Some Challenging Problems in (Active) Flow and Noise Control

A (Limited) Experimental Perspective

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Future Directions in CFD Research
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Acknowledgements

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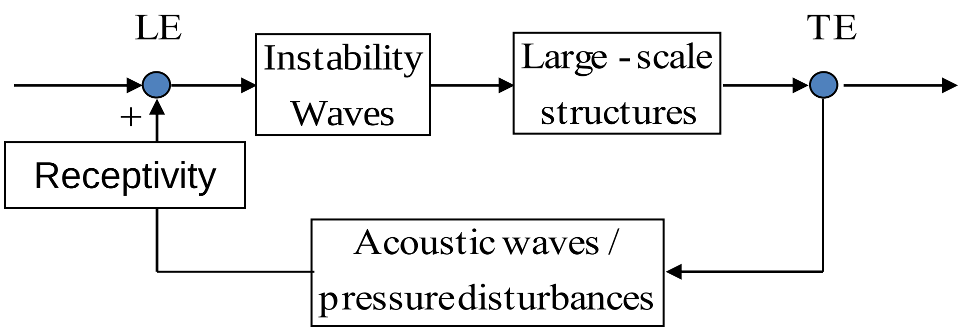
Outline

- **Problems**
  - Supersonic Cavity Flows
  - Supersonic Impinging Jets
  - Separated Flows

- **Experimental & Computational Results**
  - Base Flowfield
  - Response to Active Control
    - Steady Microjets
  - Pulsed Microjet Actuators

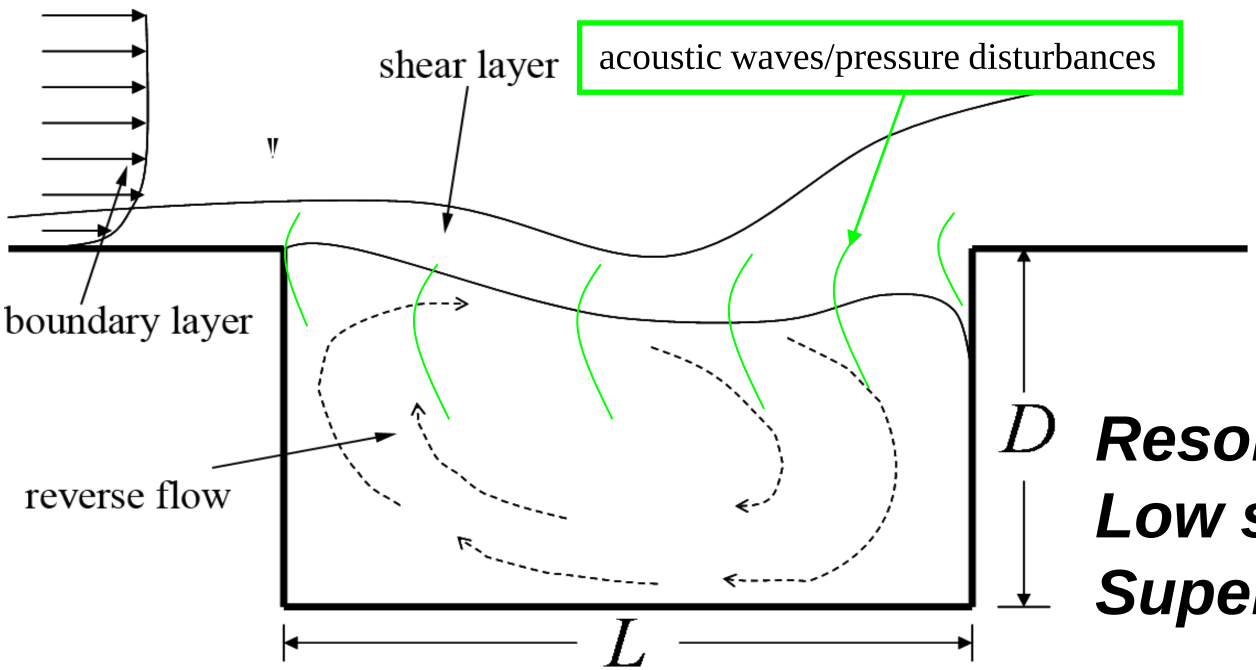
- **Final Thoughts**

Cavity Flows
Flow –Acoustic Resonance



Modified Rossiter's Model
(Heller & Bliss, 1975)

$$St = \frac{fU_\infty}{L} = \frac{(m-r)}{\left(M\left(1+\frac{\gamma-1}{2}M^2\right)^{-0.5} + \frac{1}{k}\right)}$$

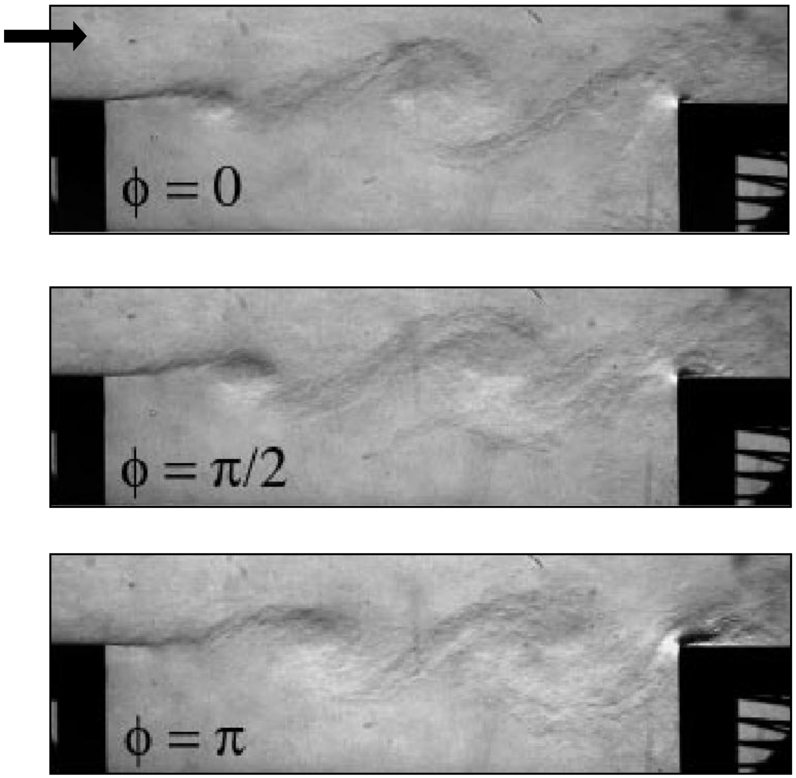


m – Mode no.
r – Phase delay
k – U_{conv}/U_∞

Resonance observed for Low subsonic to high Supersonic Flows

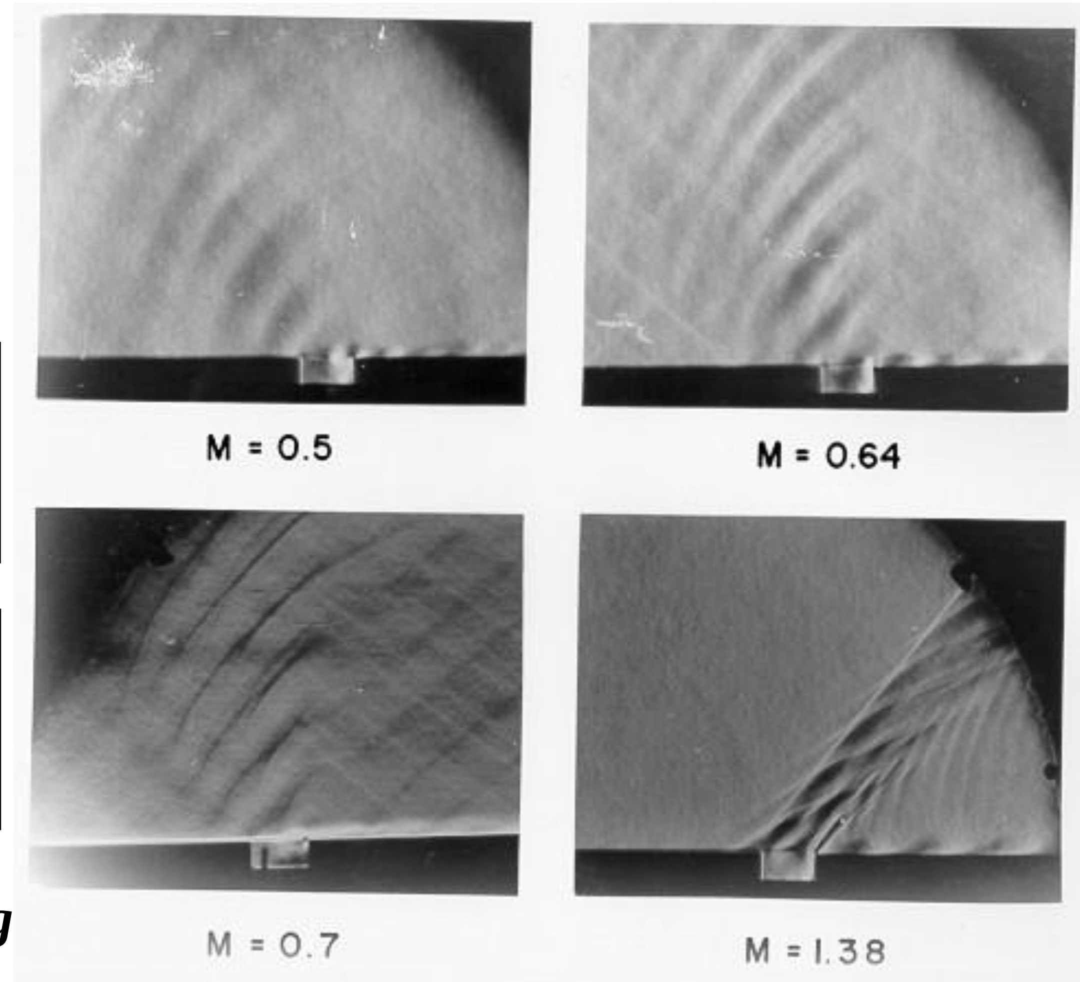
Cavity Flow Visualizations

Subsonic Flow



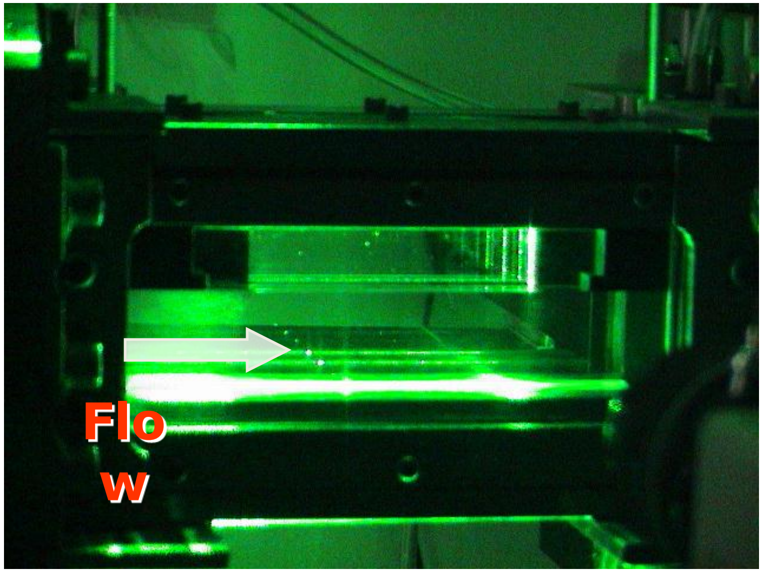
Phase-locked Schlieren Imag
***L/D* = 2, *M* = 0.5**
(Kegerise, et al., 1999)

