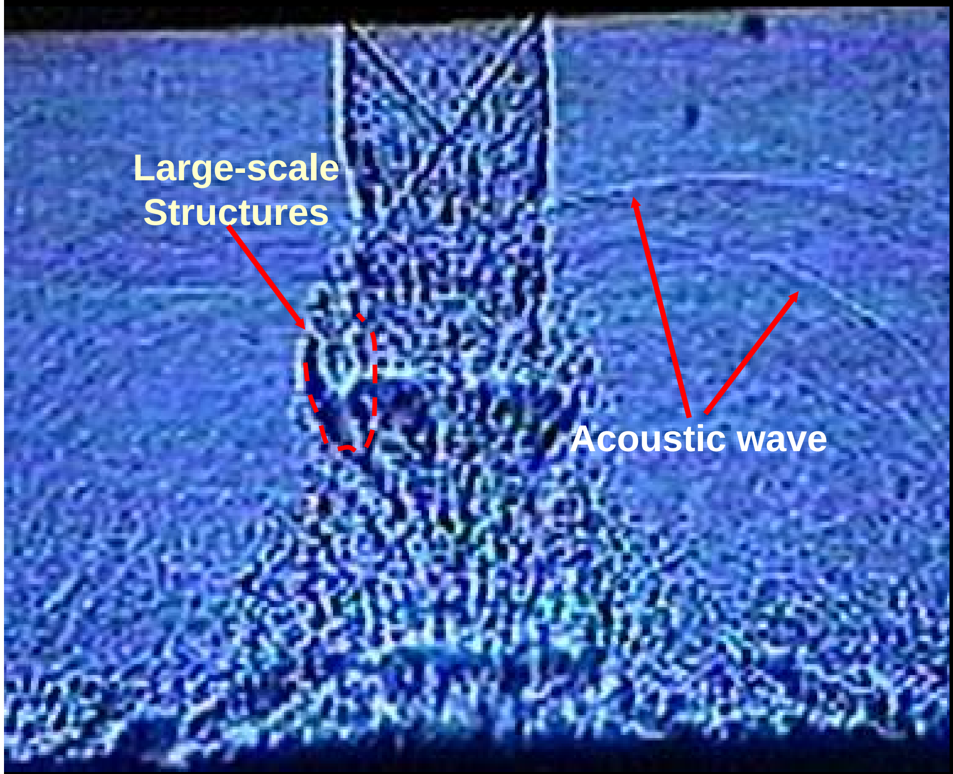
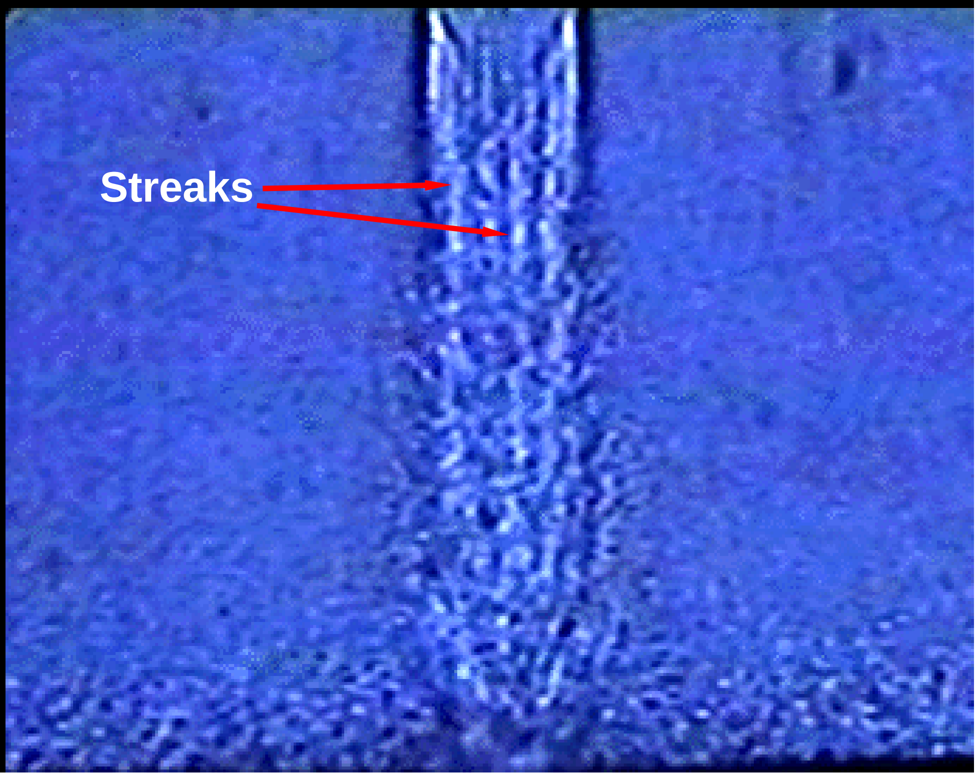
Effect of Microjet Control

Shadowgraphs NPR = 3.7, h/d = 4



No Control

With Control



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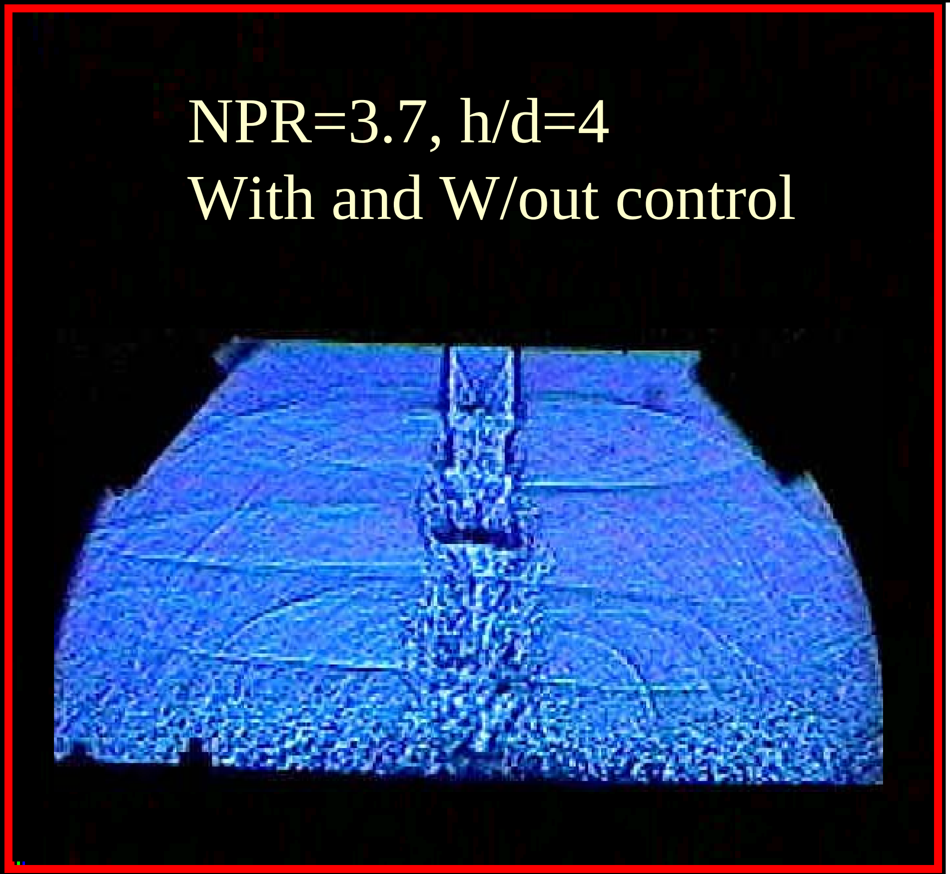
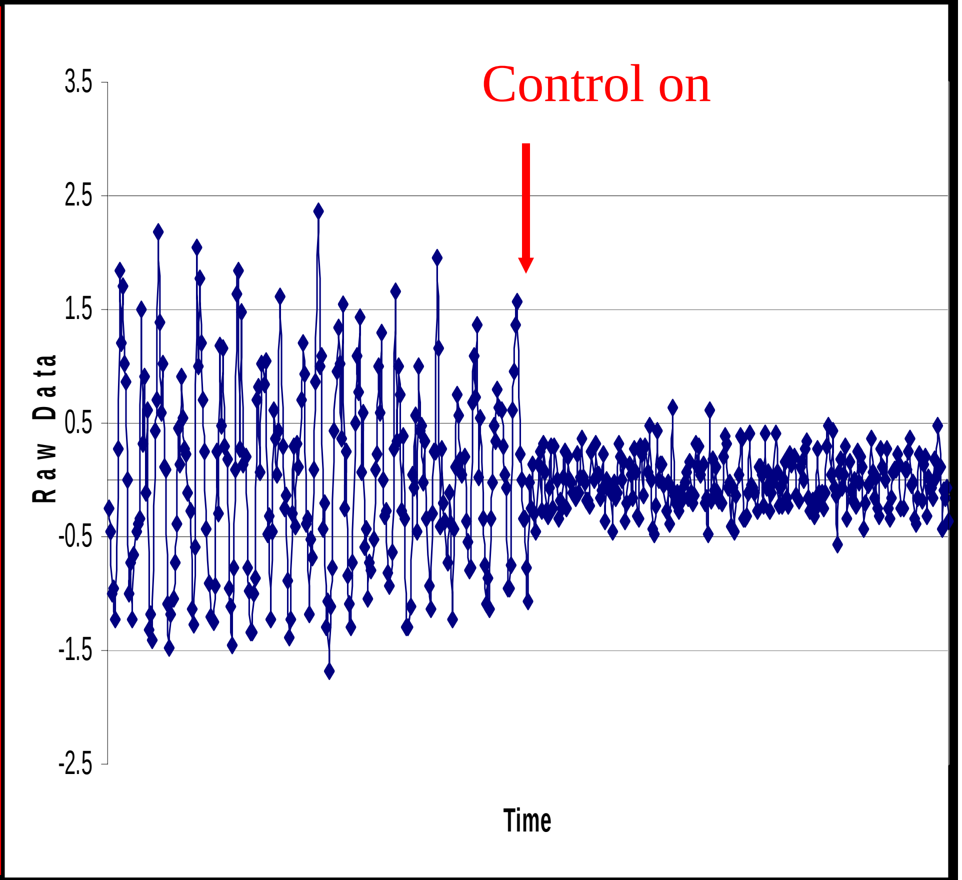
Effect of Microjet Control

NPR 3.7, h/D = 4





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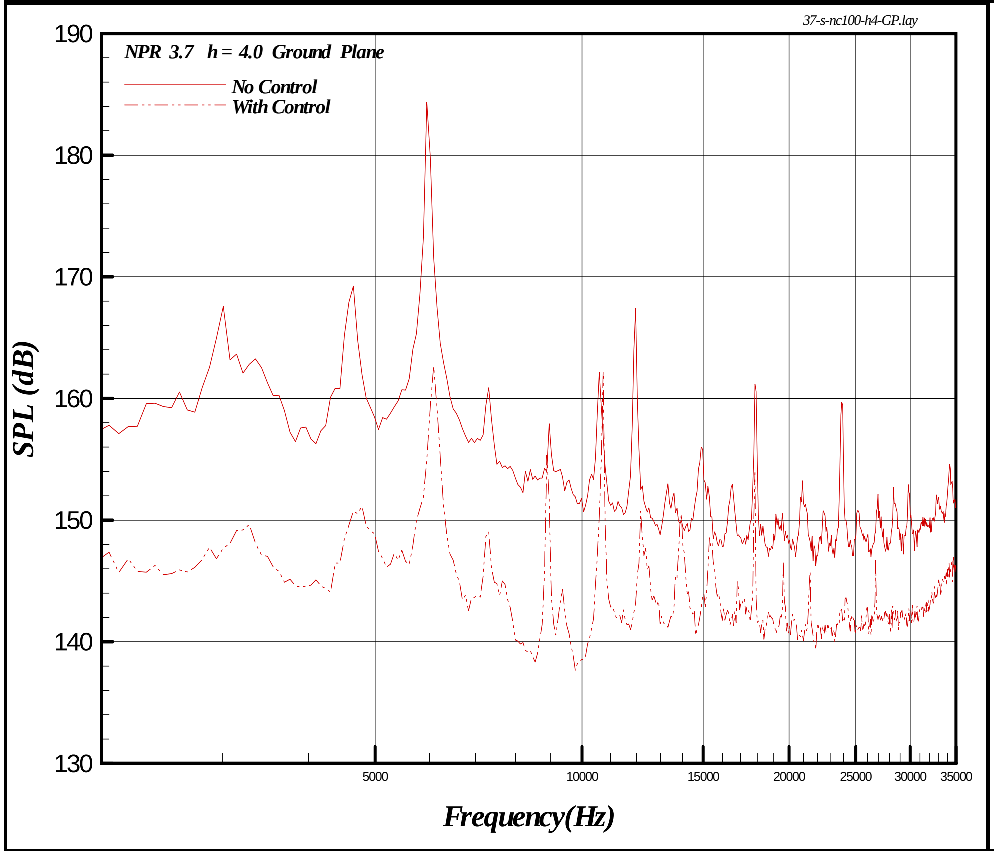
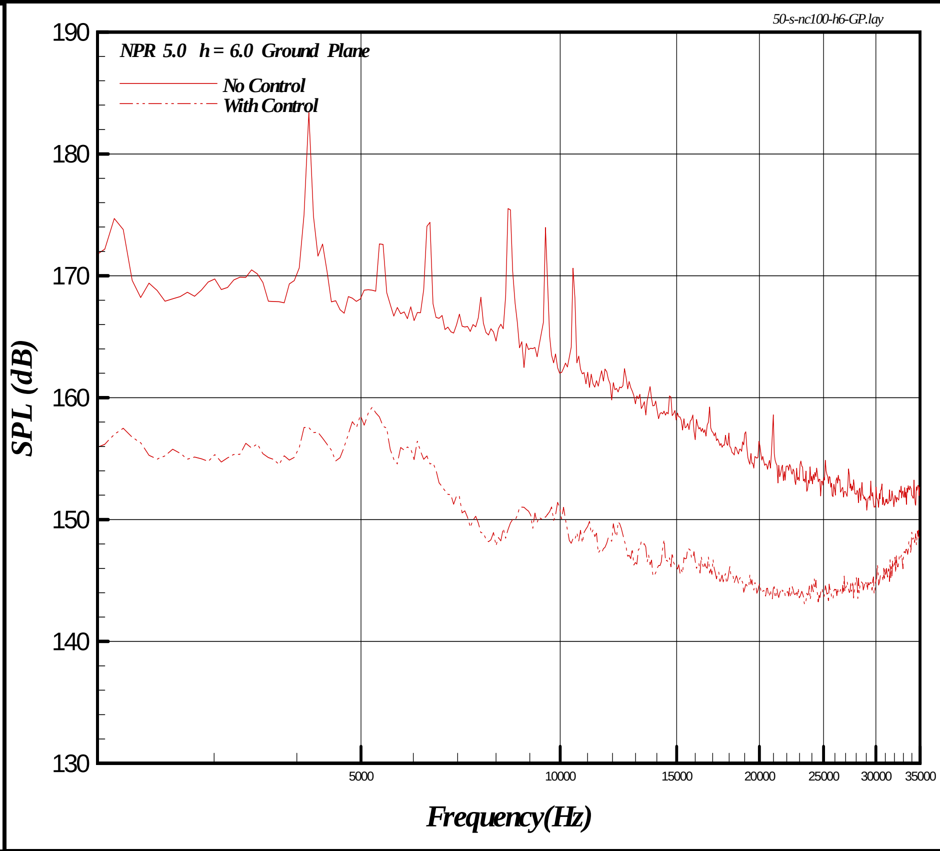
Pressure Spectra