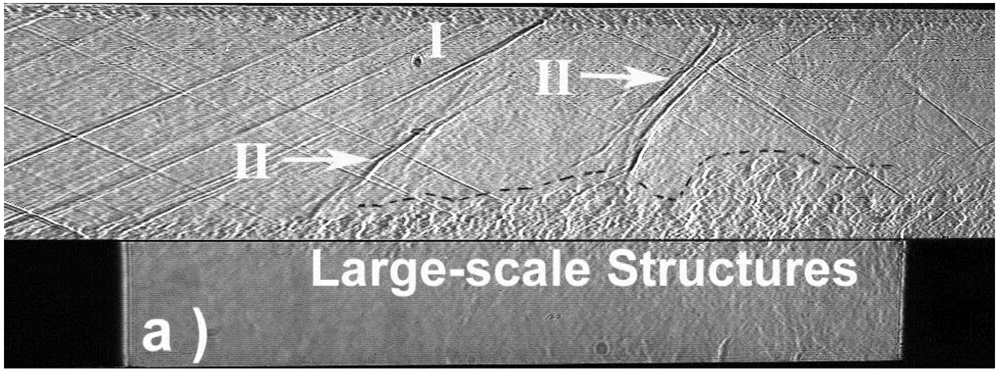
Subsonic to Transonic

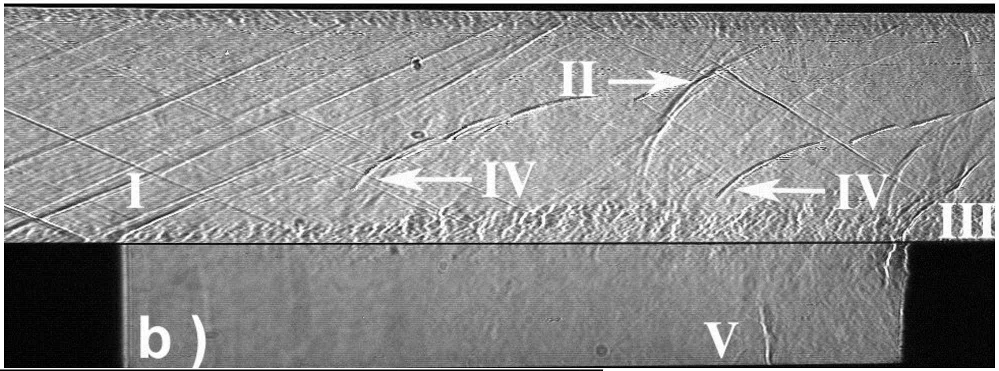


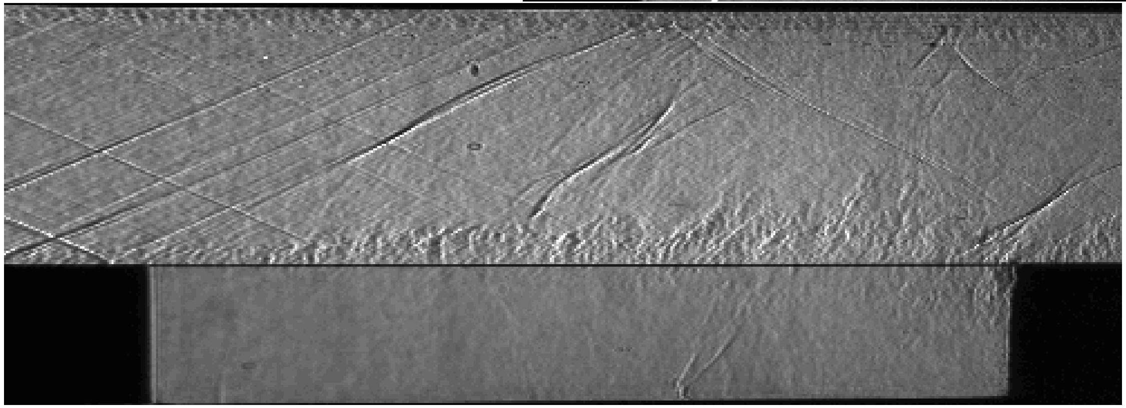
Krishnamurti, 1955

Supersonic Cavity Flow
M = 2





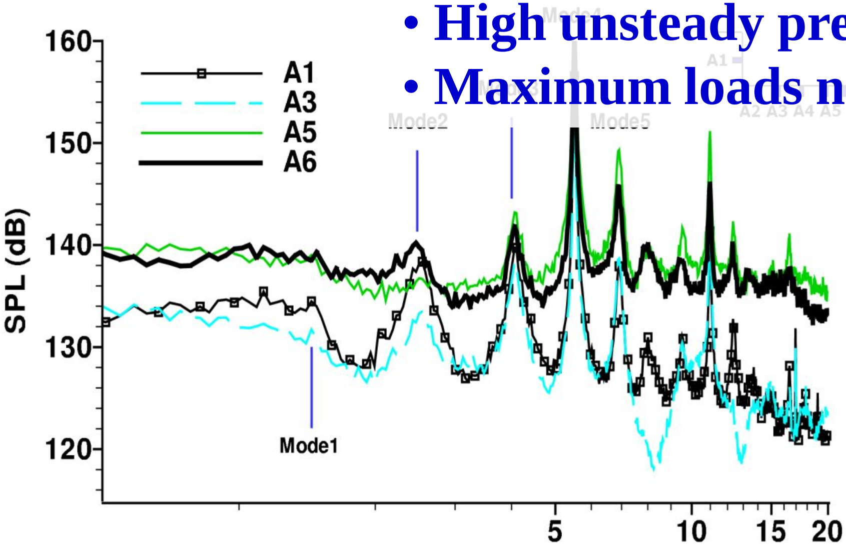


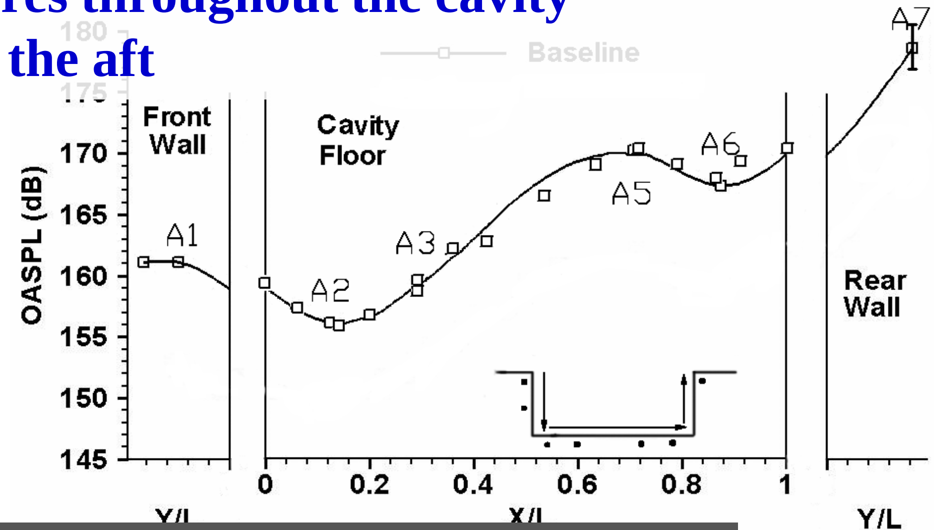


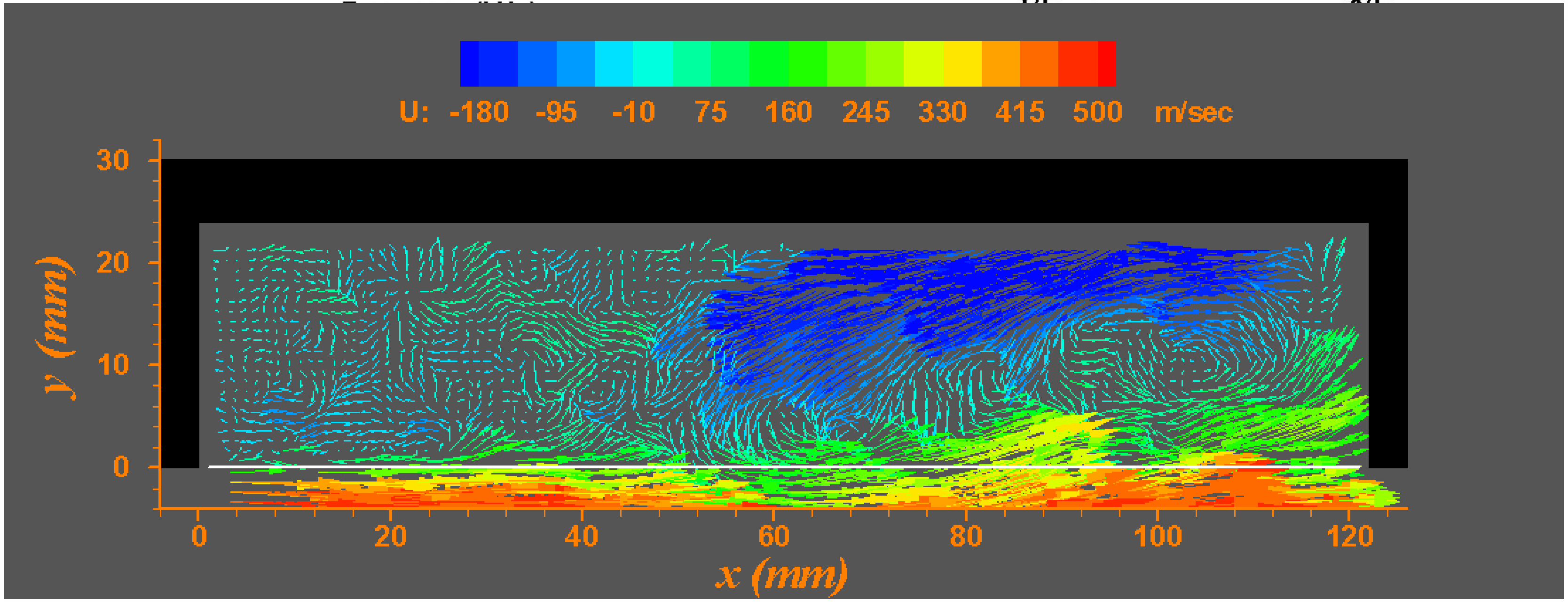
"Quantitative" Measurements

$M_\infty = 2$, $L/D = 5$

- **High unsteady pressures throughout the cavity**
- **Maximum loads near the aft**



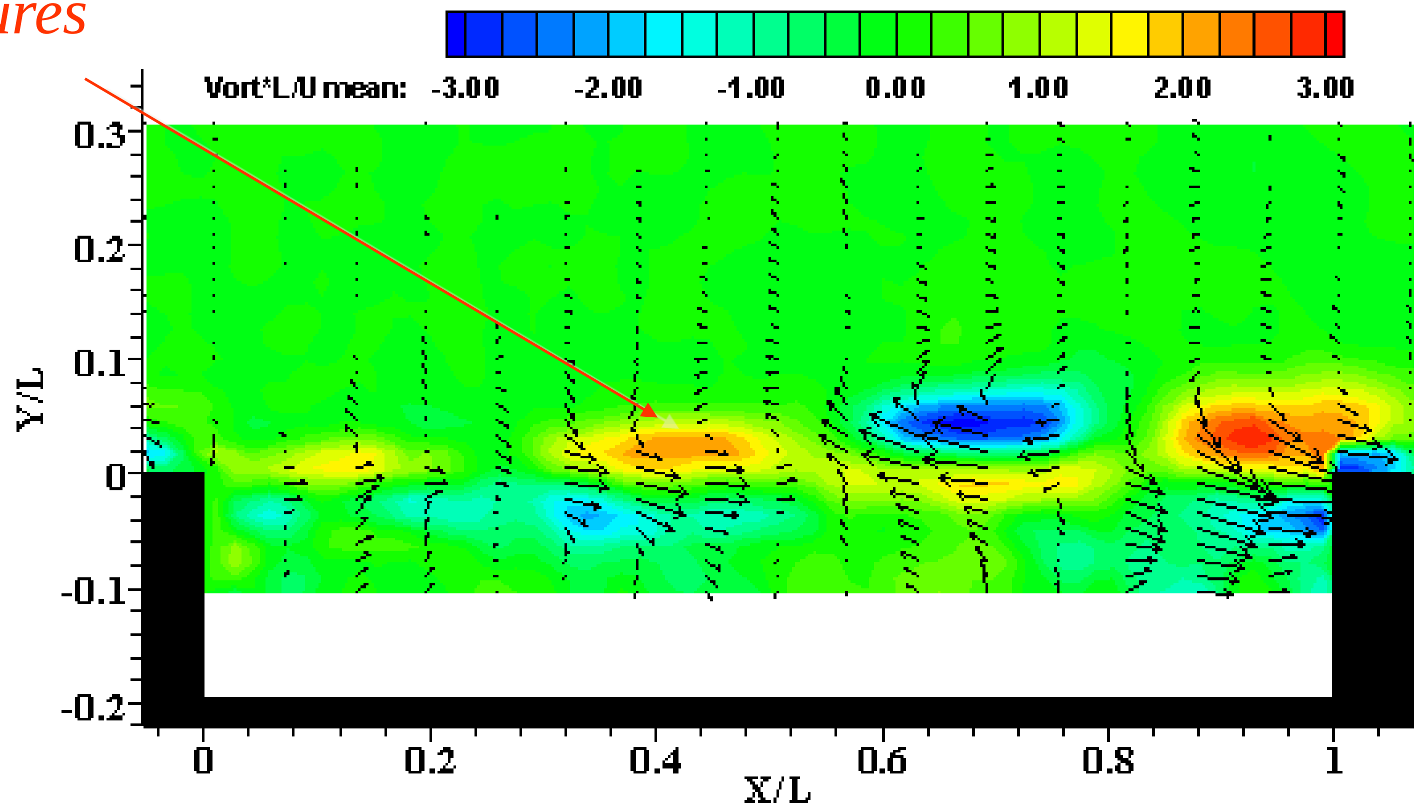




Velocity Field Phase-Conditioned

Large- scale structures

L/D ~ 5



$$< \omega > = \omega - \overline{\omega}$$

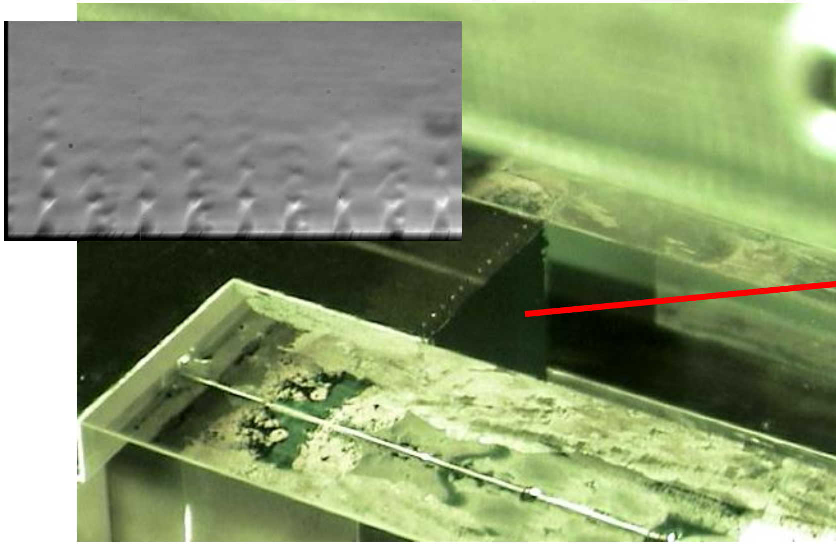
Periodic component

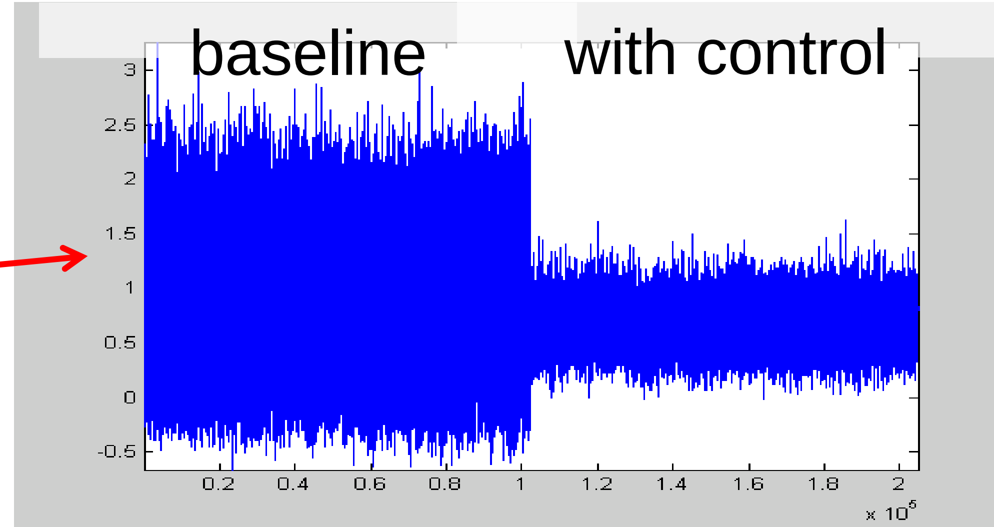
Phase-conditioned component

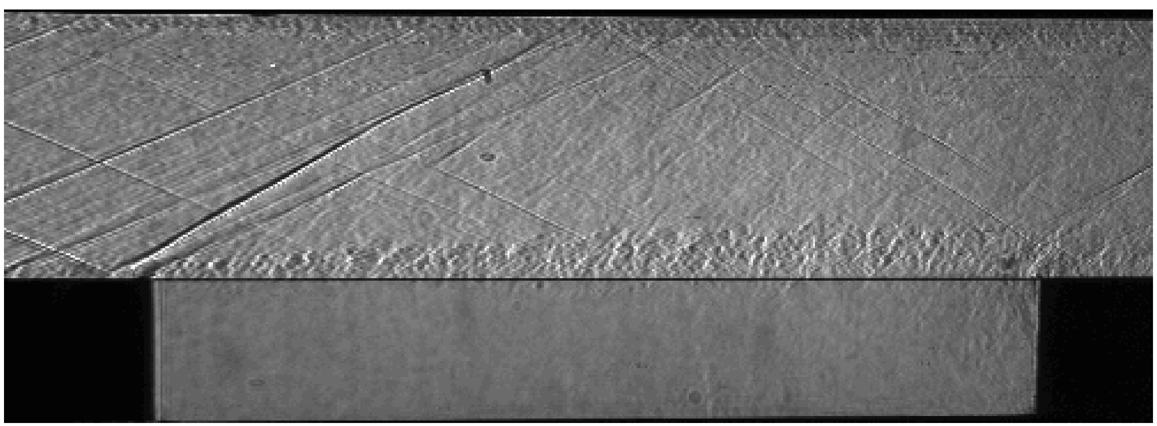
Ensemble averaged component

Mach 2 Cavity Flow

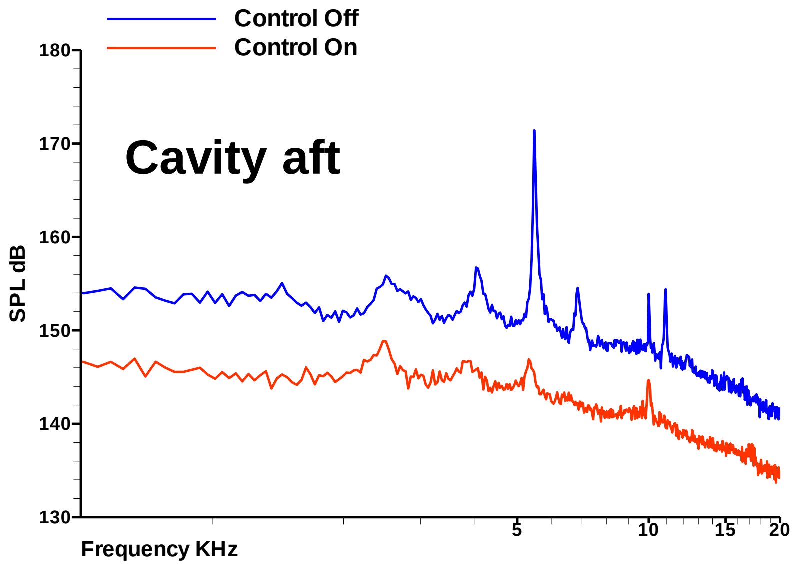
Effect of *Microjet Control*

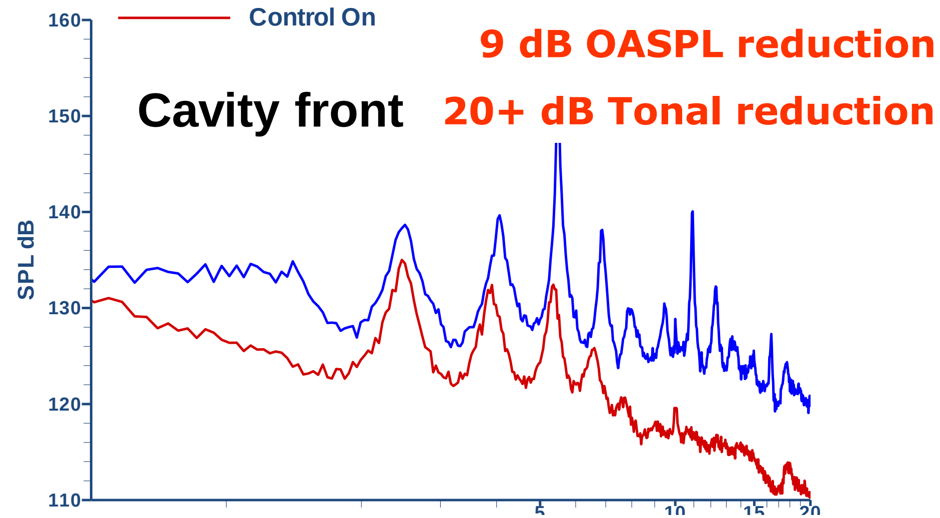


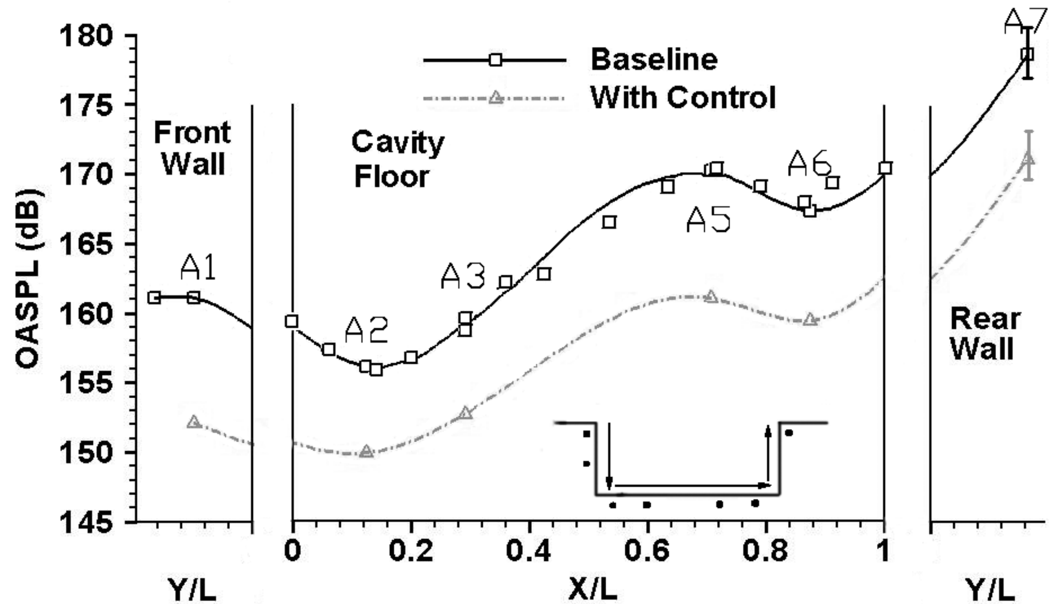




Effect of *Microjet Control*
Unsteady Pressure Spectra



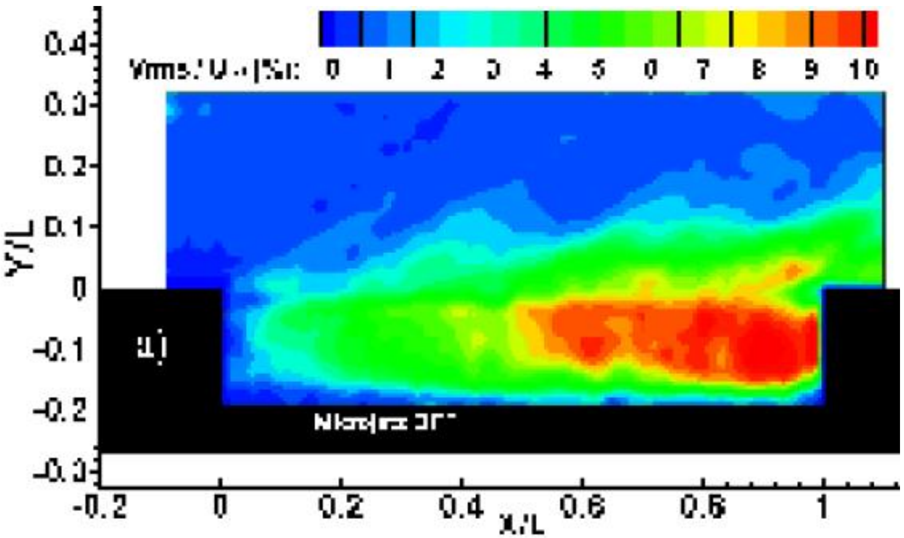




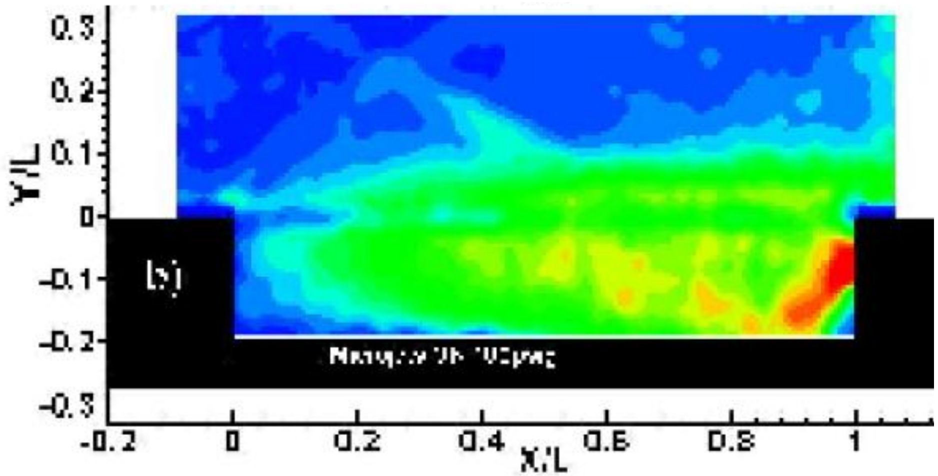
Zhuang, Alvi, Shih
AIAA J, 2006

Effect of *Microjet Control*
Unsteady Velocity, V_{rms}

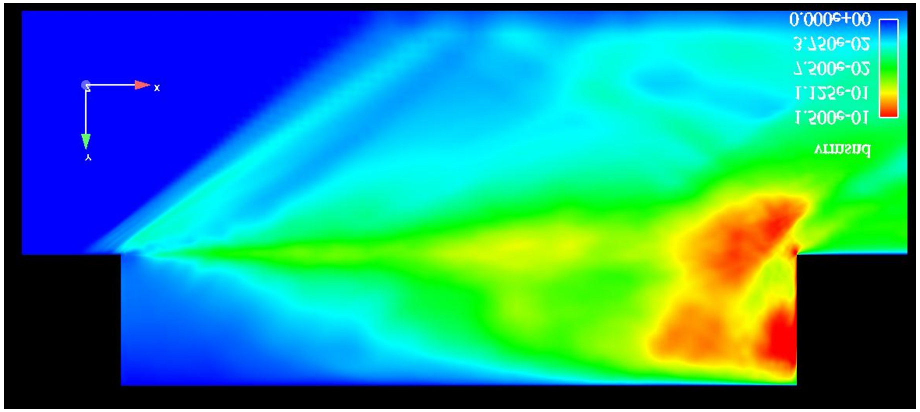
Ensemble-Averaged (using PIV)