Ground Plane



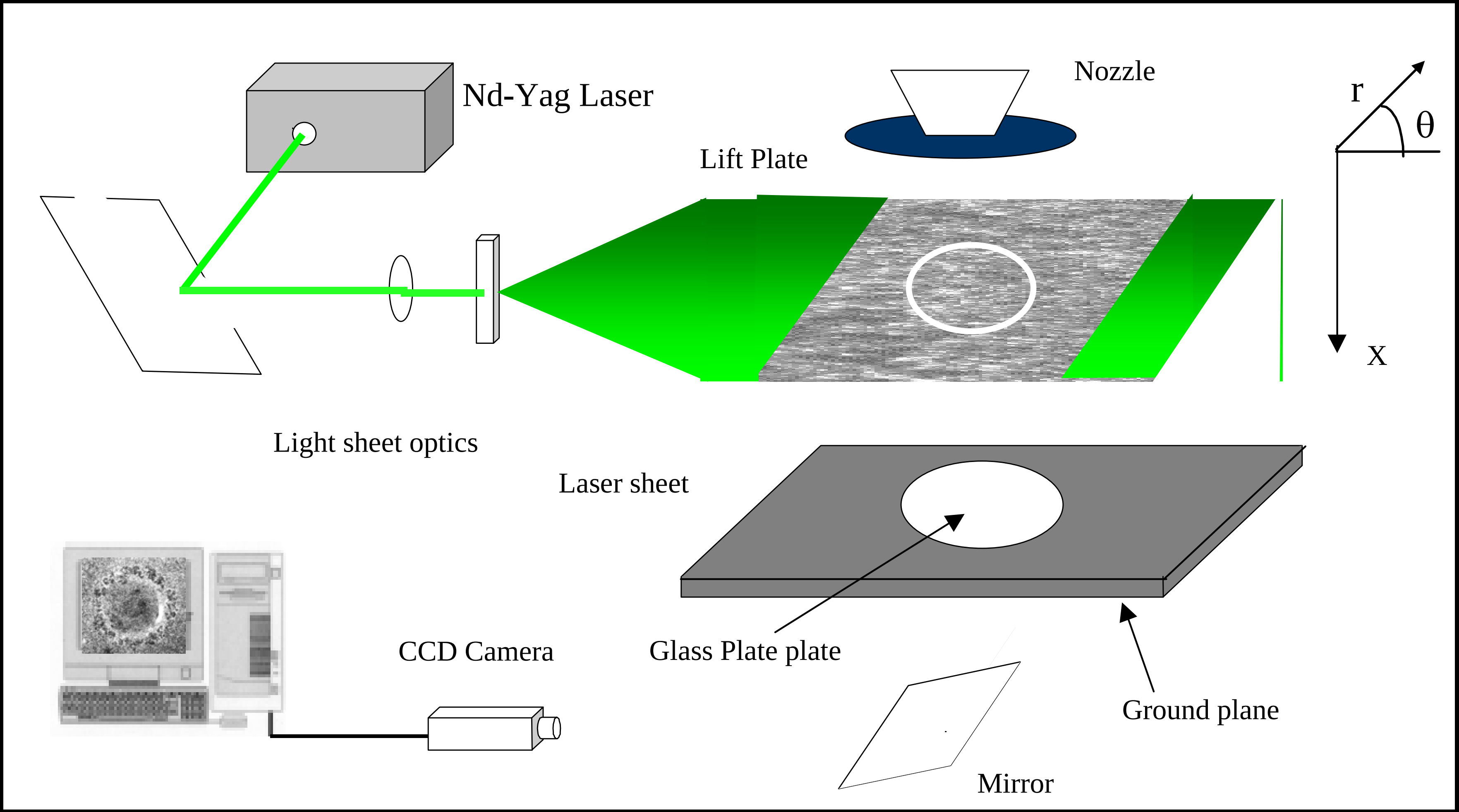


NPR 3.7

No Control
With Control

NPR 5

Cross Section PLS & PIV Setup



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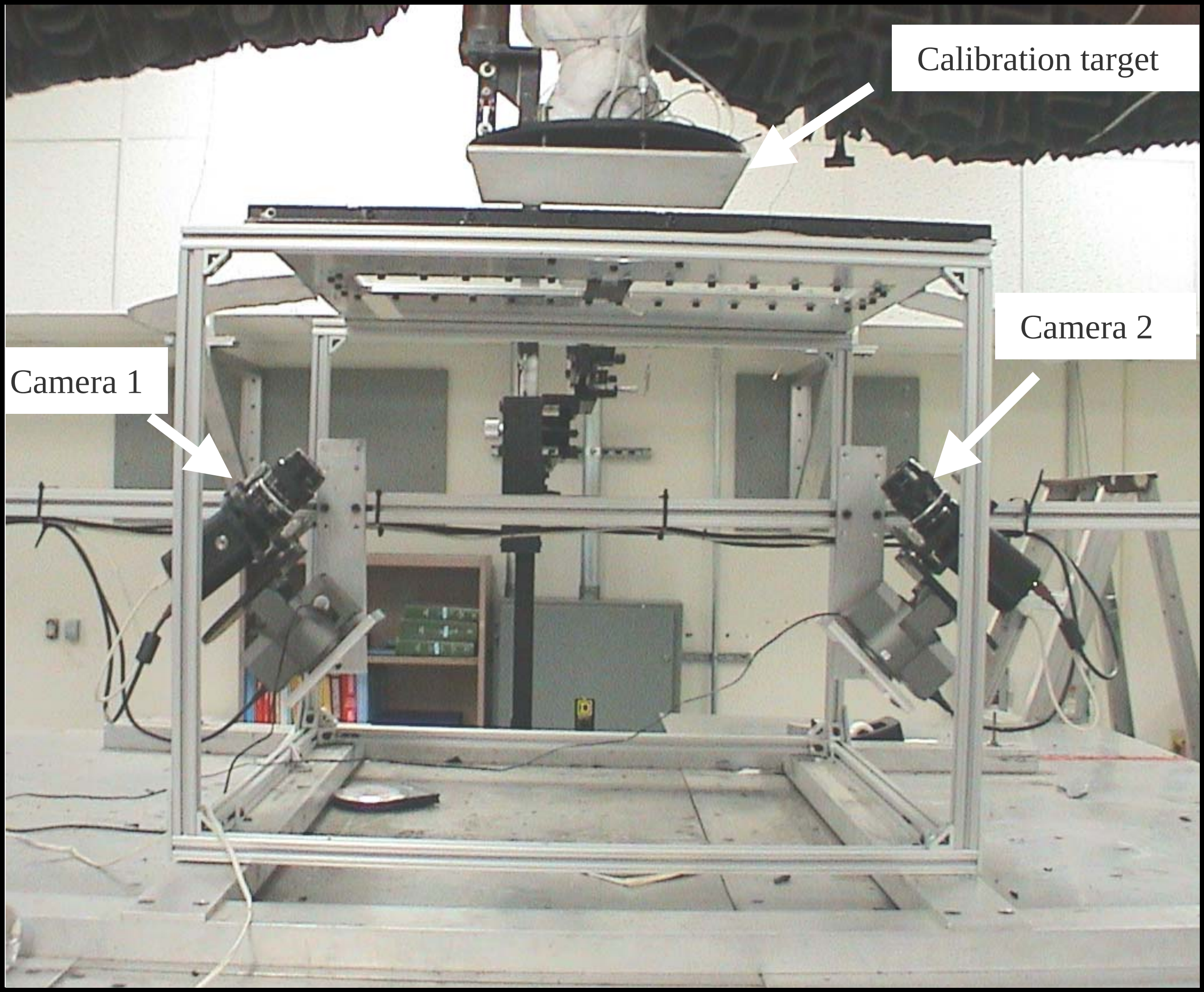
PLS Images, Averaged

NPR=5 h/D=4

No Control

With Control

3D PIV Setup



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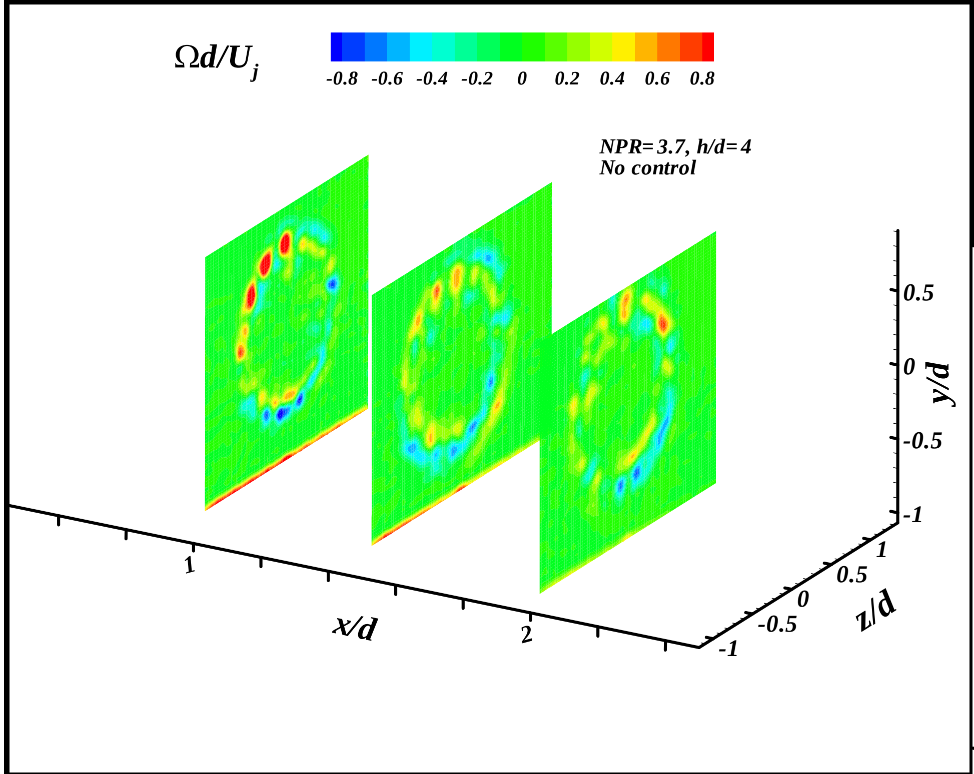
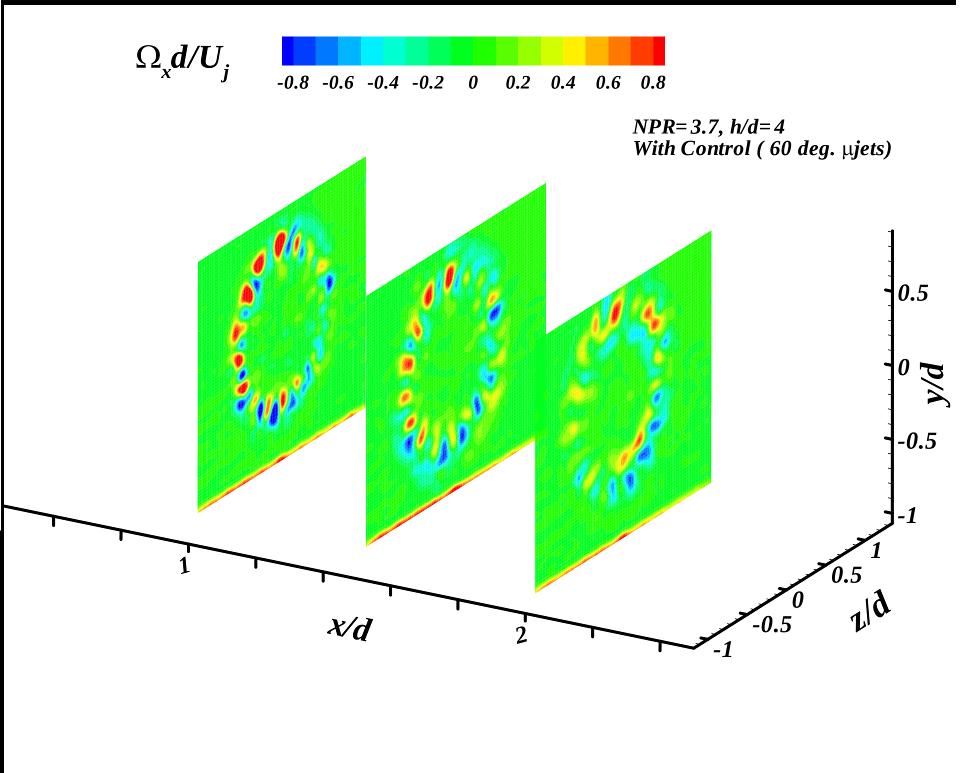
Effect of Microjet Control on Streamwise Vorticity

NPR=3.7, h/d = 4, 90 deg. μjets



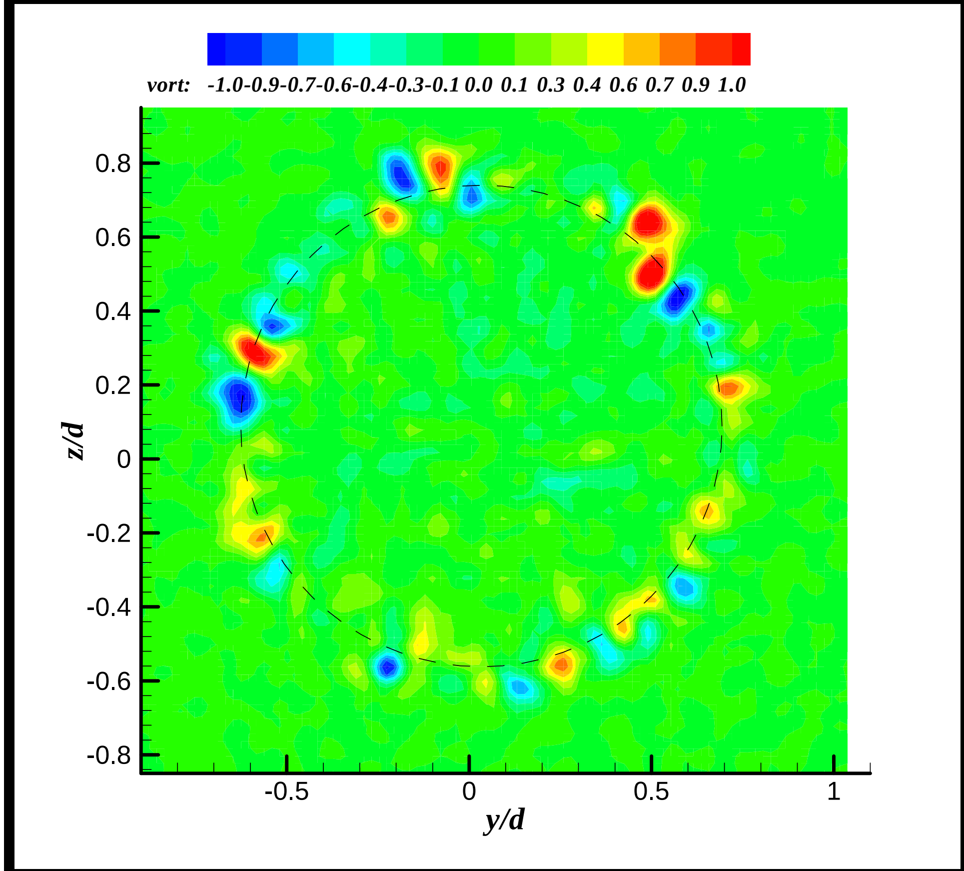
No Control

With Control

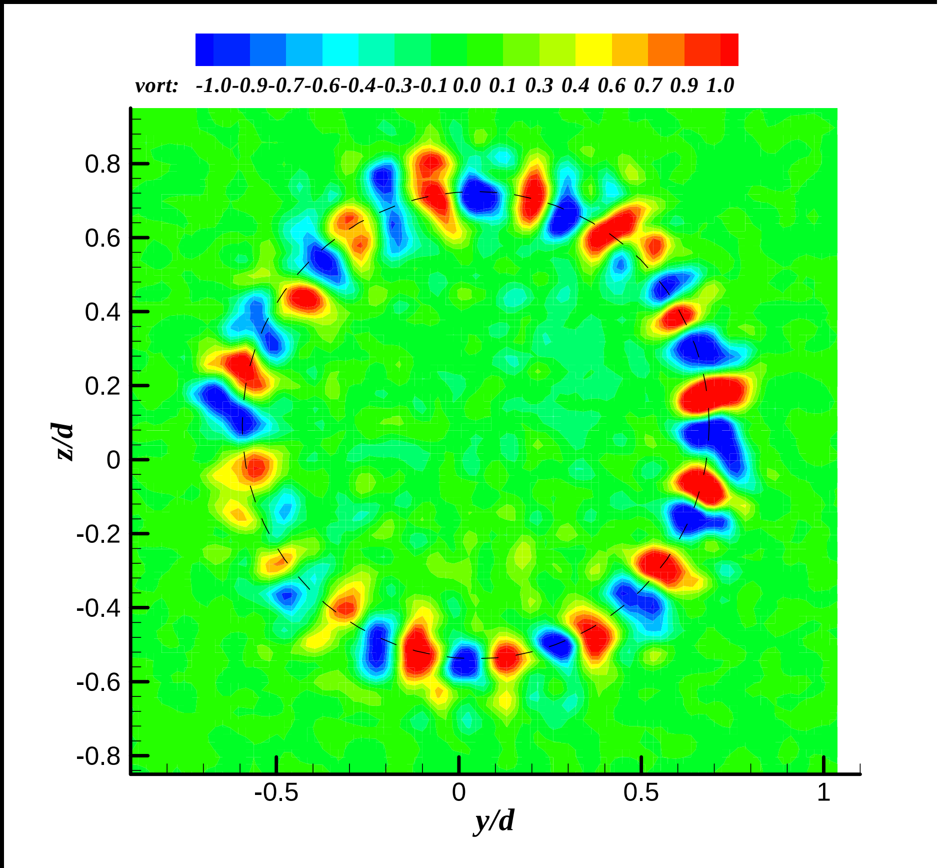


Effect of Microjet Control on Streamwise Vorticity

NPR=5, h/d = 4, x/d = 1, 90 deg. μjets



No Control



With Control

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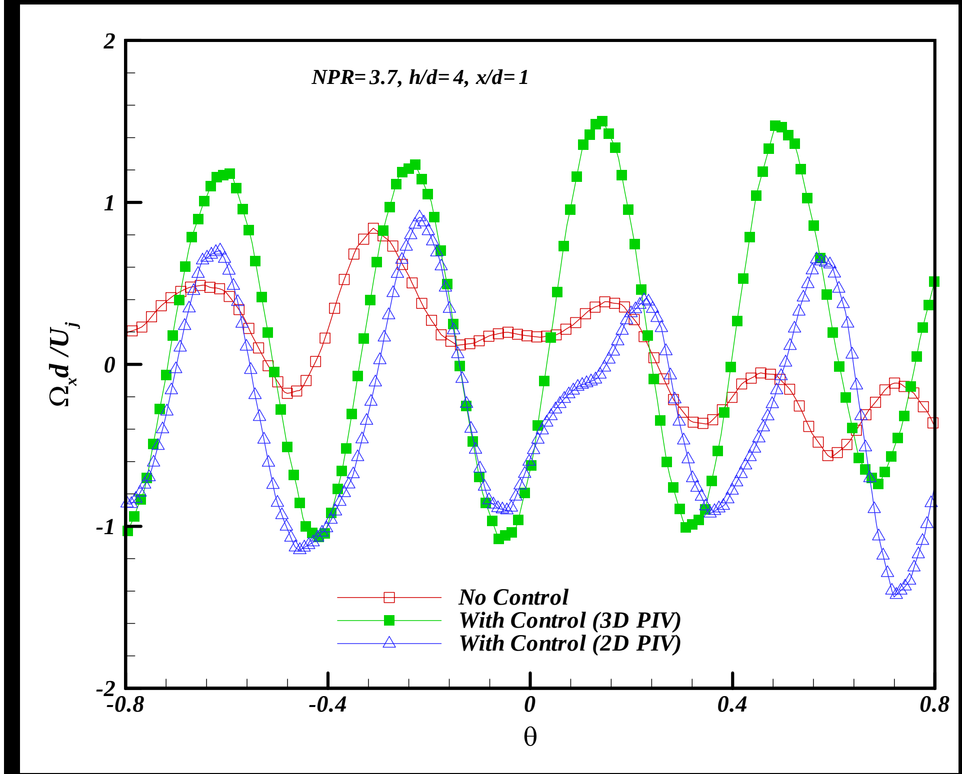
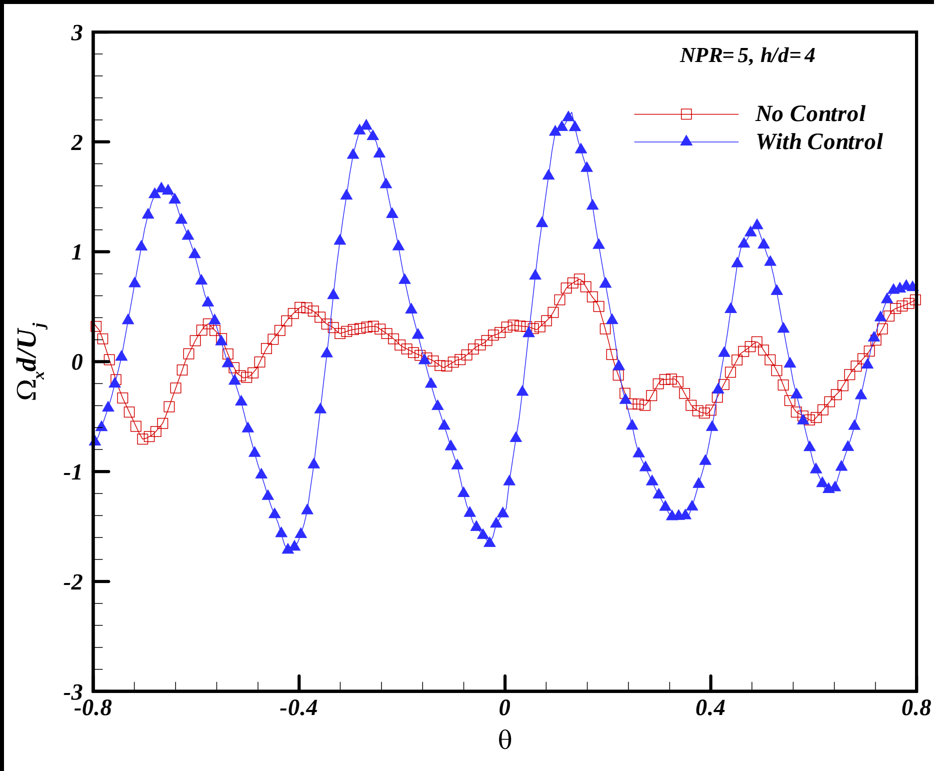
Effect of Microjet Control on Streamwise Vorticity

h/d = 4, x/d = 1, 90 deg. μjets

No Control
With Control (3D PIV)
With Control (2D PIV)



NPR = 3.7



NPR = 5

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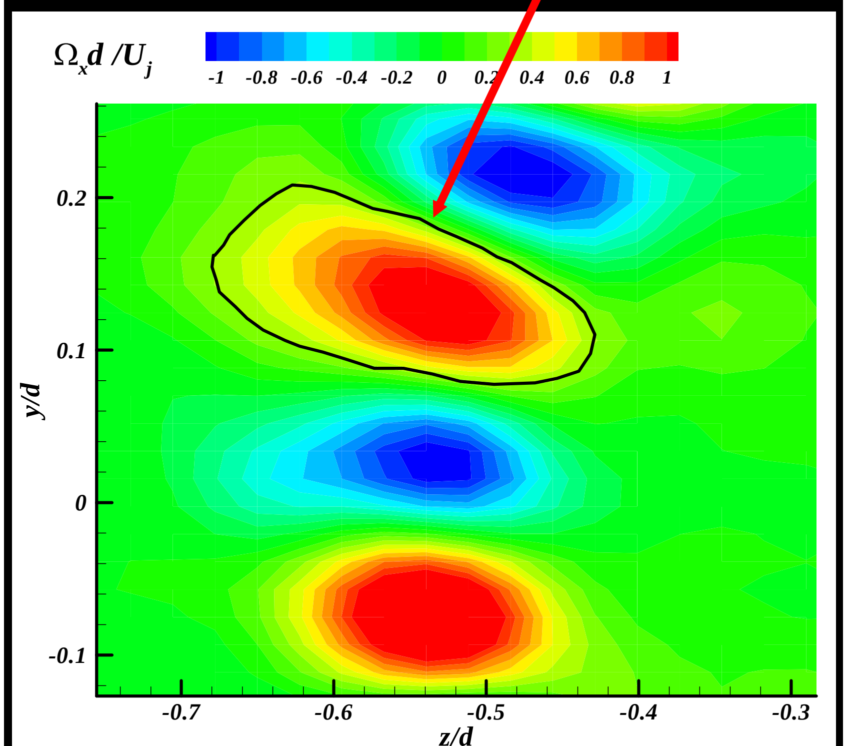
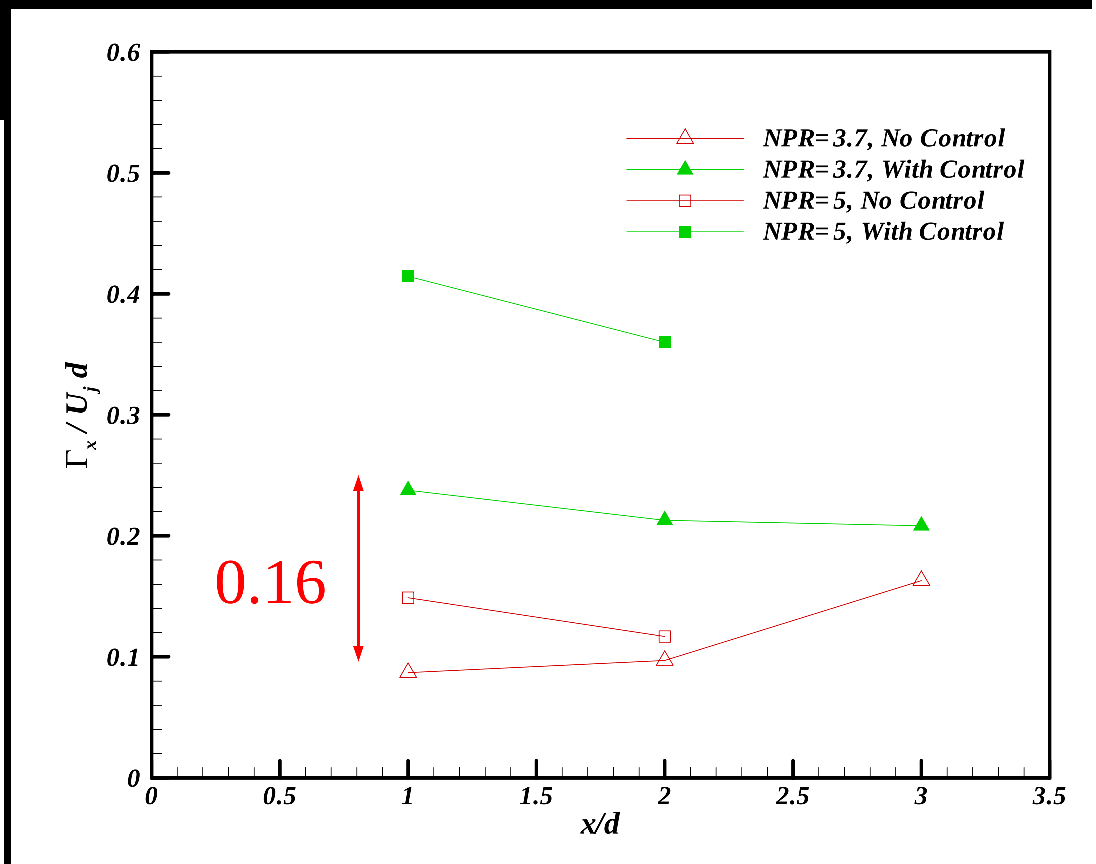
Streamwise Development of the Average Circulation