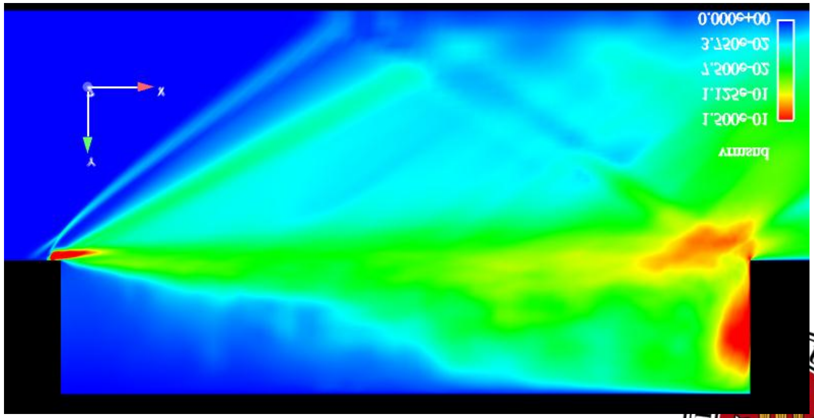


Baseline



Microjet Control

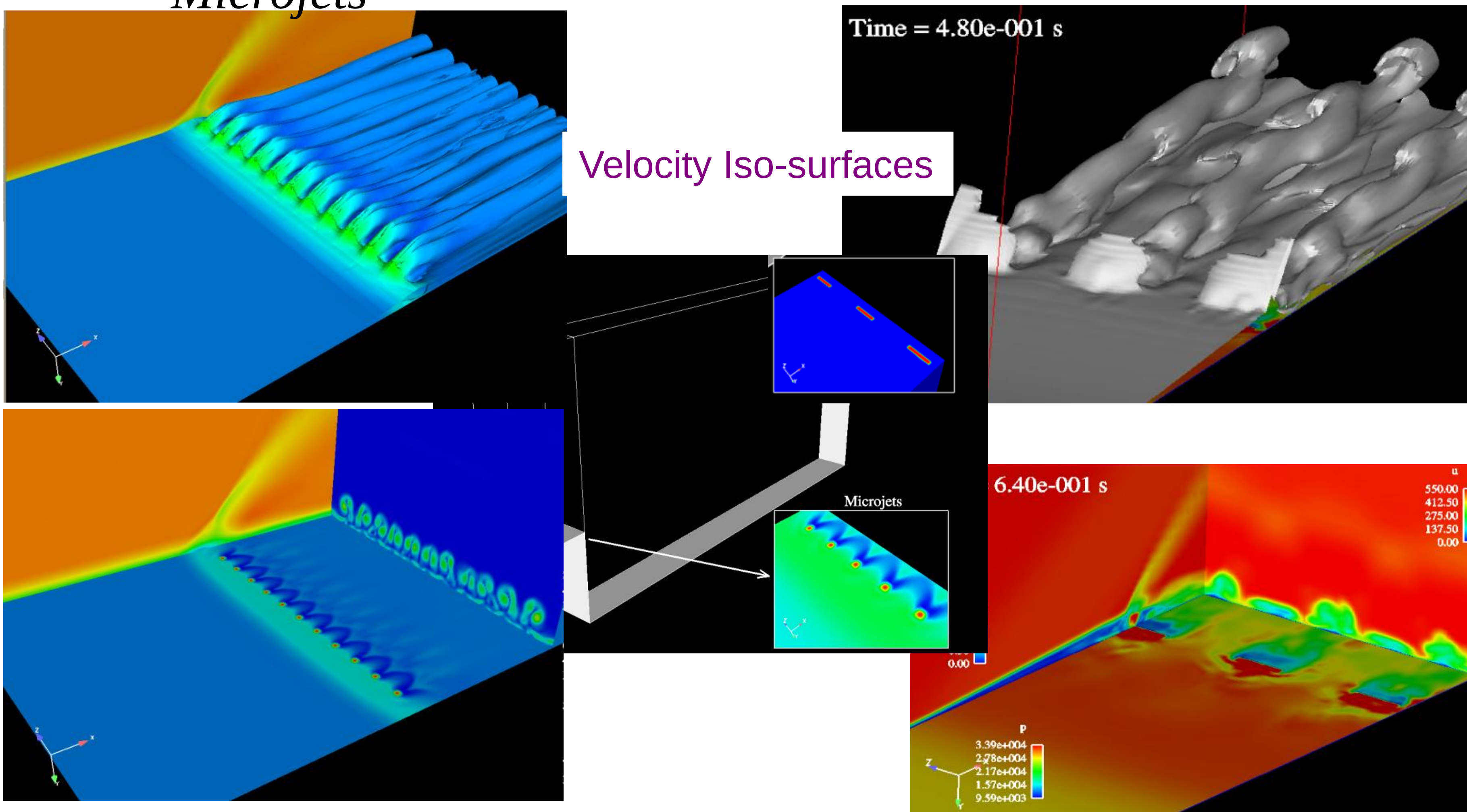




LES (courtesy CRAFT Tech)

Microjets & Slot Jets Simulations*

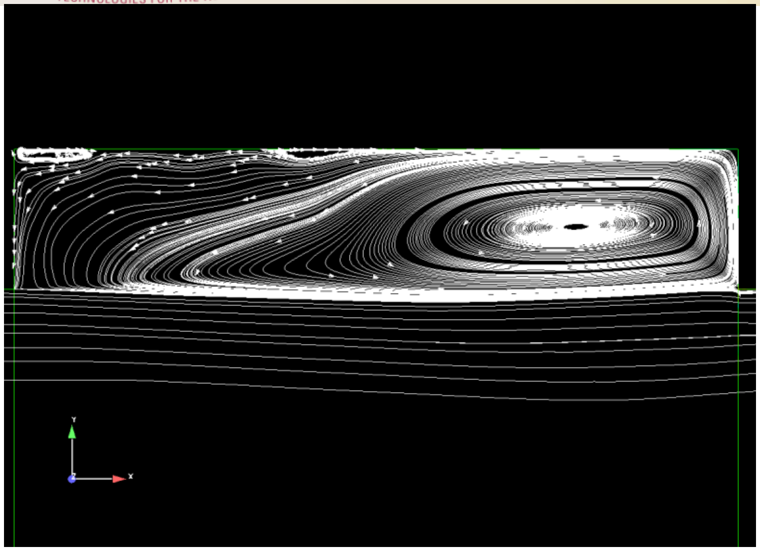
Microjets



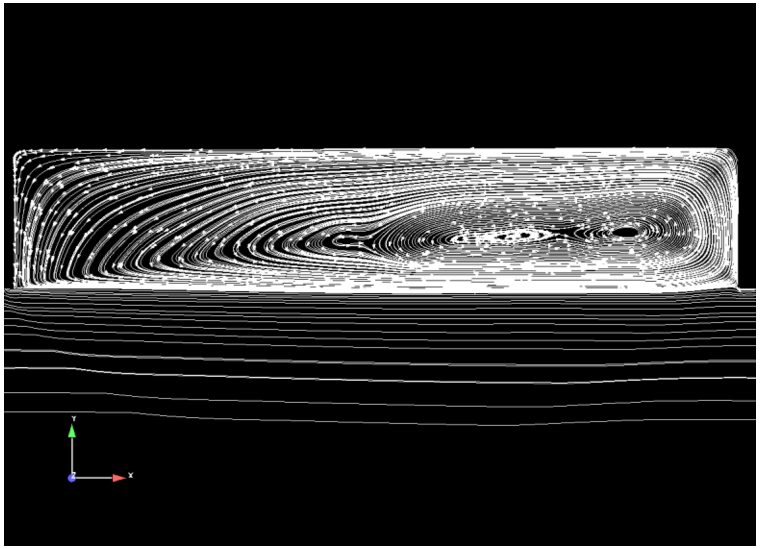
Slotjets

* S. Arunajatesan et al.
AIAA Jrnl, 2009

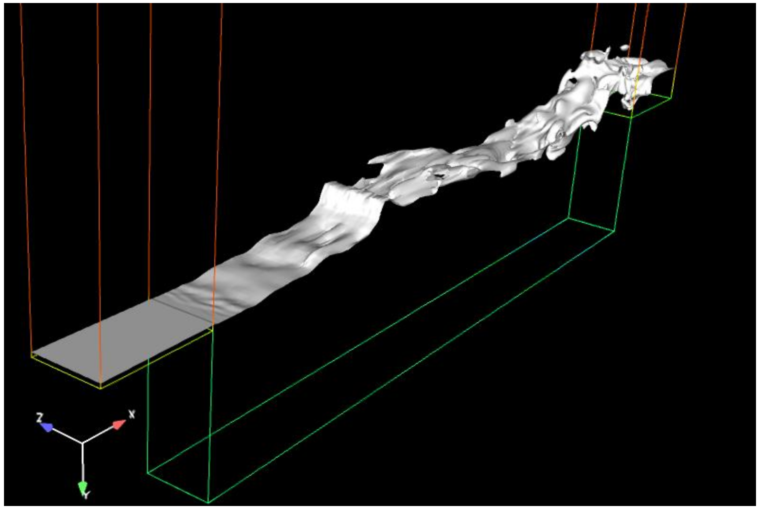
Effect of Microjets : Simulations*

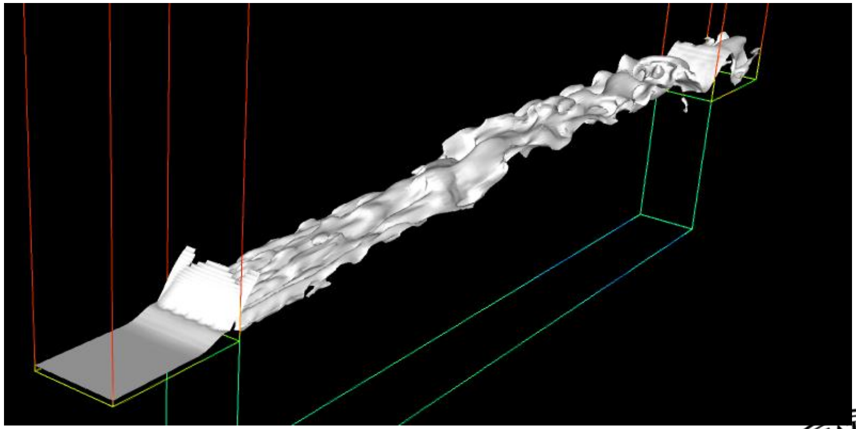


Baseline



Microjet Control

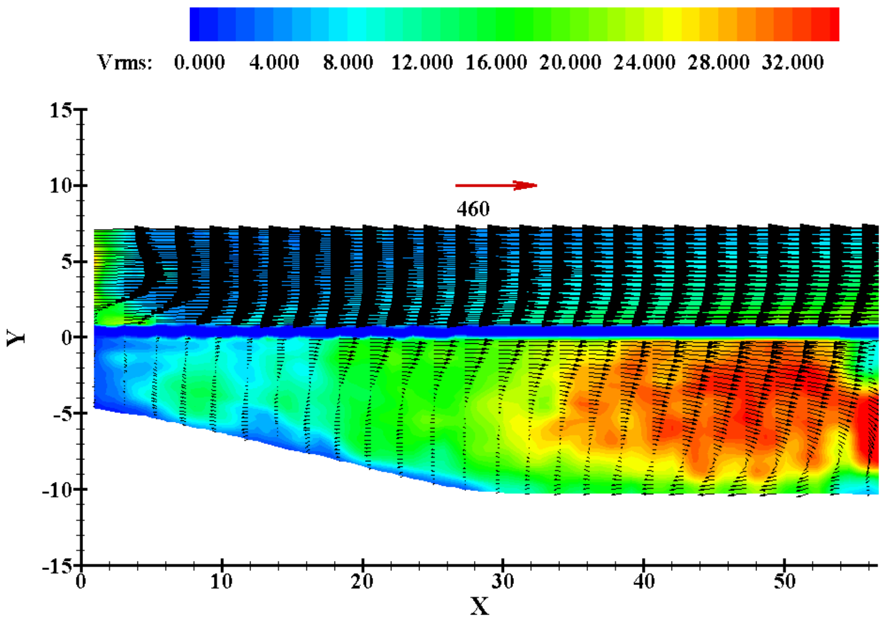


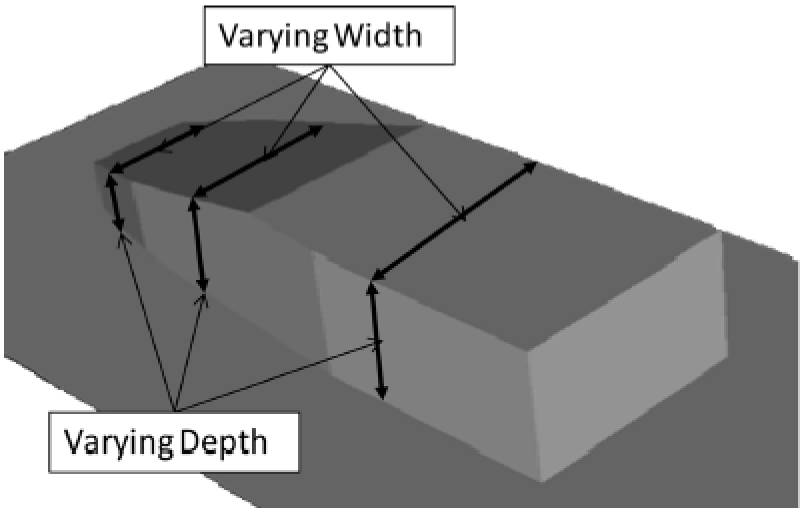


Velocity Iso-surfaces

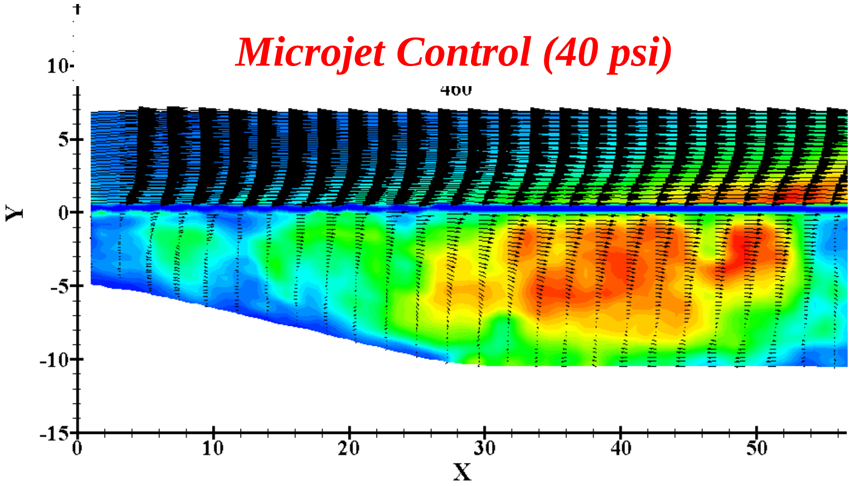
*Courtesy CRAFT Tech

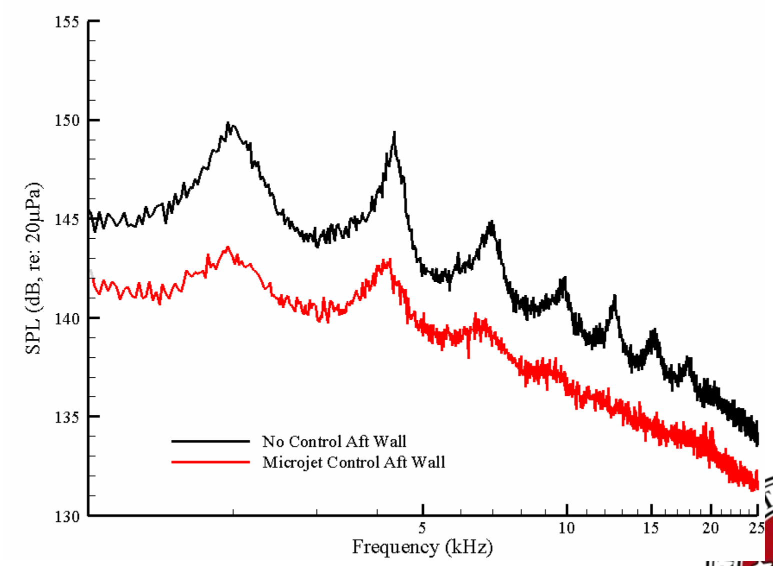
Complex Cavity Flows





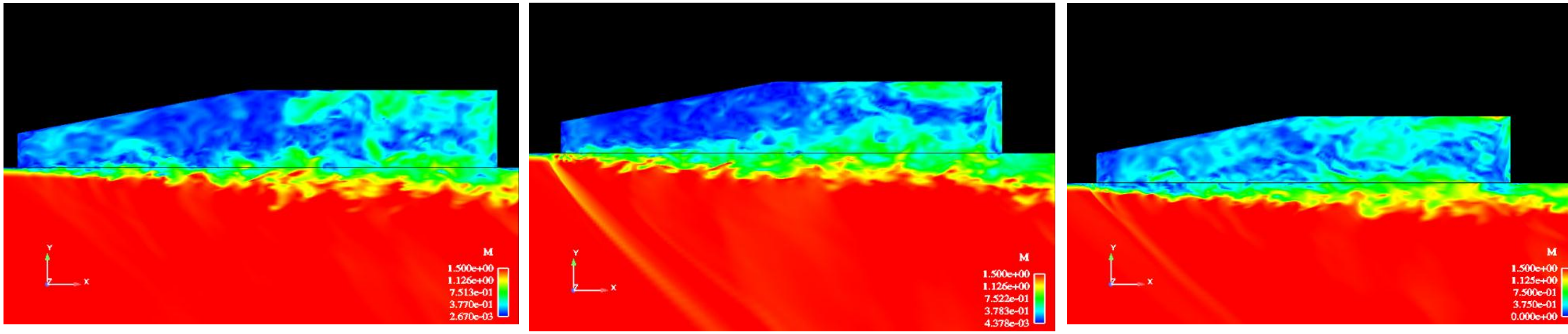
Microjet Control (40 psi)





* S. Arunajatesan et al., *AIAA Jrnl*, 2009

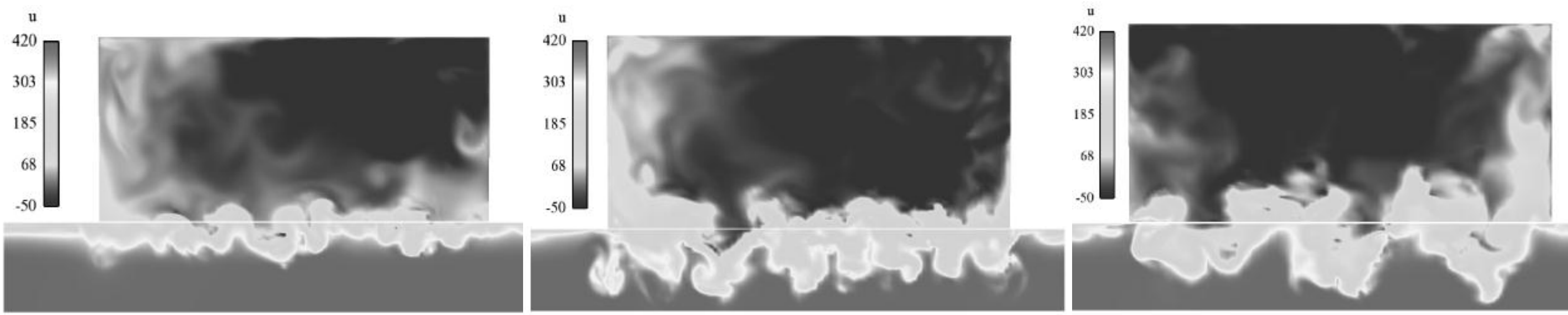
Unsteady Flow Field - Simulations



Baseline

Microjets

Slotjets

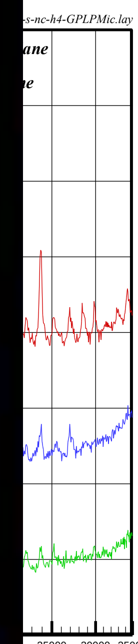


Simulations provide insight into the 3-D nature of the flow

* S. Arunajatesan et al., *AIAA Jrnl*, 2009

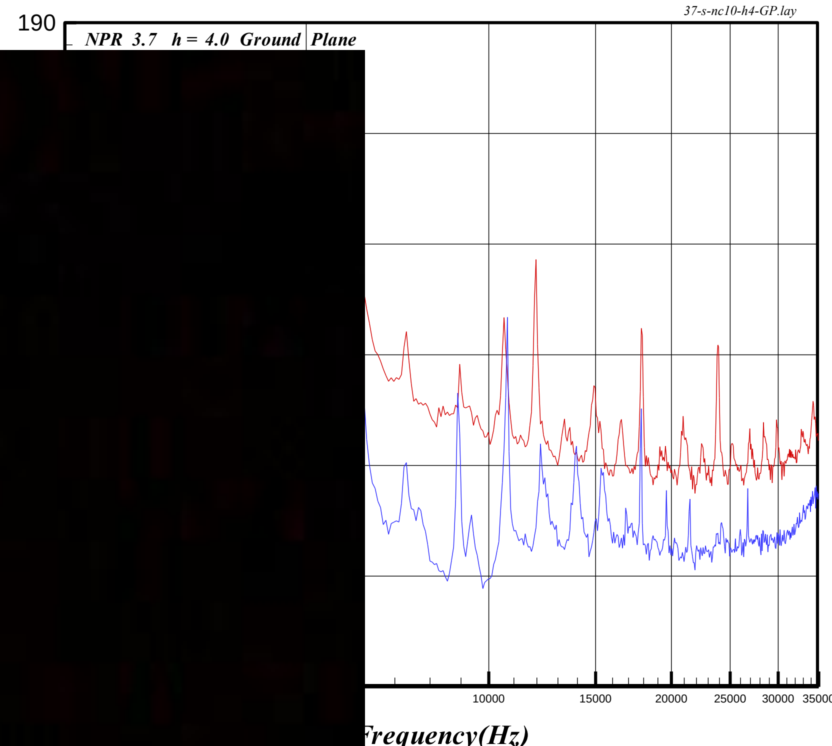
Supersonic Impinging Jets

ra



I

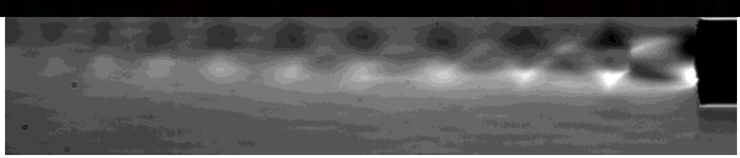
Control of Impinging Jets Using *Steady* Microjets



[redacted] and Noise

[redacted] by 4-12+ dB

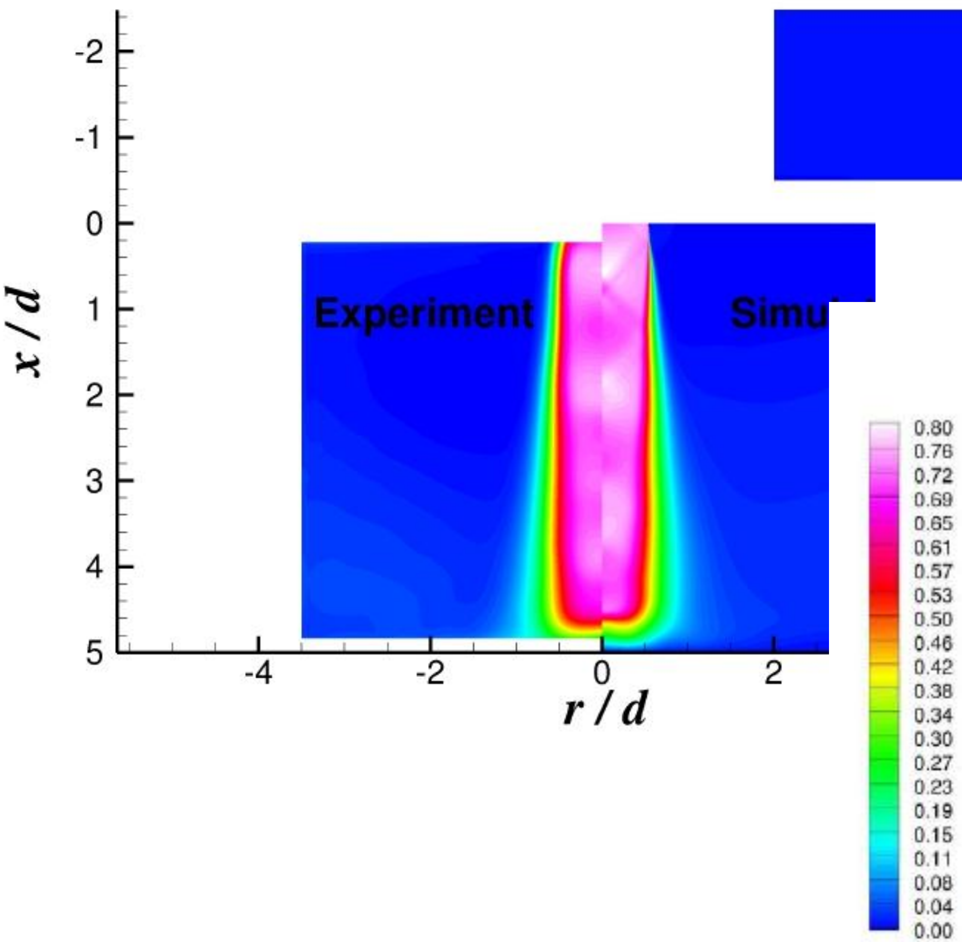
To date, control demonstrated for cold and hot impinging Jets