NPR=3.7 and 5, h/d = 4, x/d = 1, 90 deg. μjets

$$\Gamma = \int \vec{\Omega} \bullet \vec{n}\, dA$$





Summary

- **Microjet control successfully disrupts the feedback loop and leads to:**
  - ➢**Eliminate or significantly reduce the impinging tones**
  - ➢**Reduce the overall sound pressure level**
  - ➢**Reduce the unsteady loads**
- **PIV measurement clearly show microjet control:**
  - ➢**Reduce in the azimuthal vorticity**
  - ➢**Increase in the streamwise vorticity**
  - ➢**Thicken the shear layer at nozzle exit**
- **The plausible mechanism of microjet control - *Redirect the azimuthal vorticity into streamwise direction through*:**
  - ➢**Tilting**
  - ➢**Stretching**

2. Control of Compressible Dynamic Stall using Microjets

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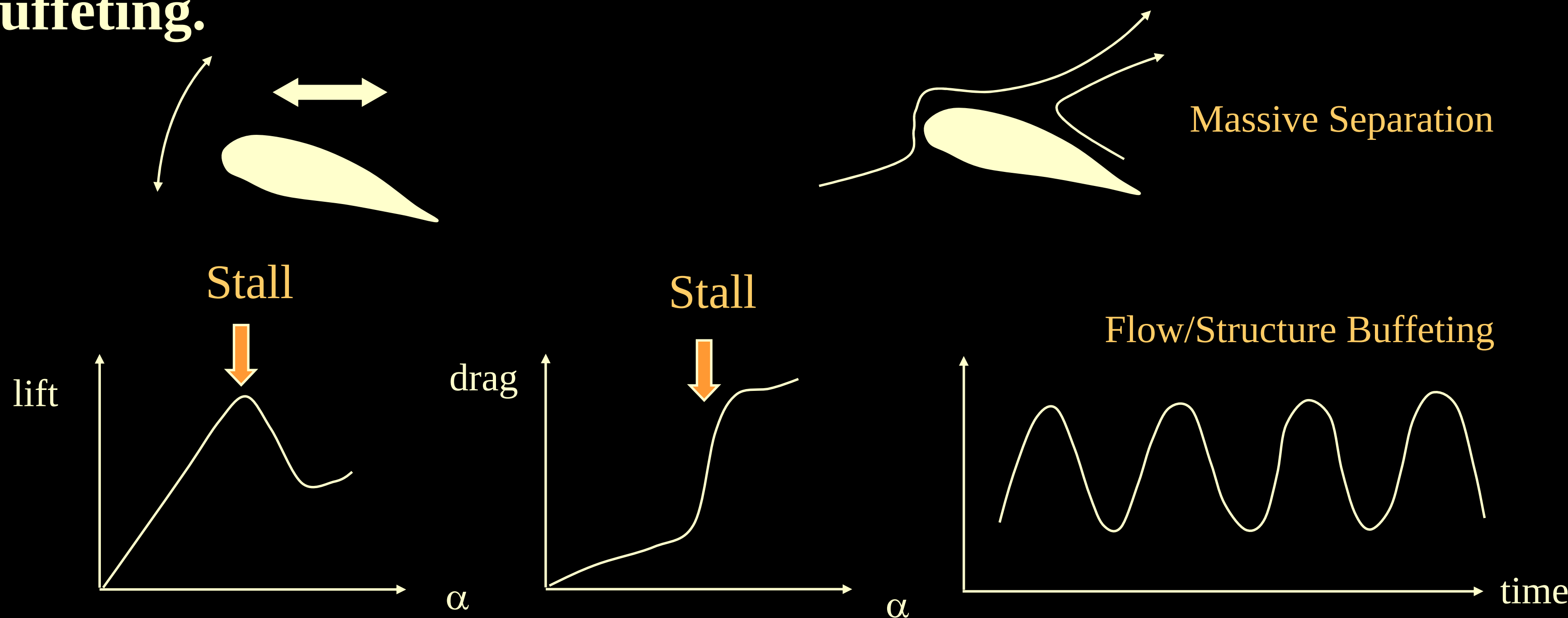
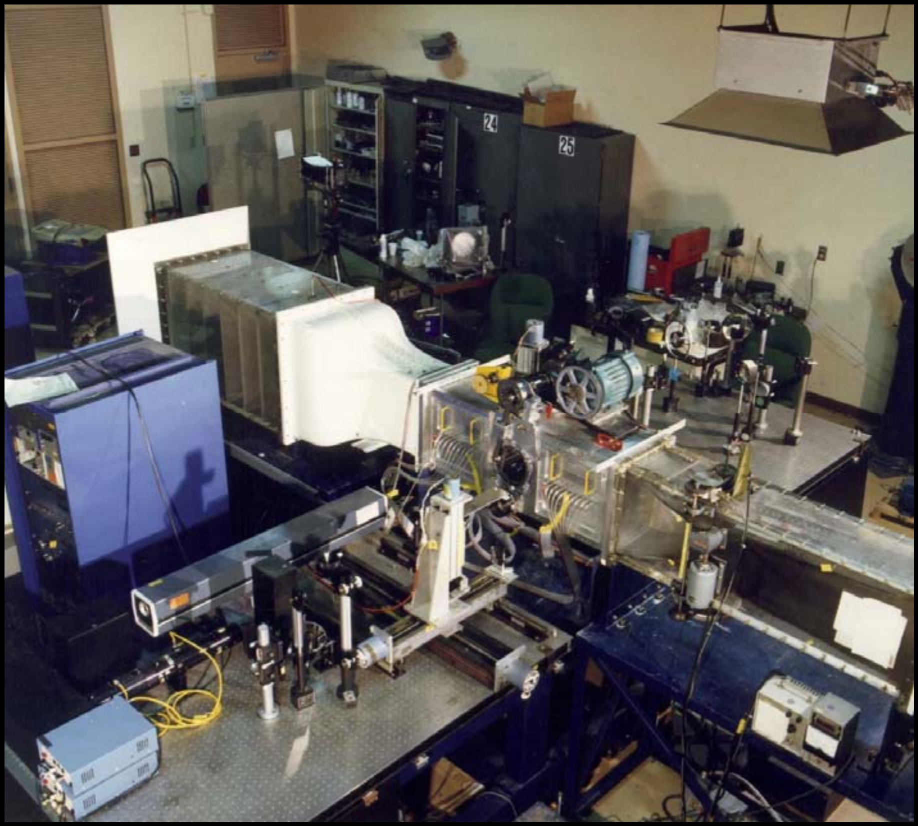
Dynamic stall: a flow phenomenon when wings and rotors experience sudden changes of their operating conditions (angle of attack, inflow conditions, etc). The flow response to these changes usually involves many adverse effects such as massive boundary flow separation, a loss of lift, drag surge, and buffeting.



Experimental Setup

- NACA 0015 airfoil
- Blow-down wind tunnel
  - Operate at Mach 0.3-0.4
- Pitch rate: k=0.05 & 0.1, pitch angle: 5 to 25 deg.
- Reynold's number
  - 1.06 - 1.40 x 10^6
- Point Diffraction Interferometry (PDI)



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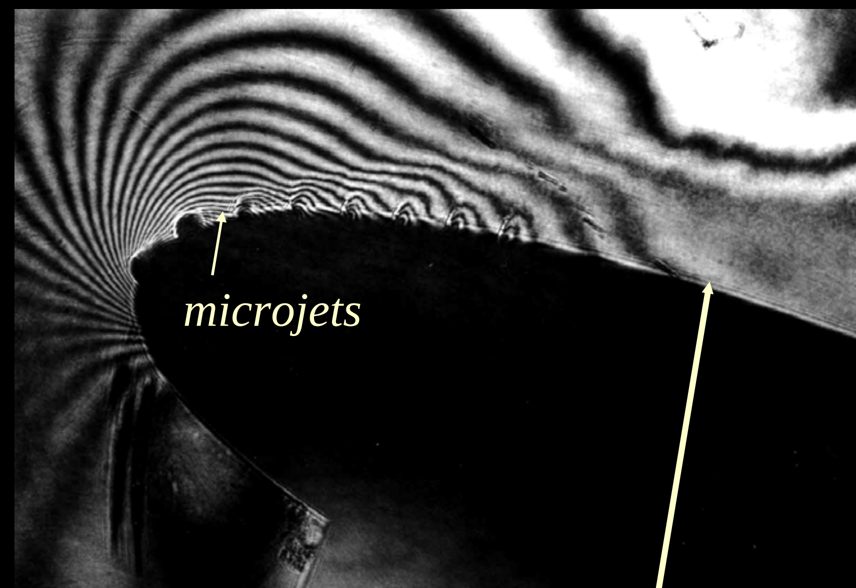
Typical Results

M=0.3, k=0.05, a=20 deg.

No control



With control

• With control, the buffeting noise due to the wake shedding is drastically reduced.

Flow Sequence, M=0.3, k=0.1

No Control

α=15.9° upward

α=18.0° upward

α=20.0° (apex)

With Control

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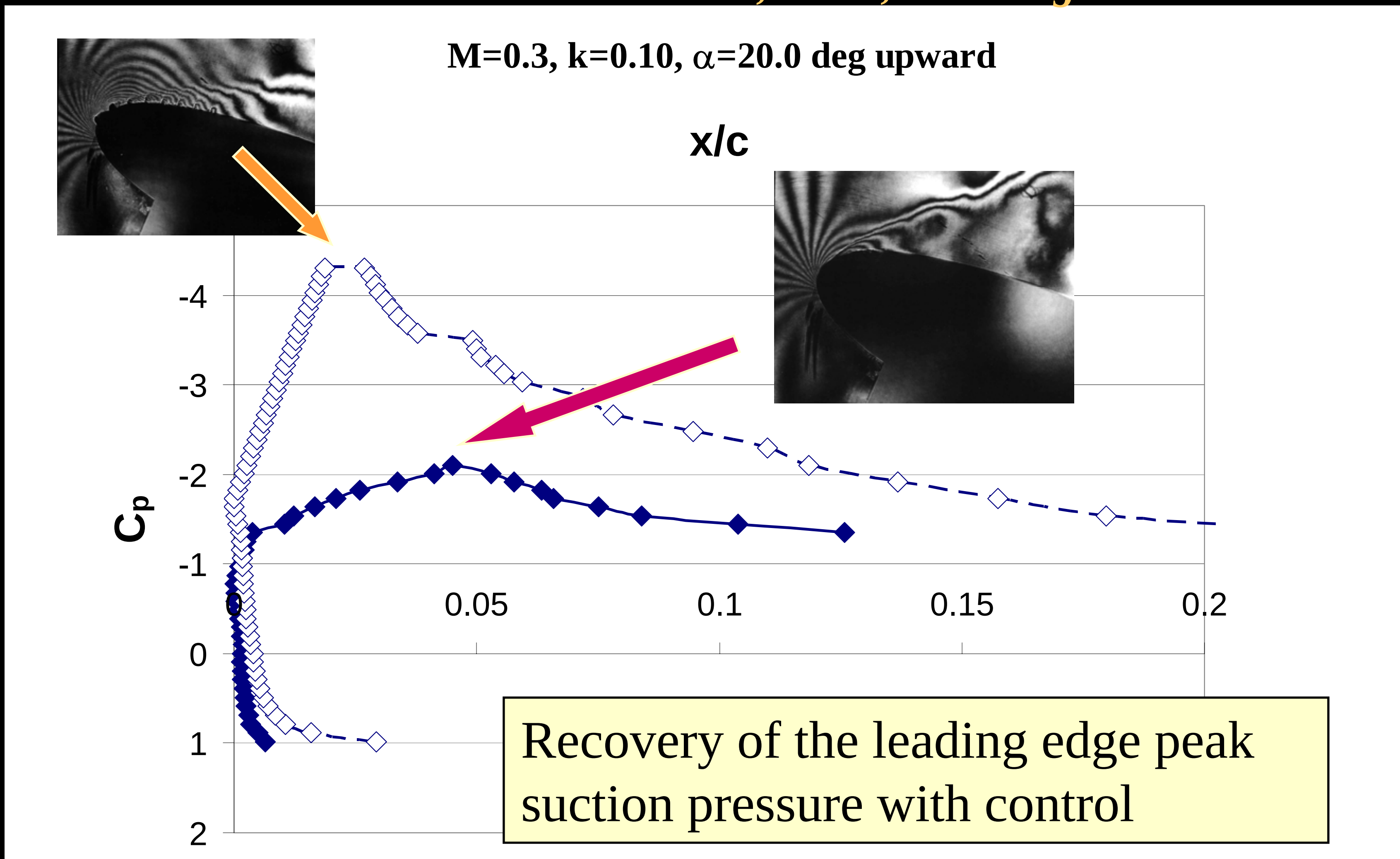
Surface Pressure Distribution
M=0.3, k=0.1, α=20 deg.