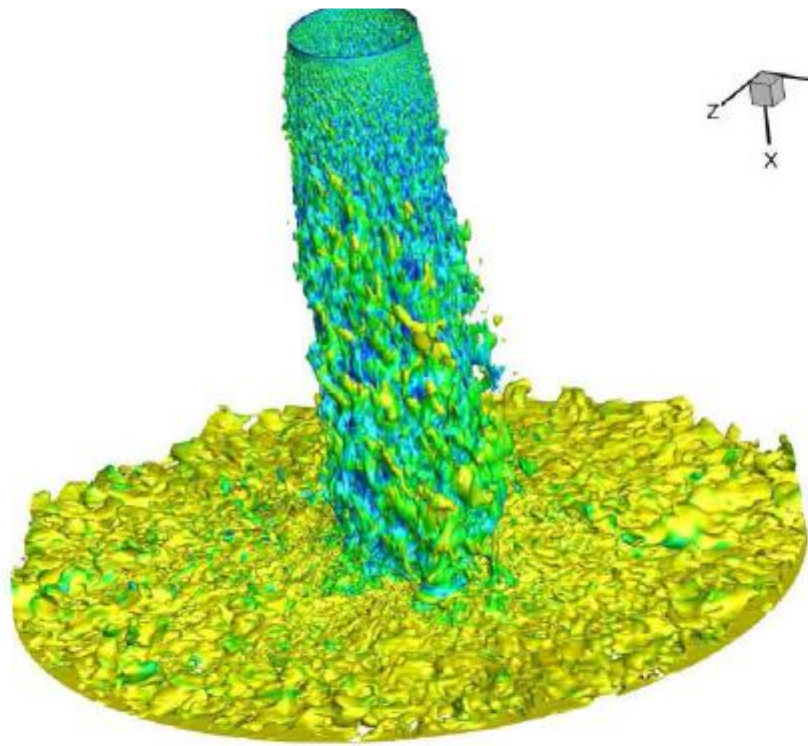
Alvi et al. - *AIAA J*, 2003, 2006; *JFM:*2008; Kumar et al. *AIAA J* 2009

*Experiments & Simulations**

Heated Mach 1.5 Jet
Mean Axial Velocity (U/U_j)

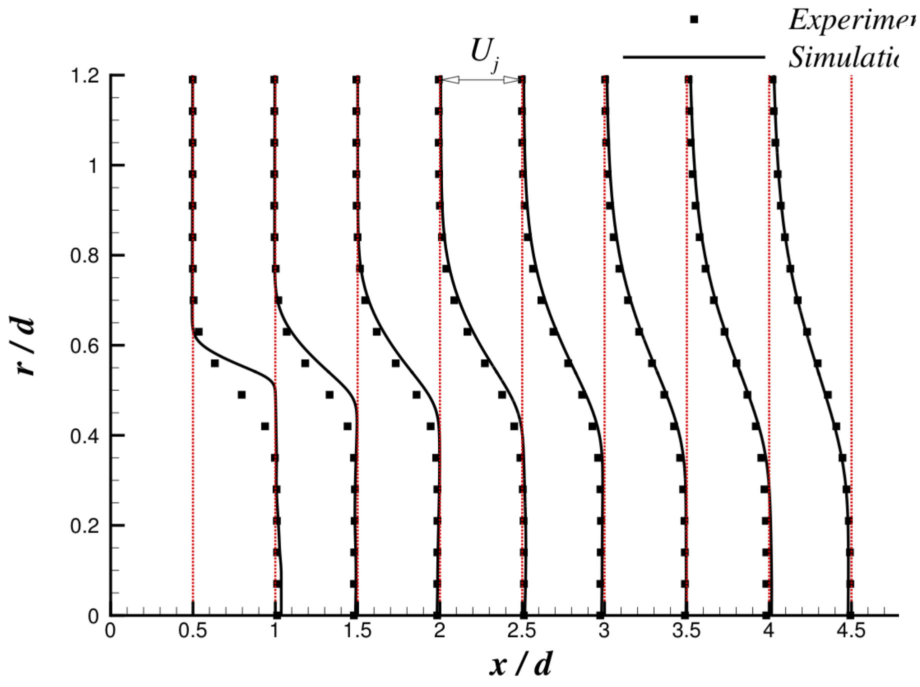


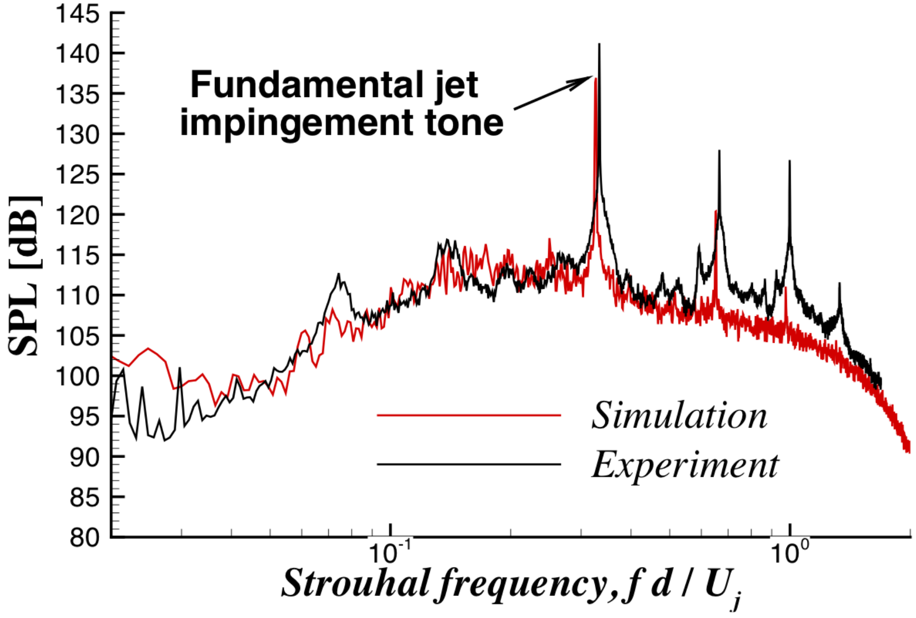
Iso-thermal Jet
Total velocity magnitude iso-surfaces



*Uzun, A. Hussaini, M. Y. et al, 2010

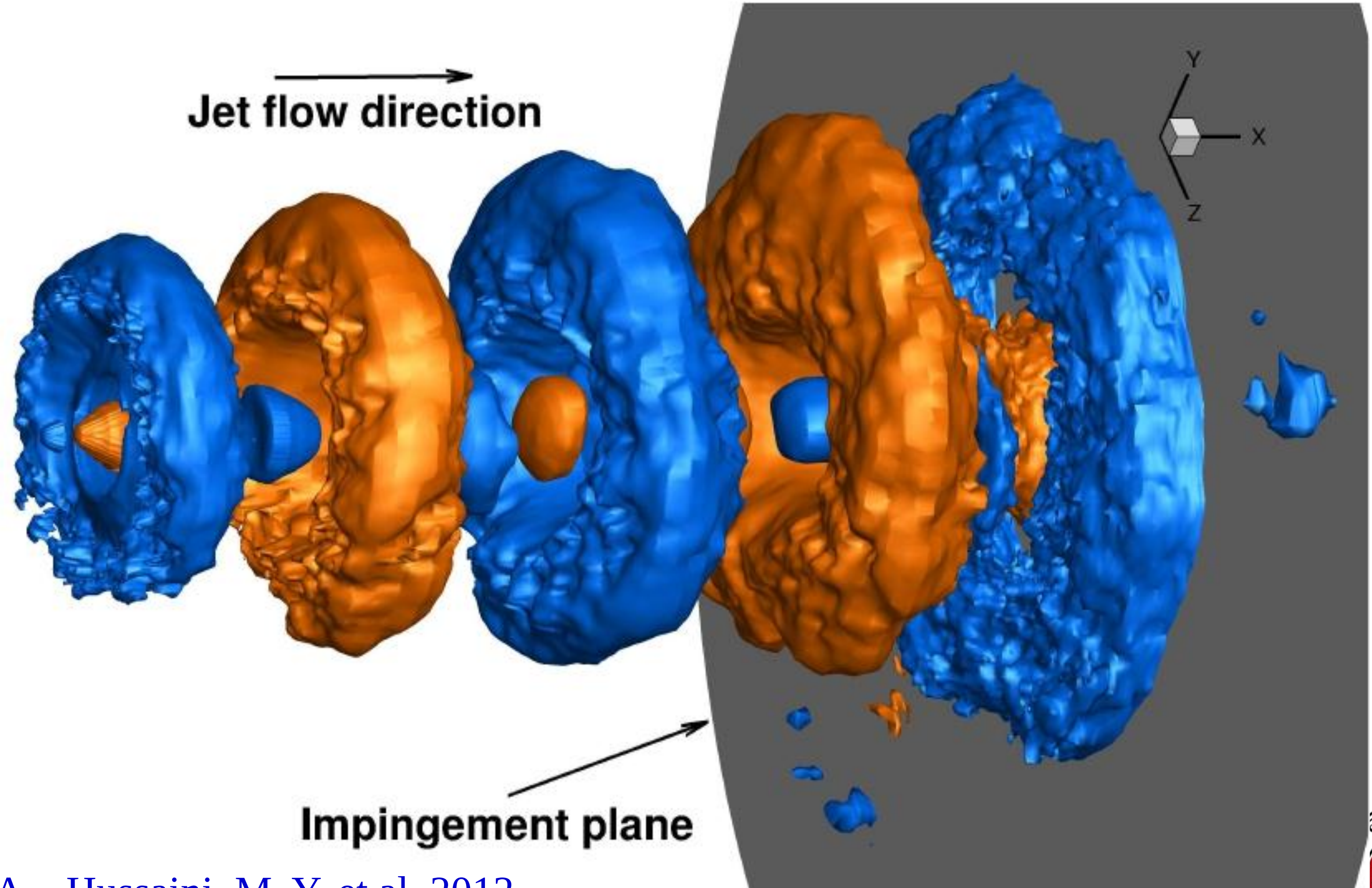
Heated Mach 1.5 Jet





Identification of Coherent Structures

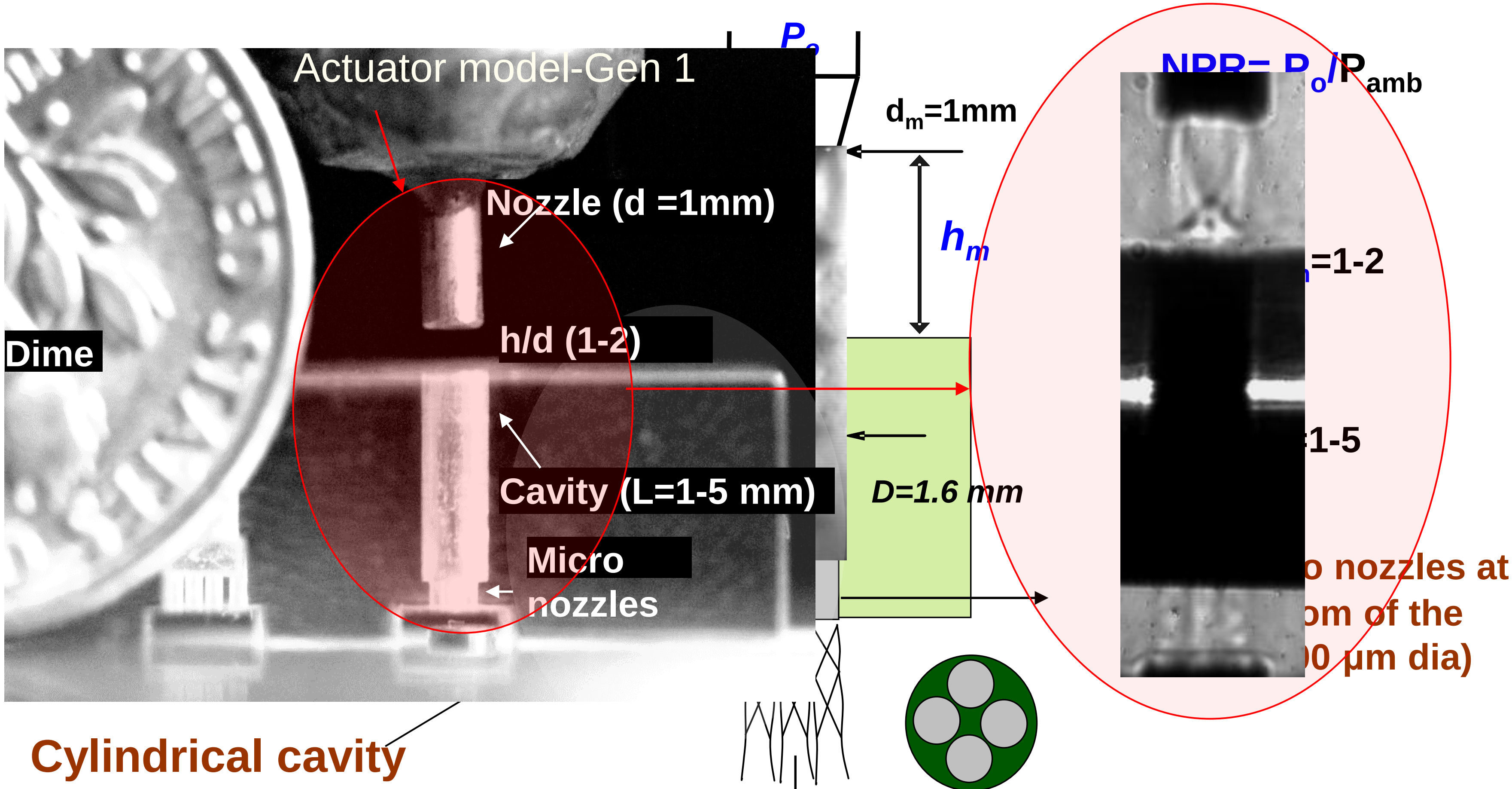
Pressure Iso-Surfaces Associated with Vortex Ring Structures at the Most Amplified Frequency using DMD