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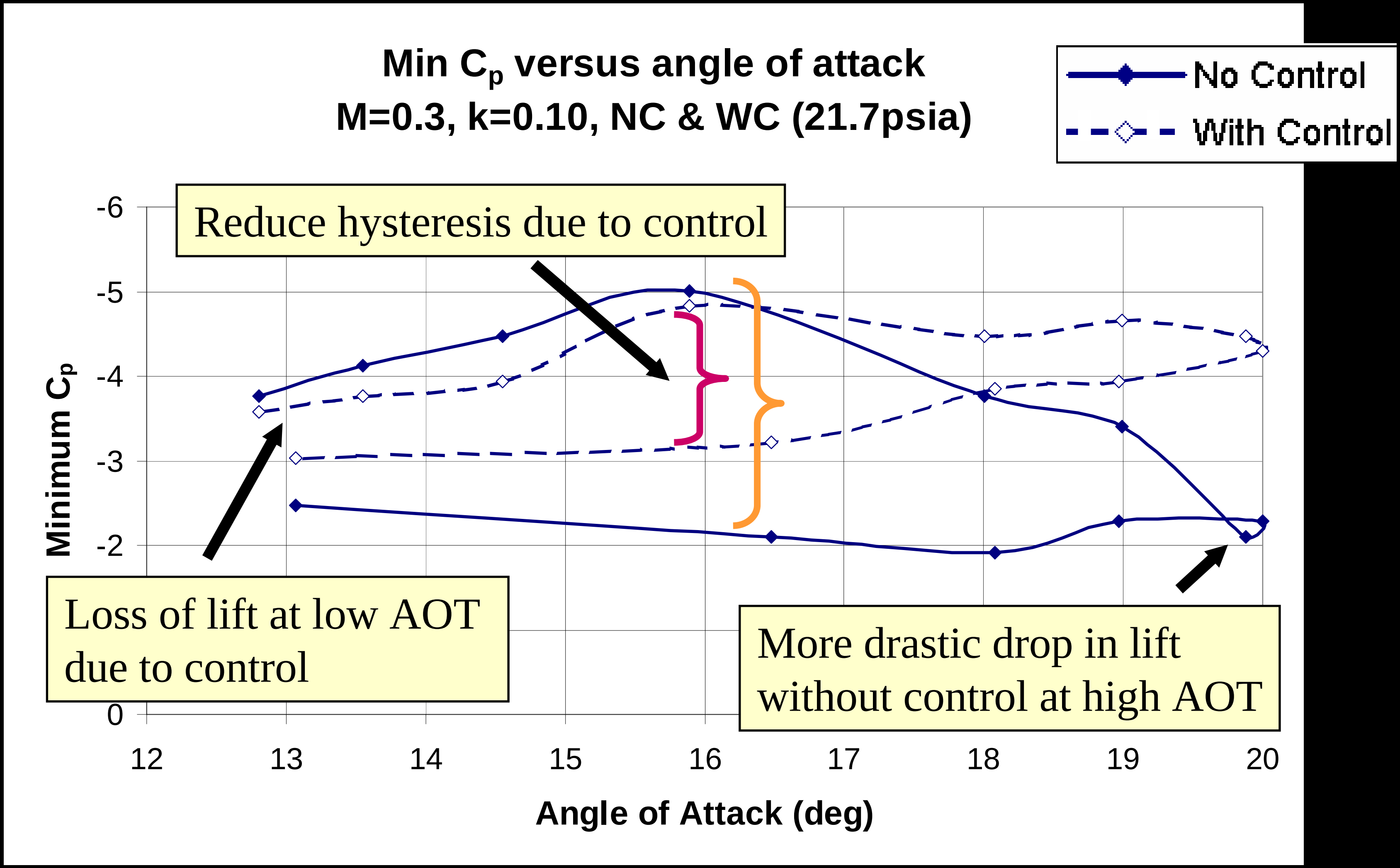
Peak Suction Pressure
M=0.3, k=0.1



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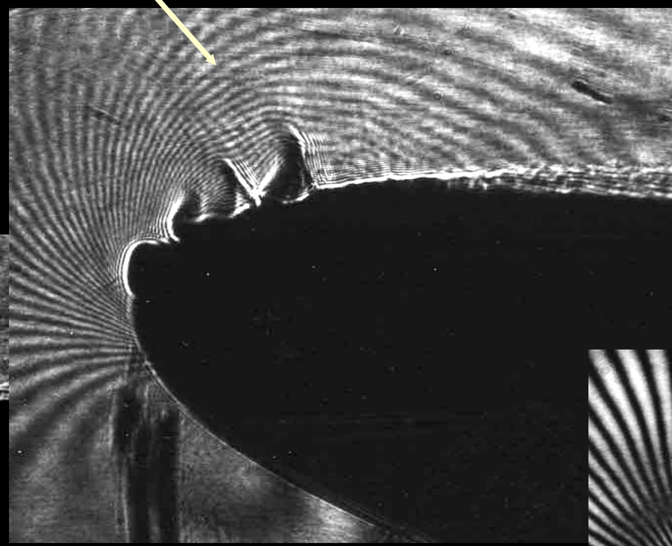
Shock-Induced Separation
M=0.4, k=0.05

Periodic λ shock structure

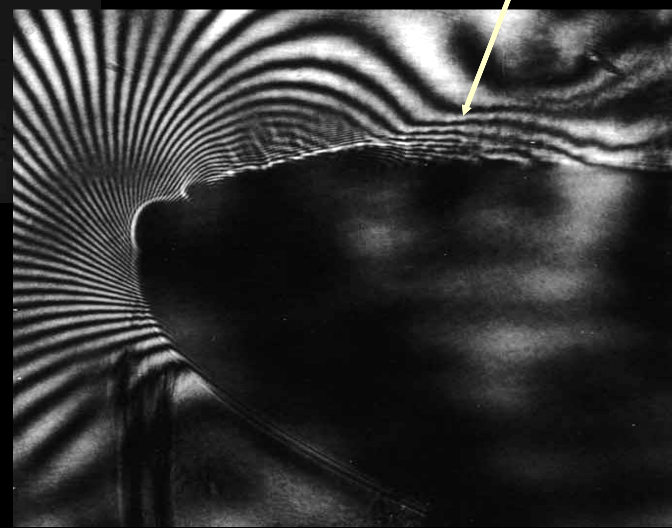
Thickening boundary layer

Triggering separation



α=12.5°

α=10.4°



α=14.5°

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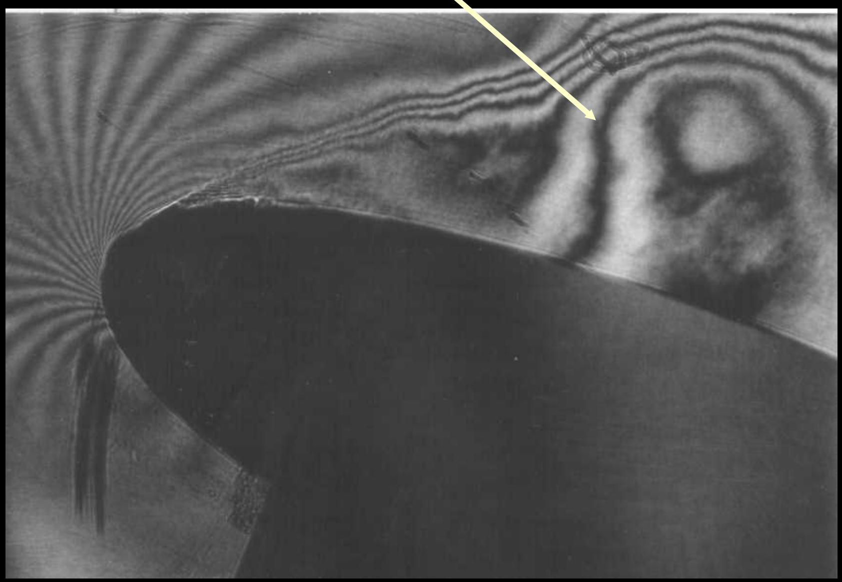
Effect of Microjet Control
M=0.4, k=0.05, α=20 deg.

Release of dynamic stall vortex

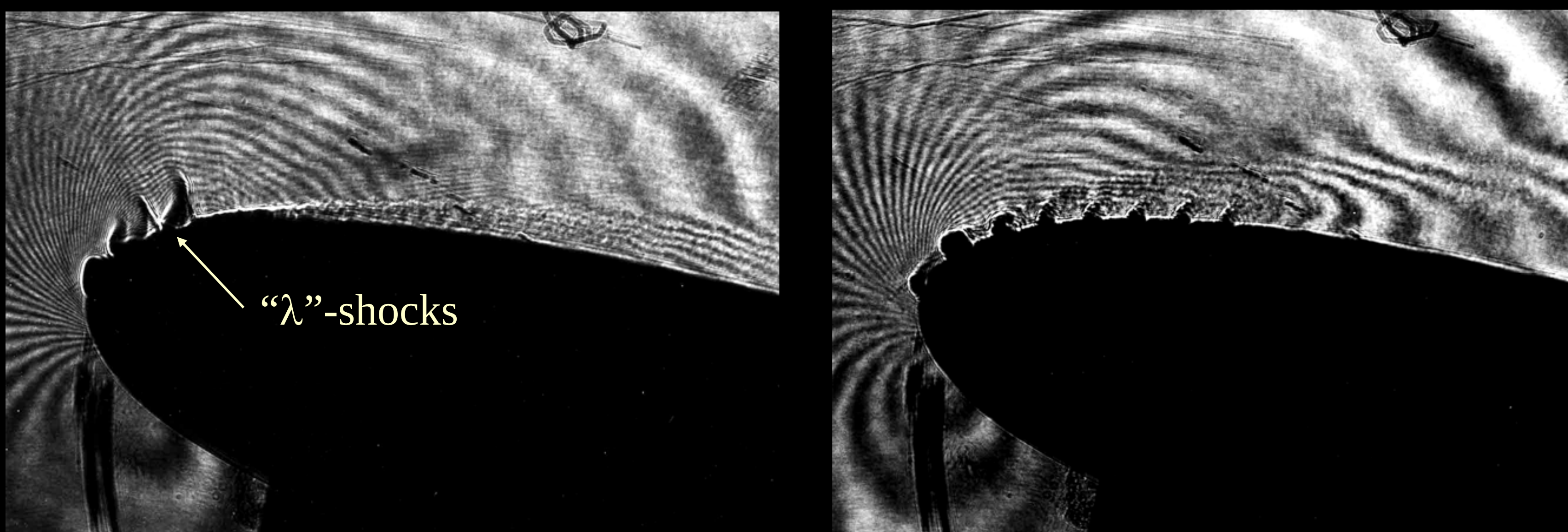


No Control

No massive separation
No vortex

Microjet Control

Shock Elimination
M=0.4, k=0.05



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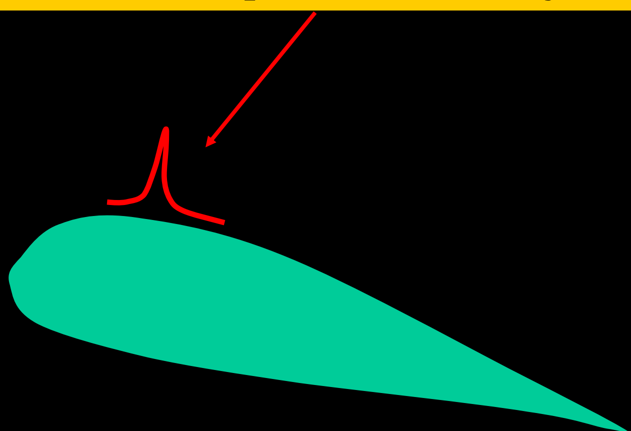
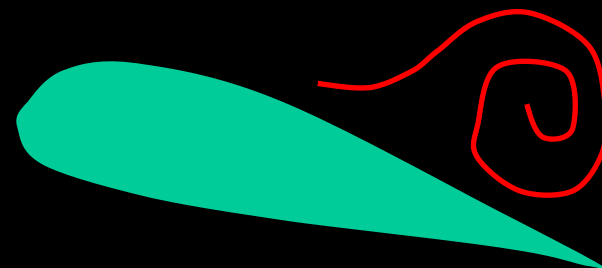
Physical Mechanism

Vorticity Accumulation and the Initiation of the Unsteady Separation Process (Van Dommelen & Shen) and/or Shock-Induced Separation $\Rightarrow$ Explosive Vorticity Eruption

Leads to the Formation of a Dynamic Stall Vortex $\Rightarrow$ Catastrophic Breakdown, Lift Loss, Drag Surge, Moment Stall





- Mismatch of time scales
- Vorticity accumulation due to an unbalanced vorticity generation, diffusion, and convection

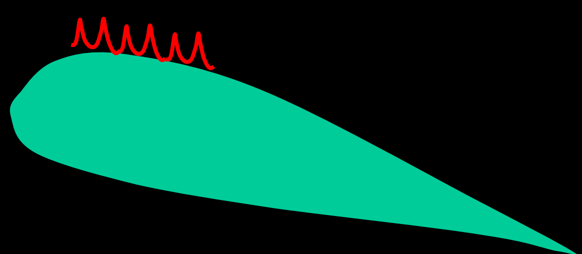
Control Strategy

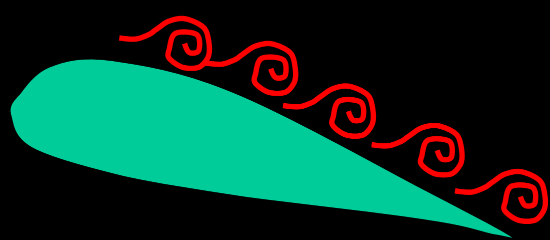
- **Tradition Schemes on Separation Control**
  - Relieve the adverse pressure gradient (nose modification..)
  - Re-energize the boundary layer (suction, blowing, vortex generators..)

- **Our Approach: Controlled Separation**
  - Eject vorticity away from the surface at a controllable manner using distributed microjets

Controlled, distributed ejection of surface vorticity $\Rightarrow$ **redistribution** of the vorticity through ejection

Increase downstream convection of vorticity $\Rightarrow$ No accumulation $\Rightarrow$ More manageable breakdown process





Summary

- Dynamic stall has been significantly reduced or eliminated $\Rightarrow$ improve aerodynamic performance

- Pressure recovery $\Rightarrow$ an increase of lift

- Elimination of the shocks at the leading edge $\Rightarrow$ alleviating the possibility of the shock-induced separation

- Suppression of the periodic shedding of the dynamic stall vortices $\Rightarrow$ reduce buffeting noise and associated vibration

3. Aeroacoustic Properties of Supersonic Cavity Flows and Their Control

Motivation

- To understand the supersonic cavity flow
- To control the unsteadiness of the flow

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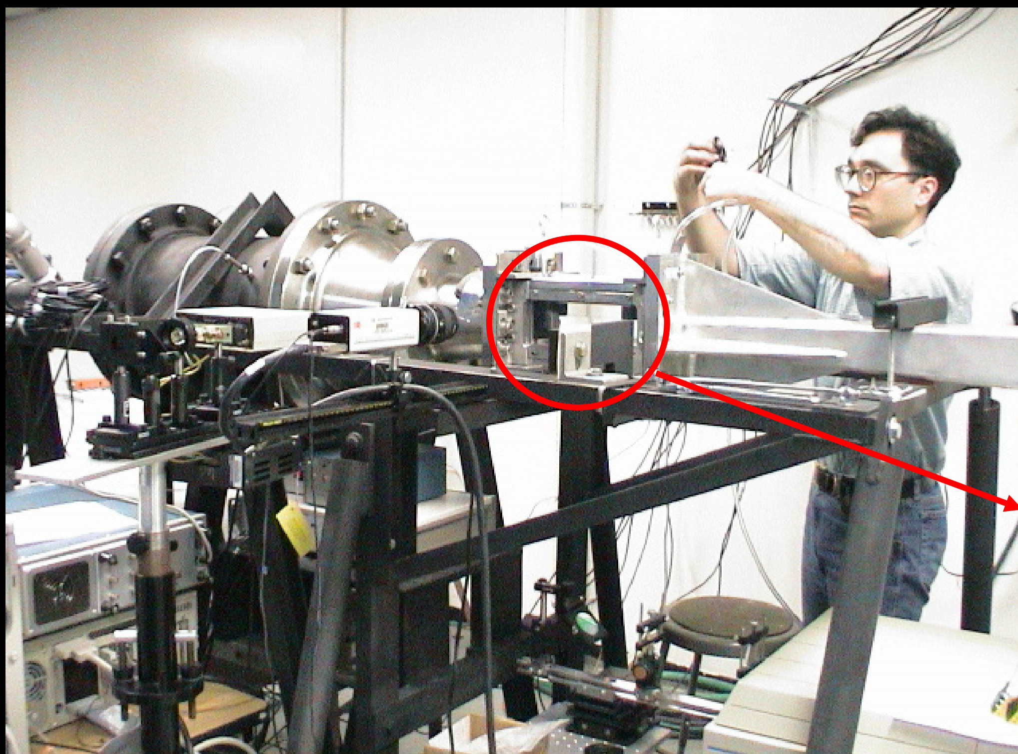
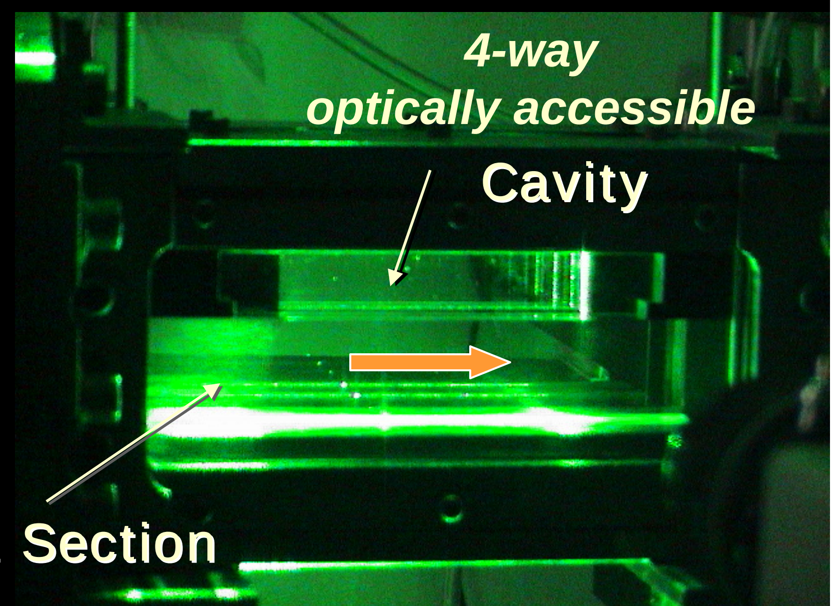
FMRL Cavity Facility



M=2.0

Re=23 X 10^6 /m

Cavity Dimensions
L=12.2 cm;
L/D=5.1, L/W=5.9



Shadowgraph movie w/o control

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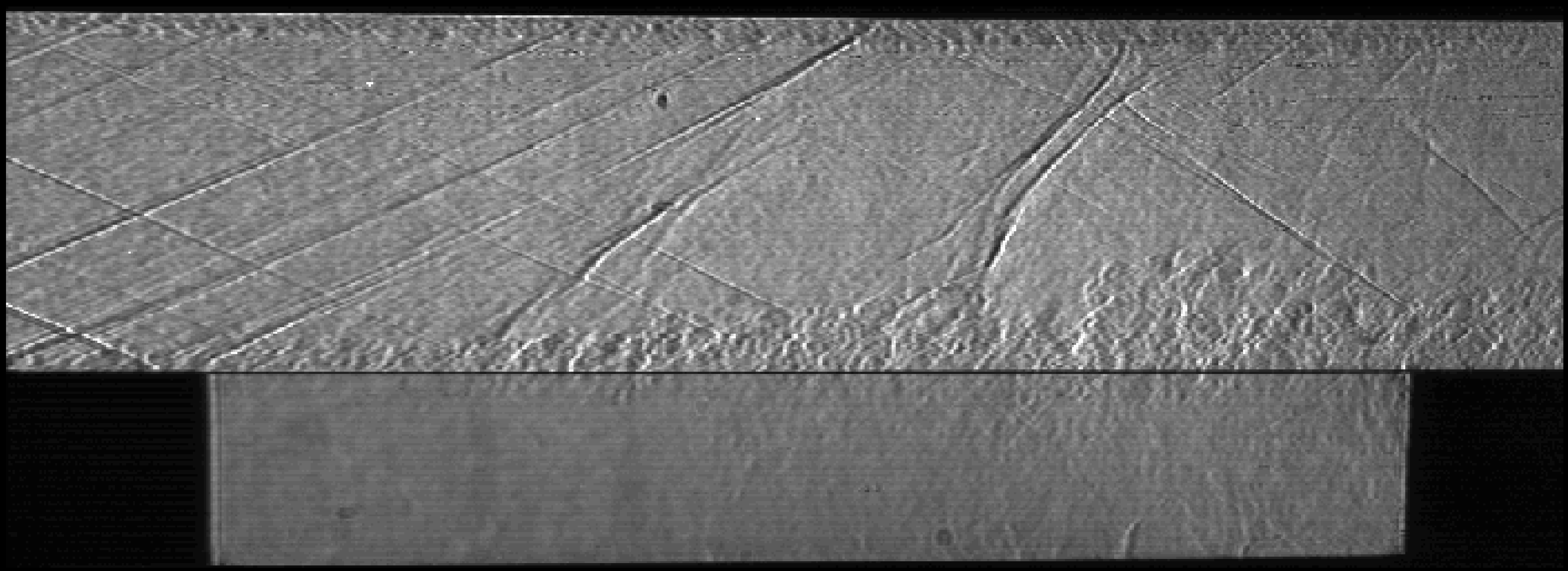
M=2



Fluctuating Pressure Measurement

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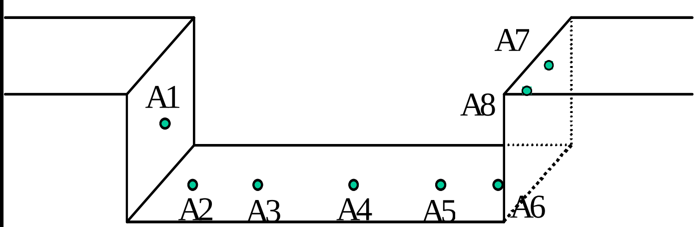
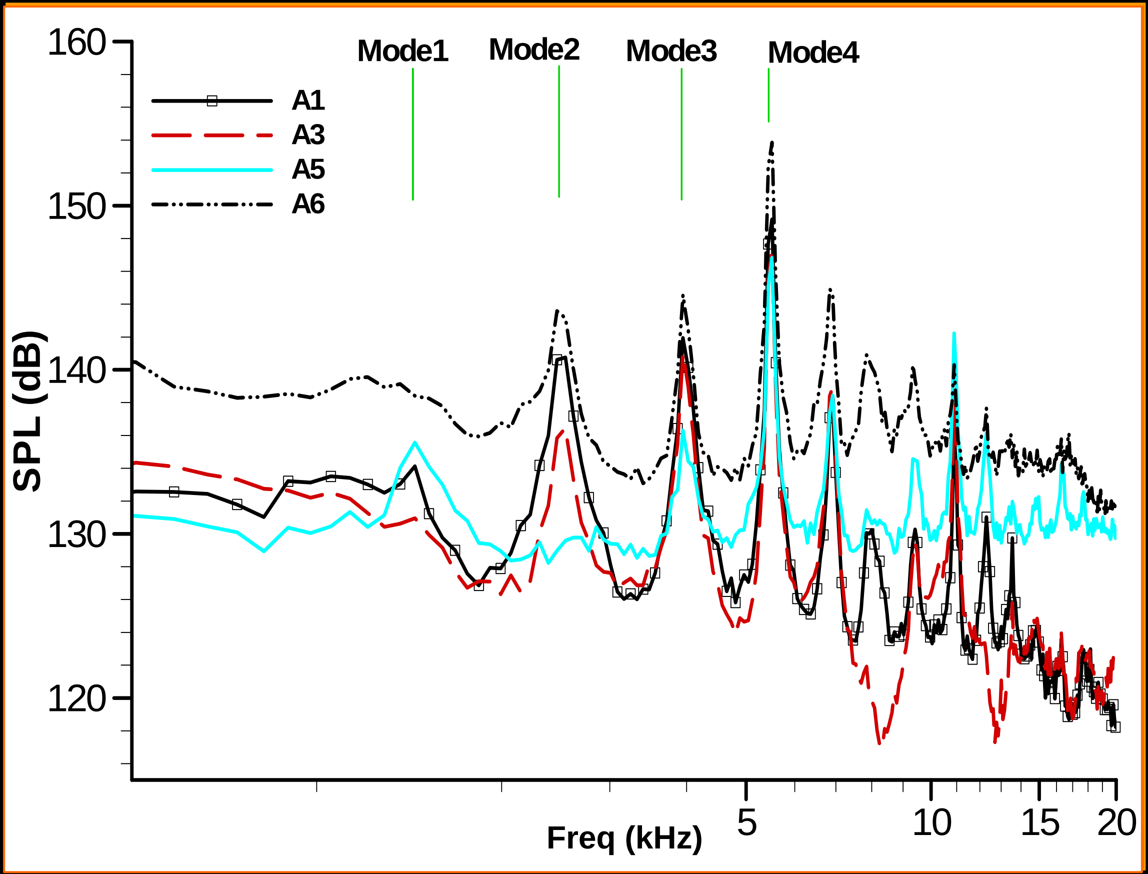
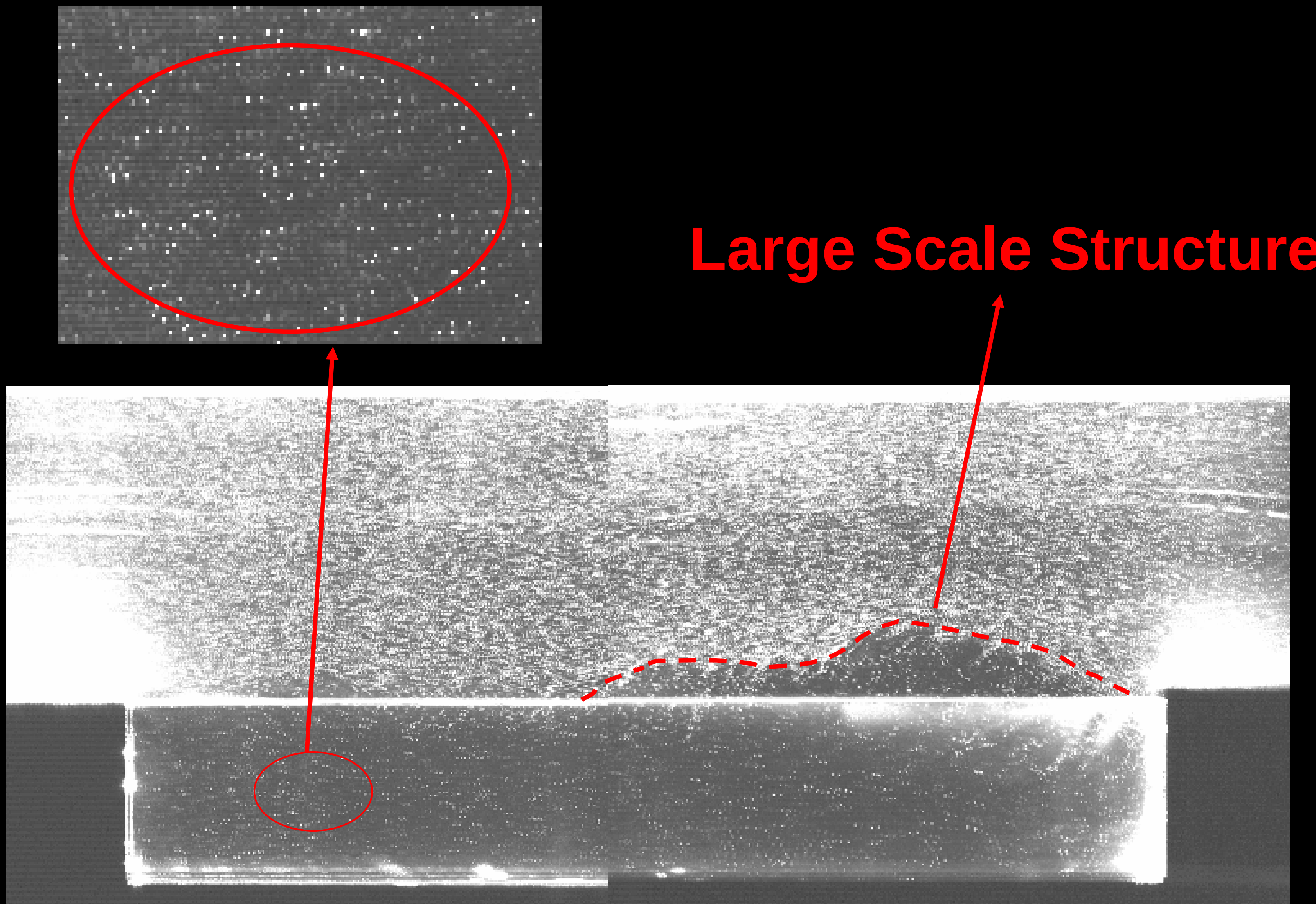