Uzun, A., Hussaini, M. Y. et al, 2012

Pulsed (Micro)Actuators

Resonance Enhanced Microjet (REM) Actuator Schematic



Unsteady Microjets

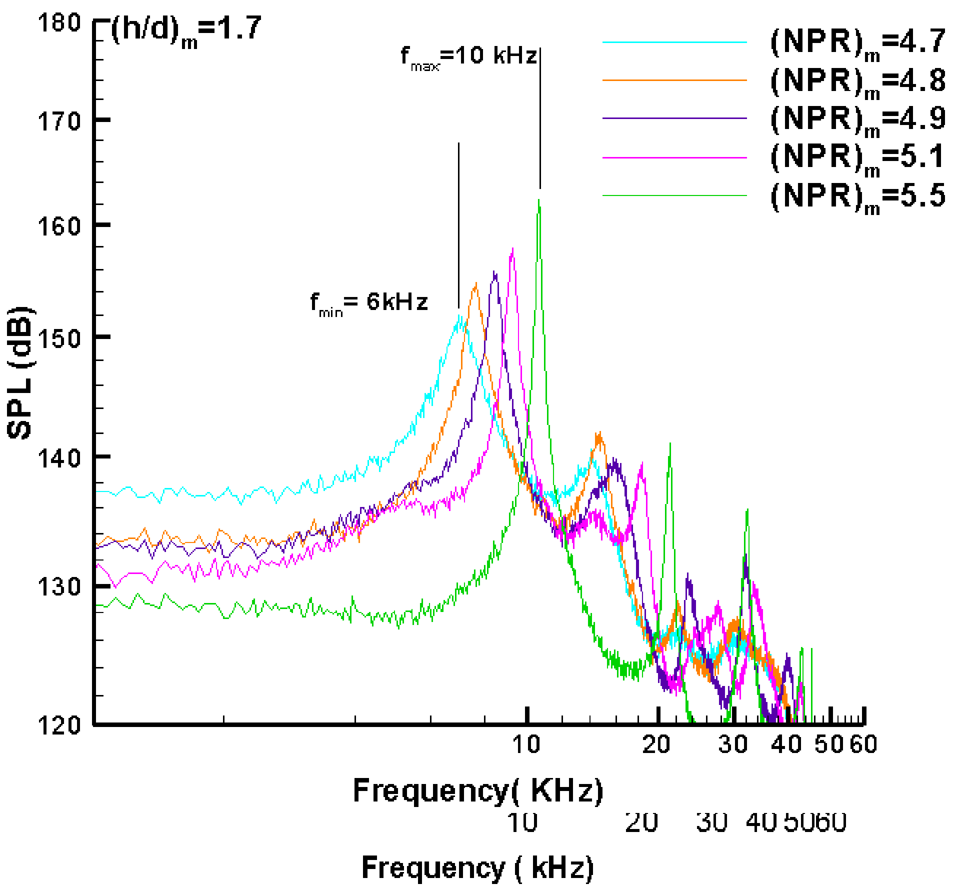
H=h

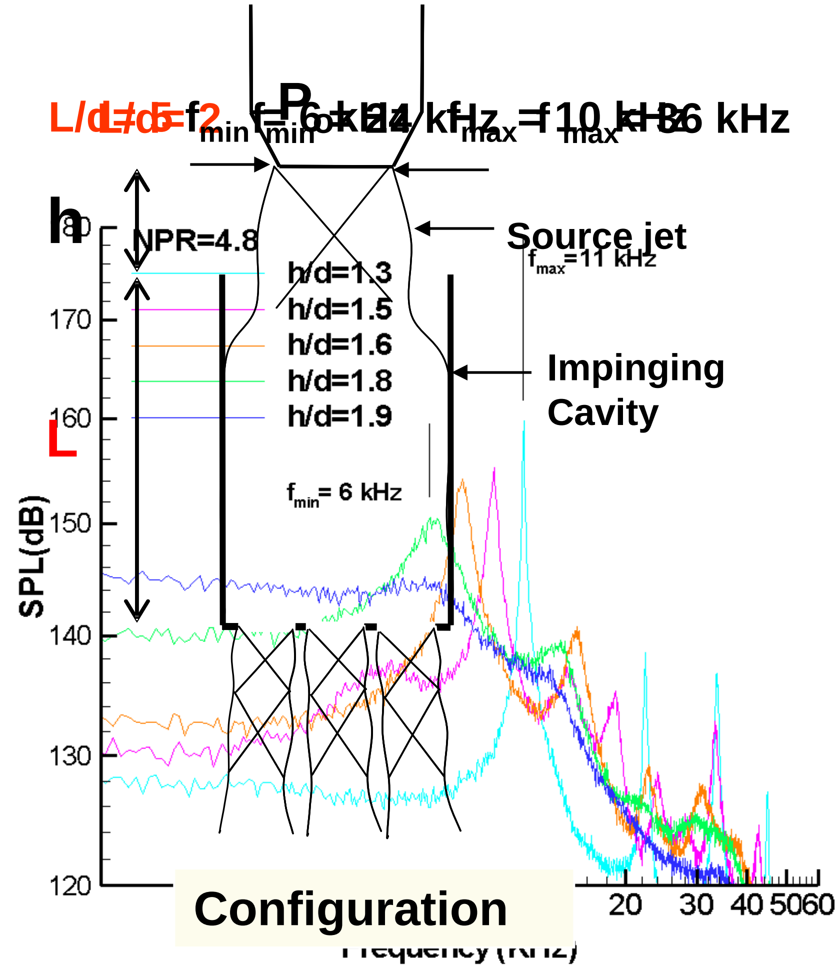
$H=h_m+L$

Solomon et al. (AIAA J 2010, 2012)

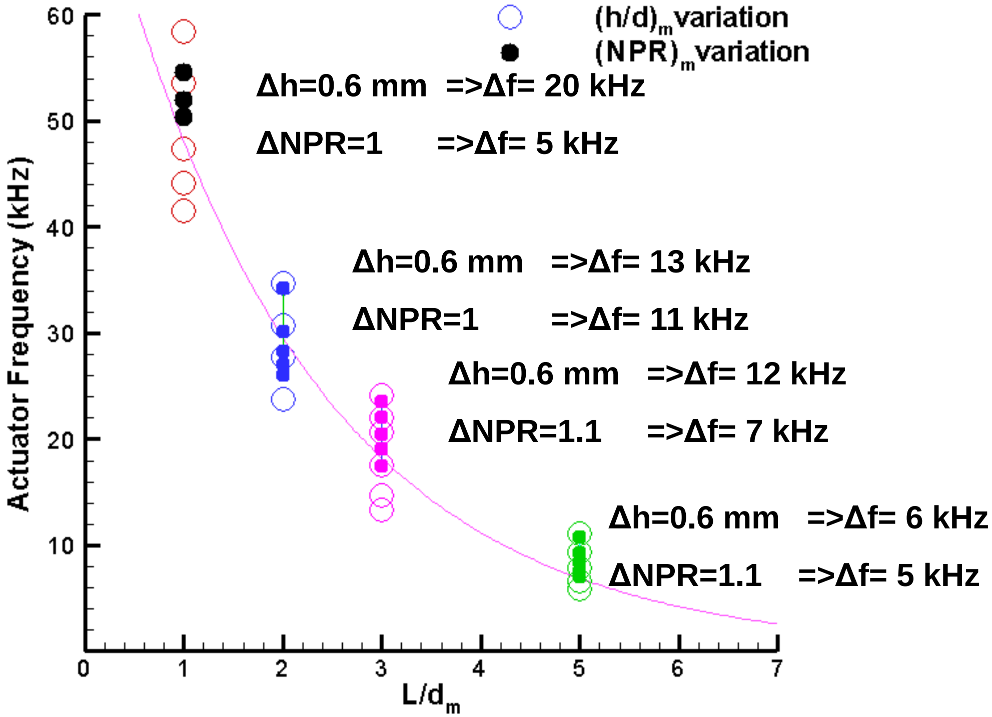
Actuator Frequency
Effect of L/d & NPR

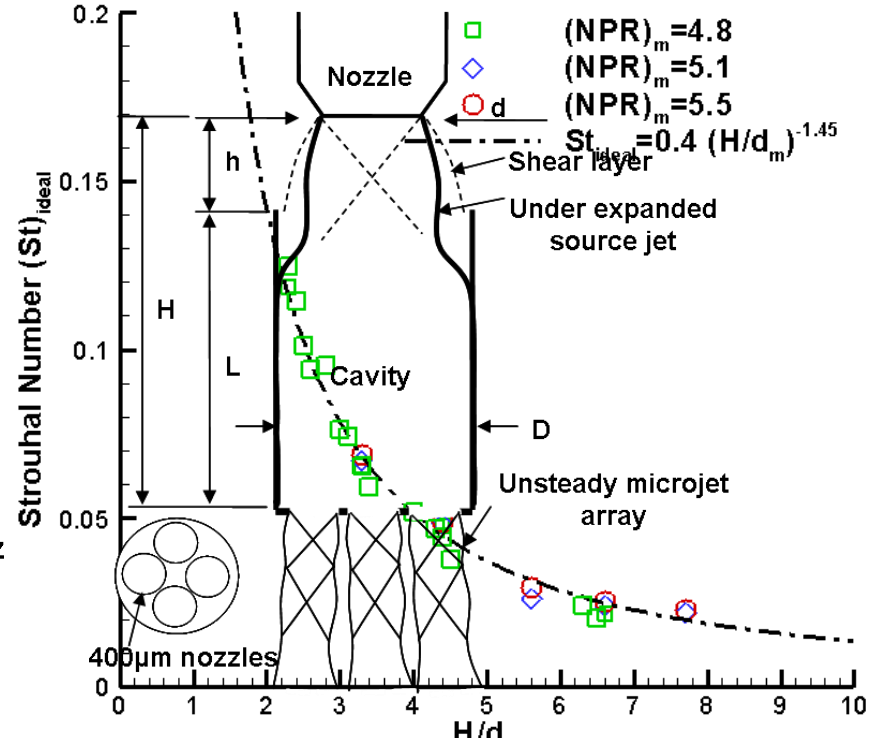
Δ NPR ~ 1 changes the frequency from 6-10 kHz





Actuator Performance Summary





$$St_{ideal} = fd_m / U_{ideal}$$

Cylindrical geometry

$$St_{ideal} = 0.4(H/d_m)^{-1.45}$$

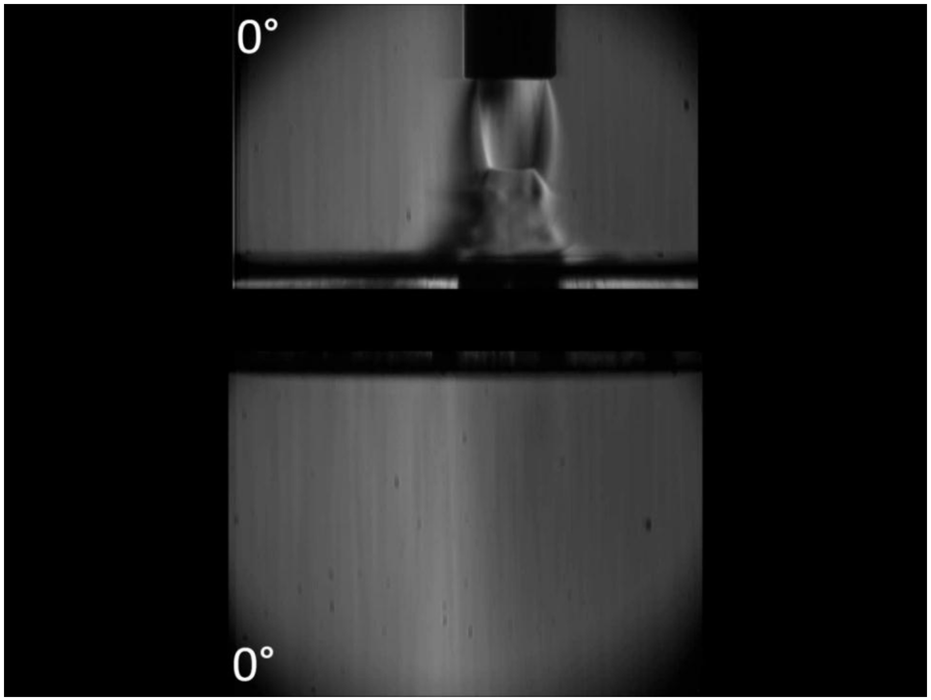
d_m : diameter of source jet

U_{ideal} : ideally expanded velocity corresponds to the source jet NPR

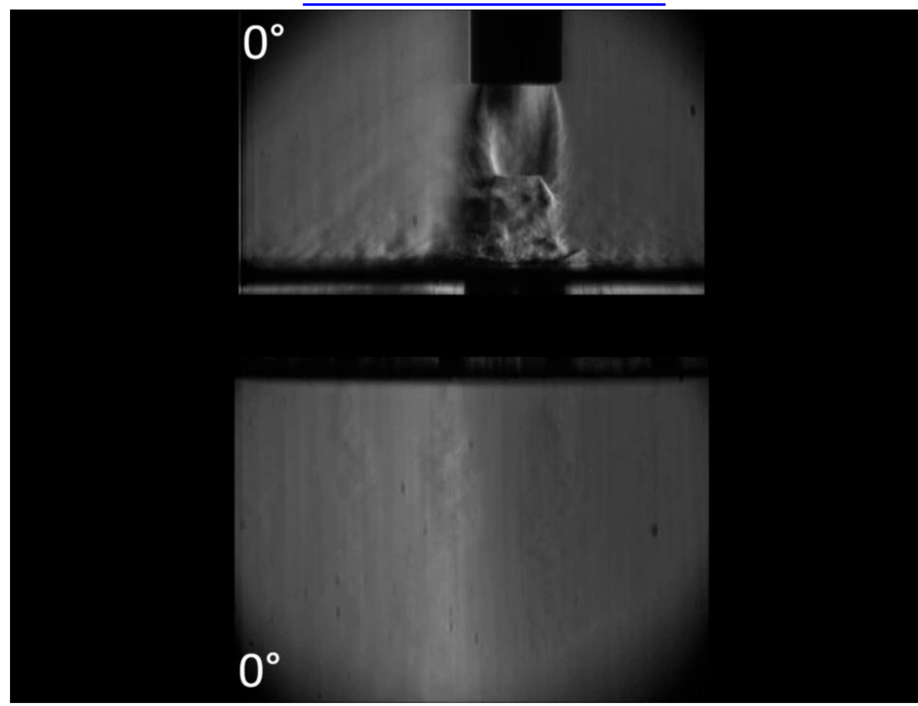
$$f = \frac{0.4}{d}\left(\frac{2}{\gamma-1}\left((NPR)^{\frac{\gamma-1}{\gamma}}-1\right)\right)^{1/2}\sqrt{\gamma RT_o (NPR)^{\frac{1-\gamma}{\gamma}}}\,(H/d)^{-1.45}$$