Spectra at different locations

Result—PIV image



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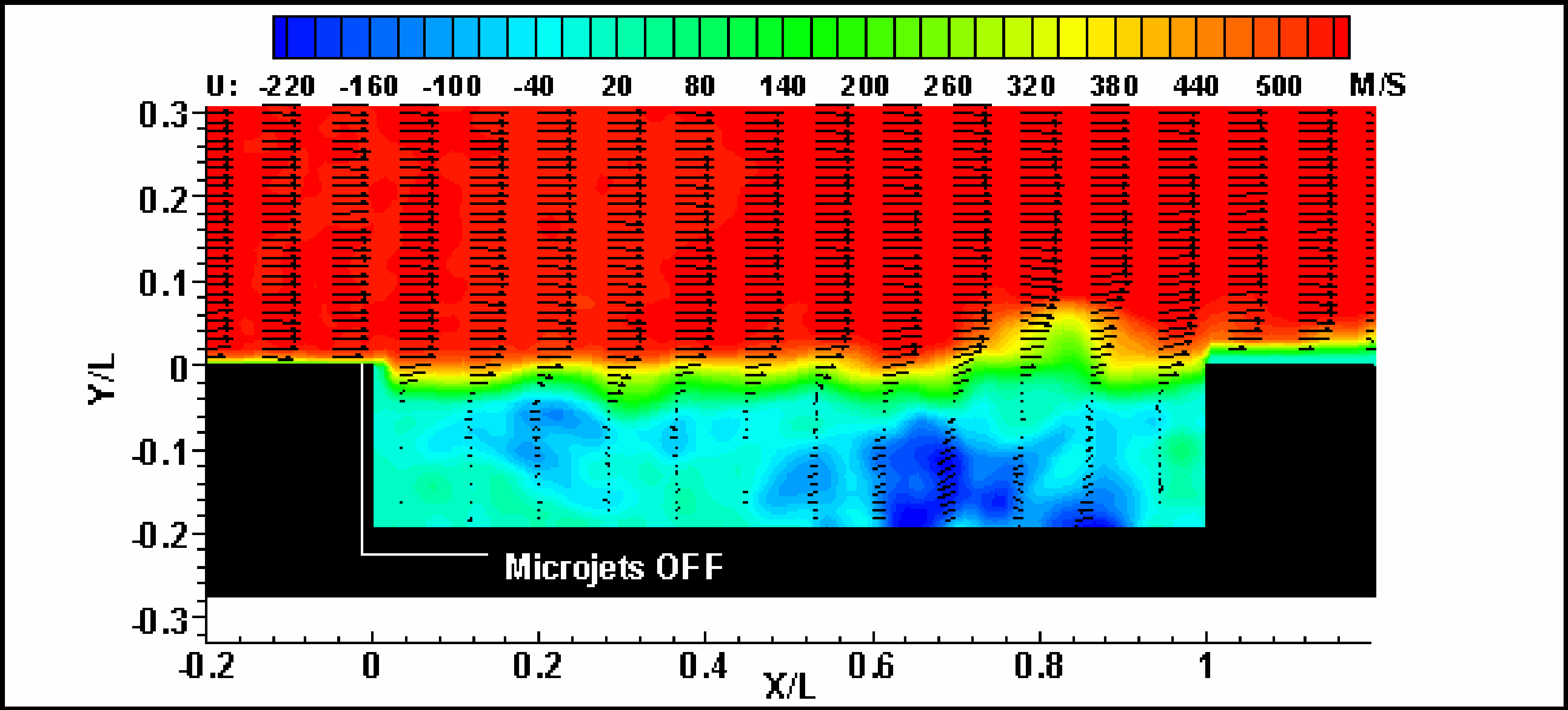
Flow realization (PIV)

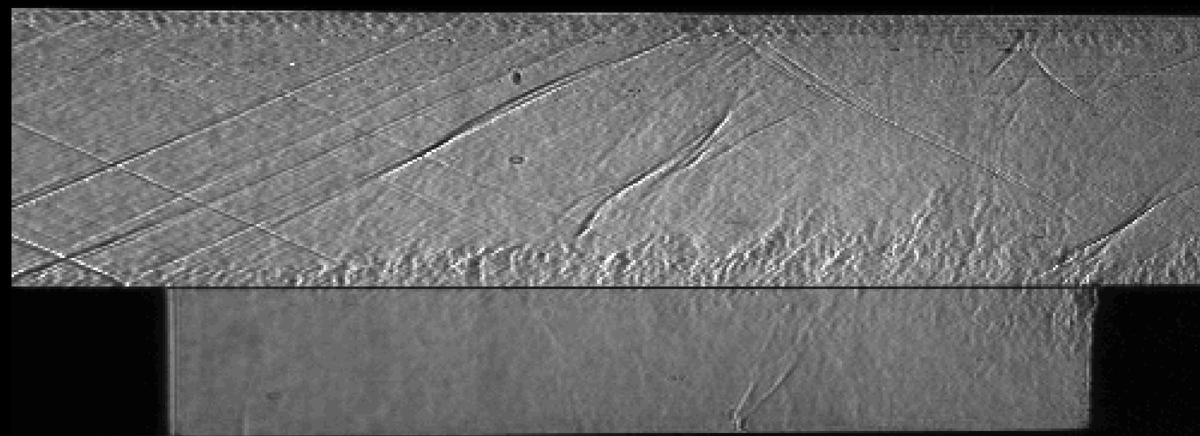


Summary of Baseline

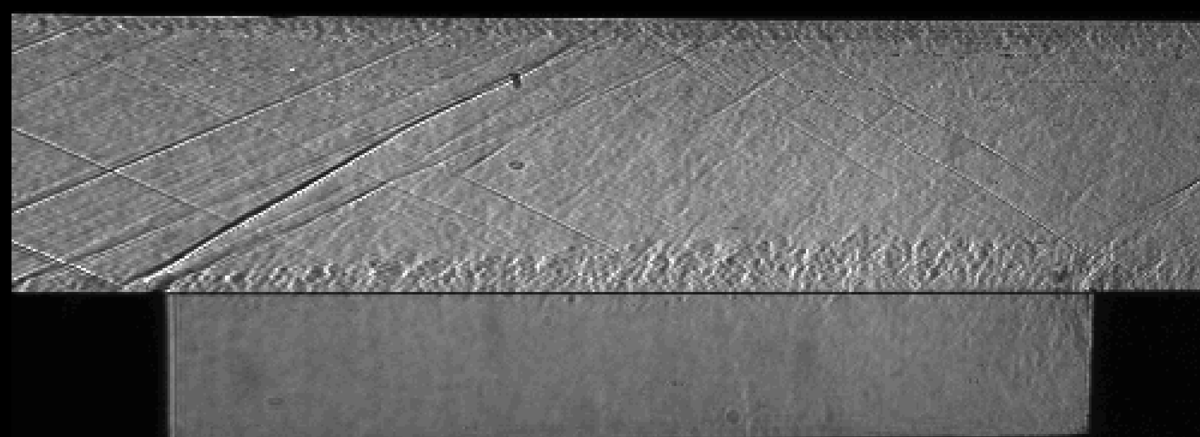
- The uncontrolled cavity flow is highly unsteady
  - Very high unsteady pressure levels, dominated by large amplitude discrete tones
  - Spatially coherent large scale structures are clearly present

Control Effort on Shadowgraph

Control OFF



Control On



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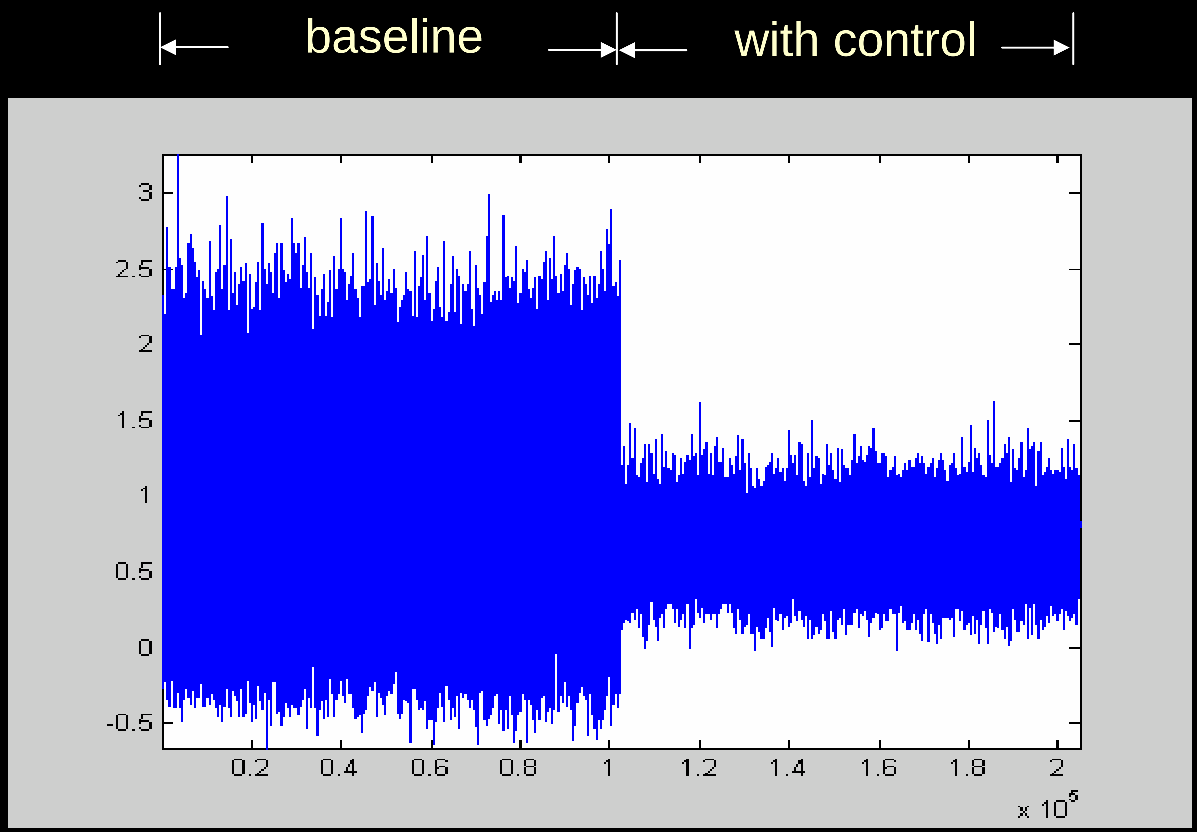

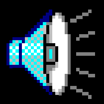

sound file

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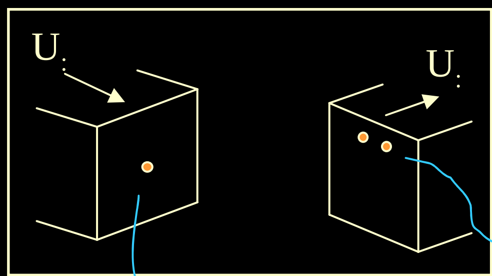
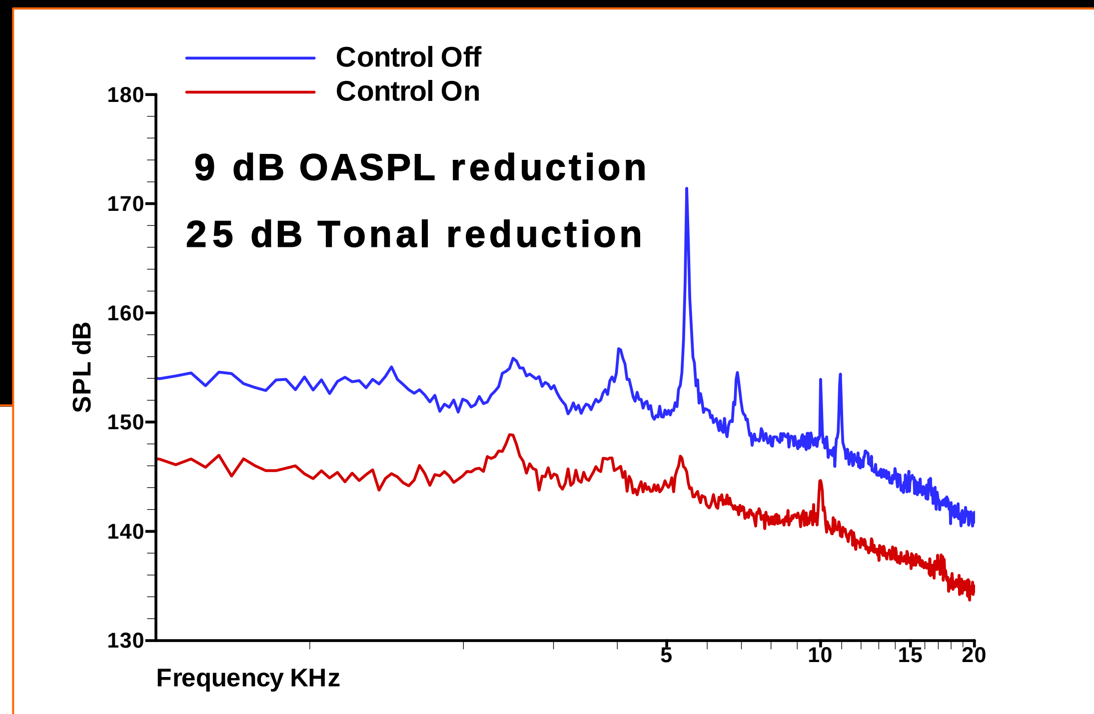
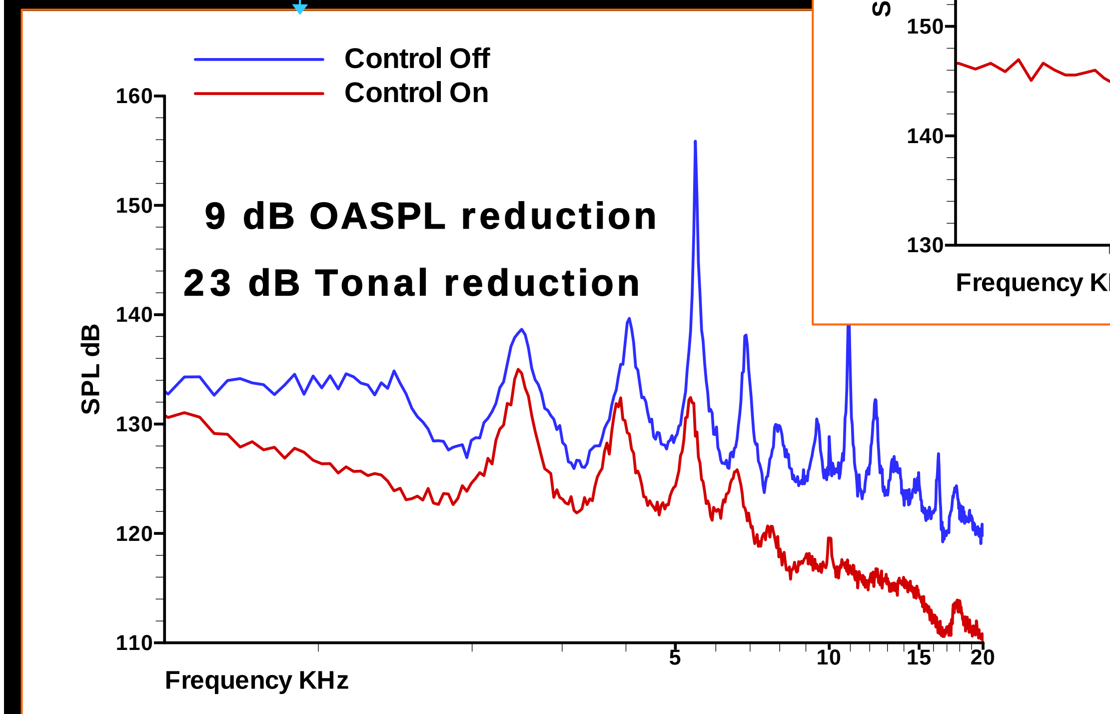
Control Effect on Unsteady Pressure







Mass Injection Ratio

(Cavity Blowing factor)

$$B_c = \frac{\rho_{microjet} V_{microjet} A_{microjet}}{\rho_\infty V_\infty L_{cavity} W_{cavity}} = 0.15\%$$

Control Effect on V_{rms}

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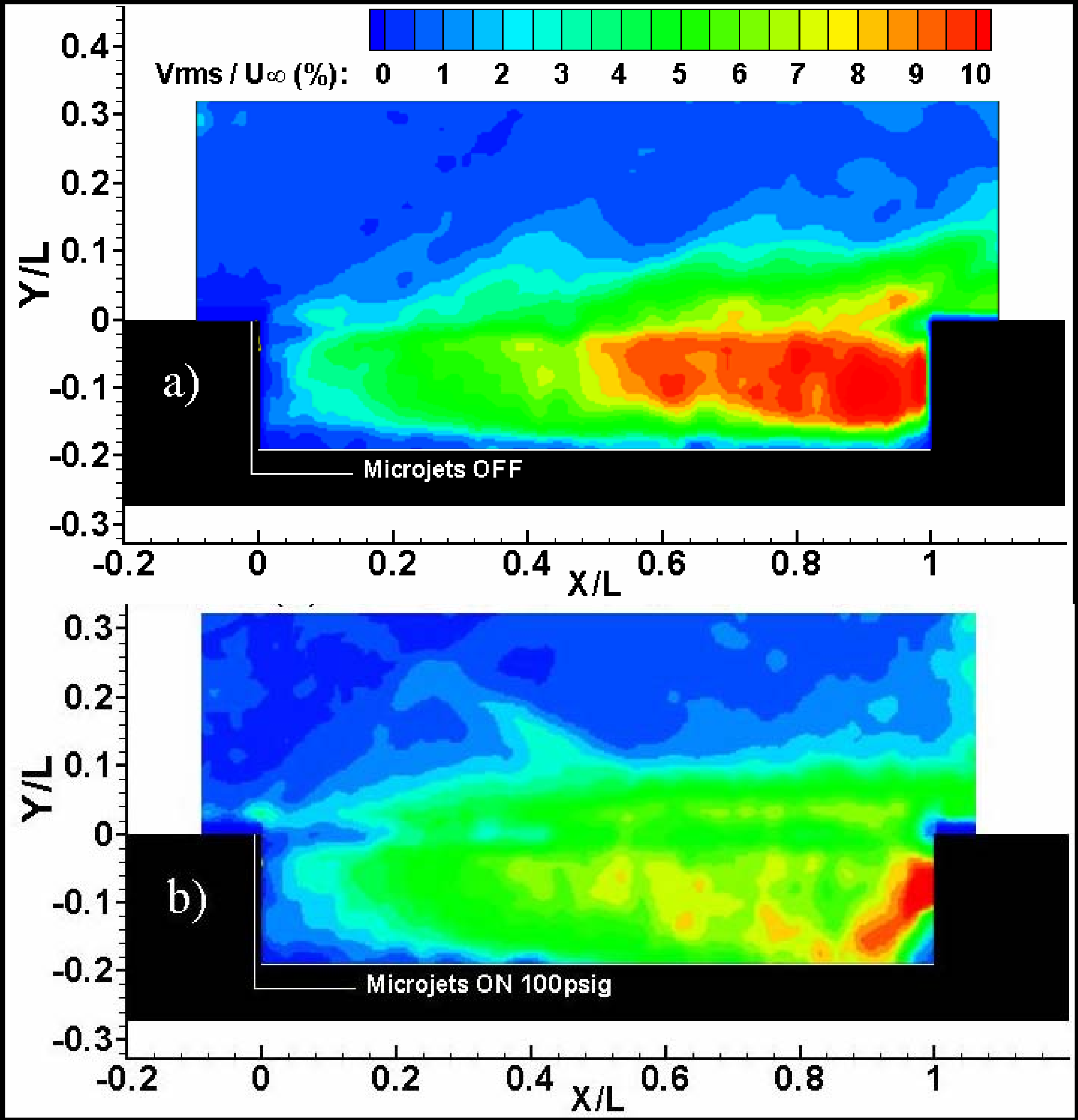
Control OFF

Control On



Control Effect on Vorticity Field

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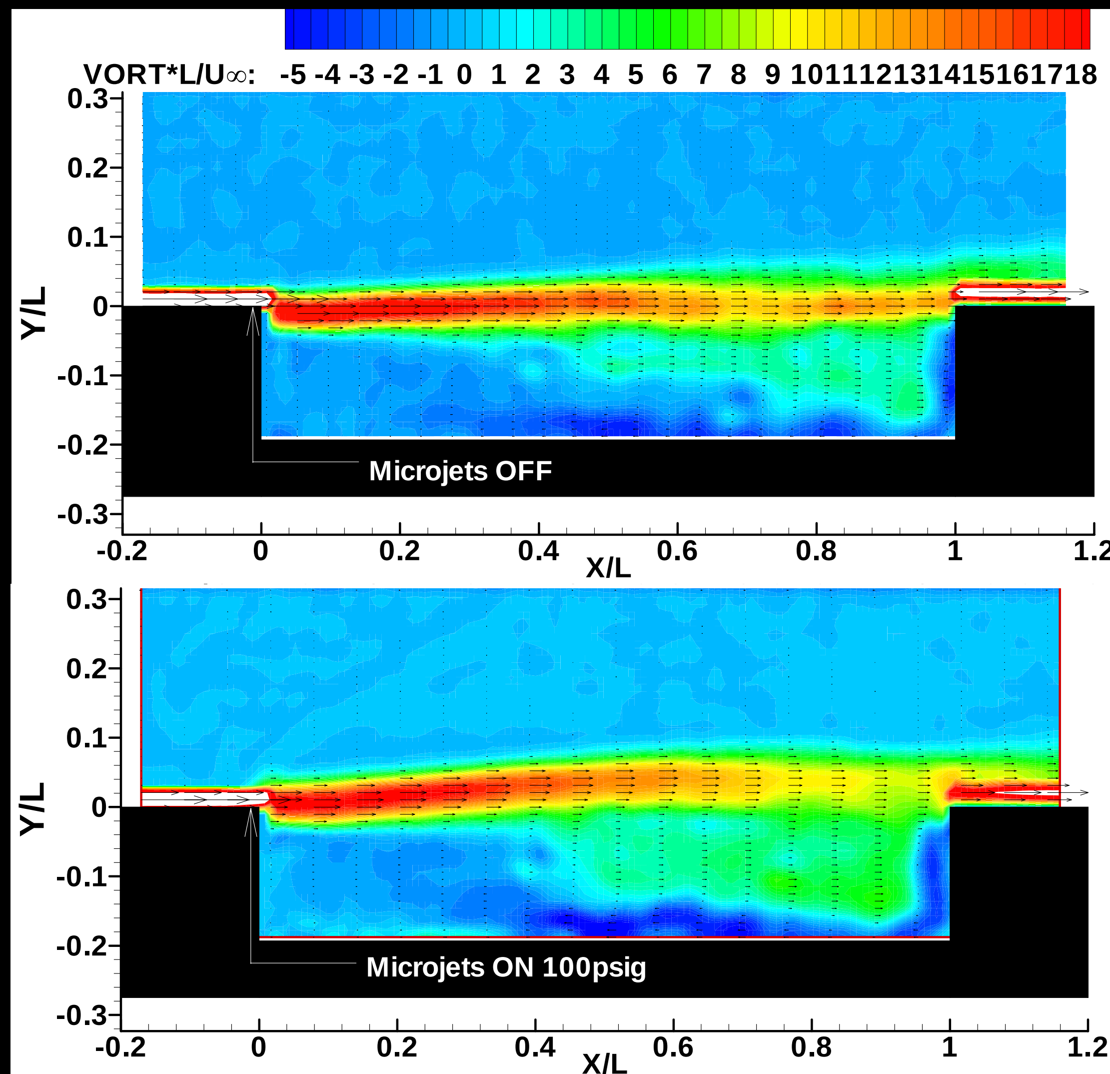
Control OFF

Control On



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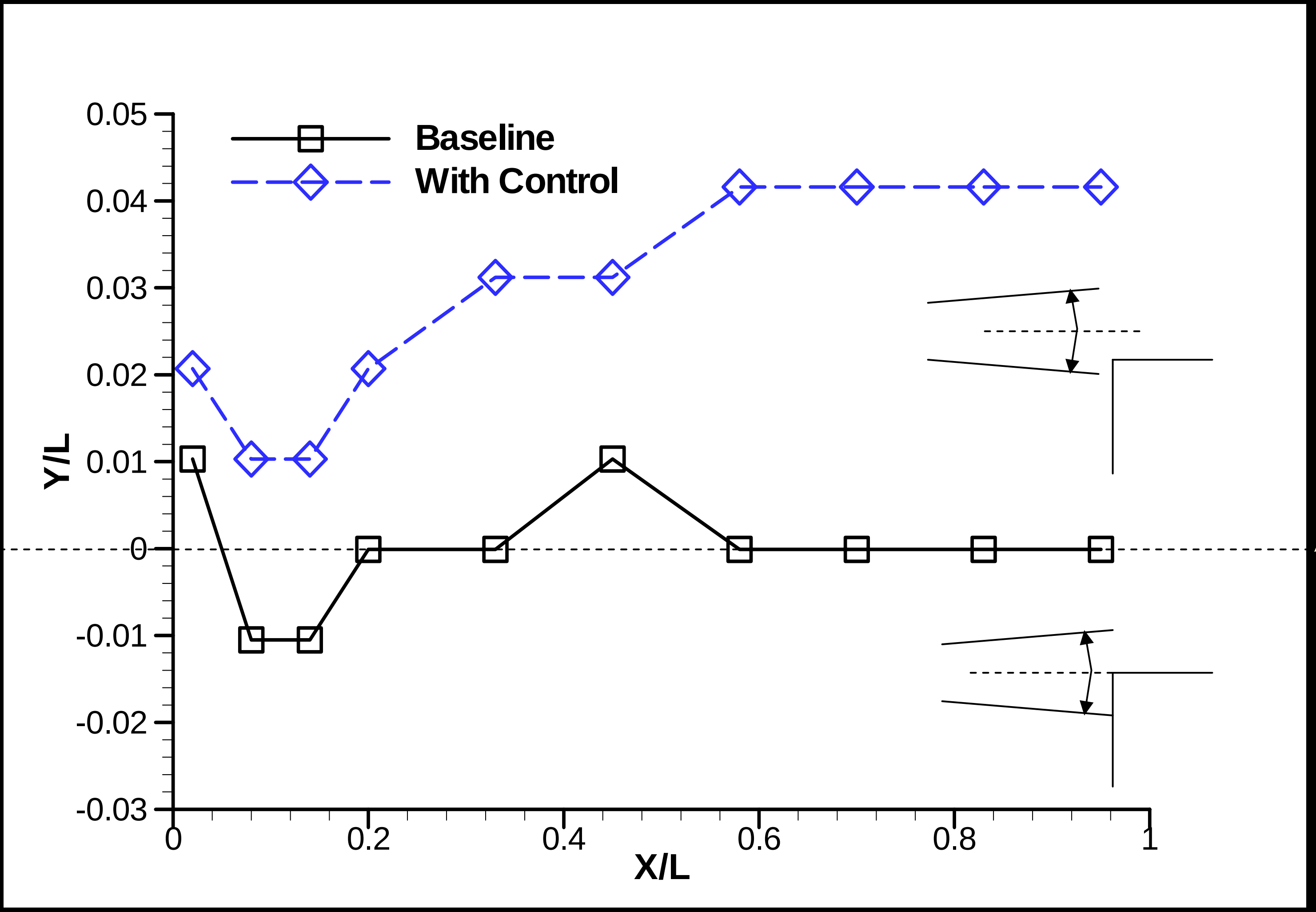
Comparison of the center of shear layer



Y/L=0 is the height of the leading edge and trailing edge

Summary

- Microjets are very effective in significantly reducing flow unsteadiness
  - Cavity tones reduced by 20 dB or more
  - OASPL or P_{rms} reduced by 9 dB or more
  - Velocity fluctuations significantly reduced.
- Microjets control achieved with minimal mass flux, less than 0.2%

Summary

- Microjet system has been shown to be very effective in controlling various compressible flow applications, generally considered difficult using conventional control schemes
- Three US patents had been filed; 1 approved, two under provisional review
- Other applications include: noise reduction for supersonic hot jet, separation control of engine inlet