Phase-Conditioned Images
REM: Pulsed Actuator

Phase Averaged



Instantaneous

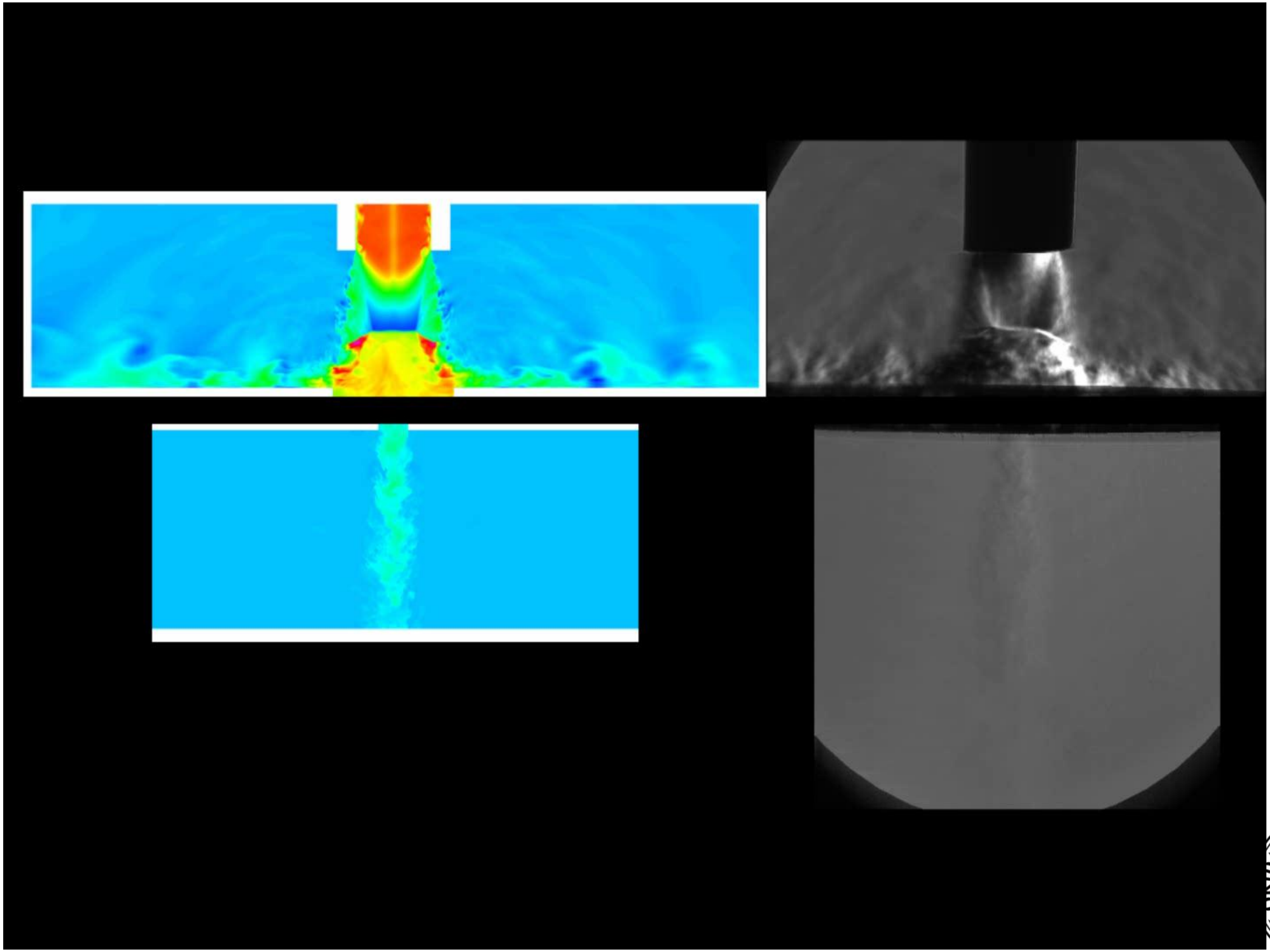


100 images averaged at each phase

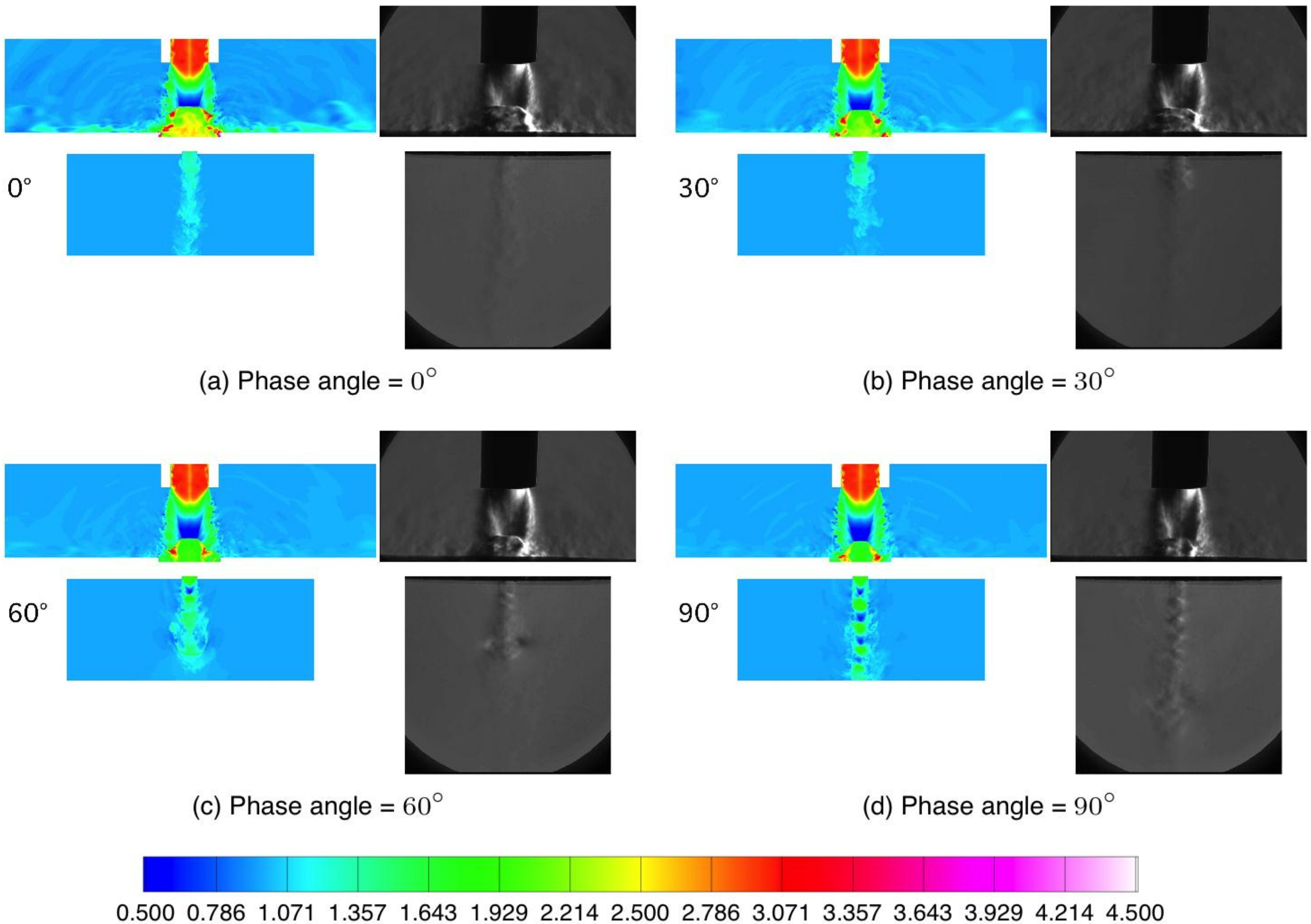
30° - 210° ‘filling’*
240° - 0° ‘spilling’*

Foster, Alvi et al.
AIAA 2011

REM Actuator
Simulations & Experiments



REM Actuator Simulations & Experiments



(a) Phase angle = 0°

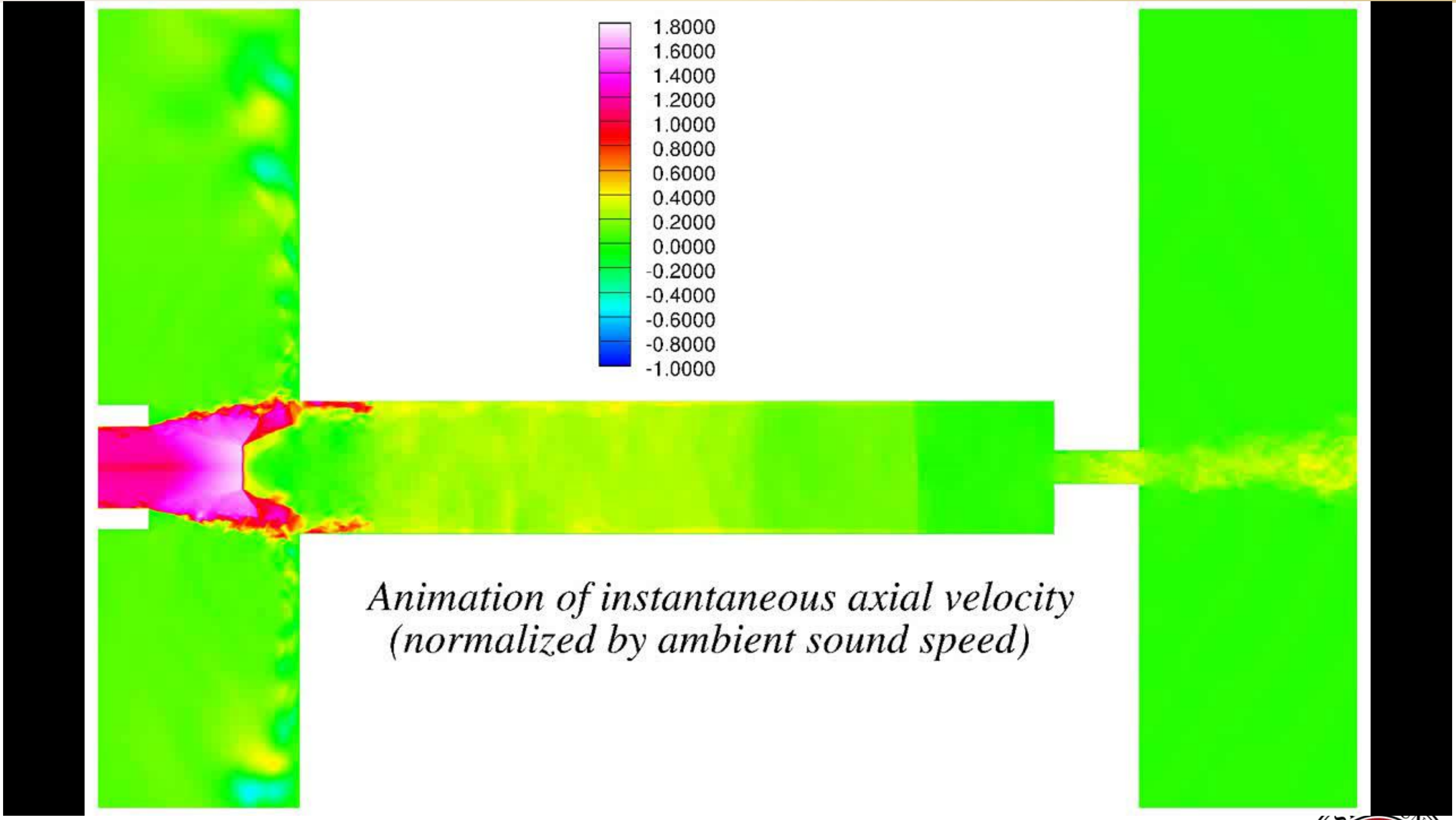
(b) Phase angle = 30°

(c) Phase angle = 60°

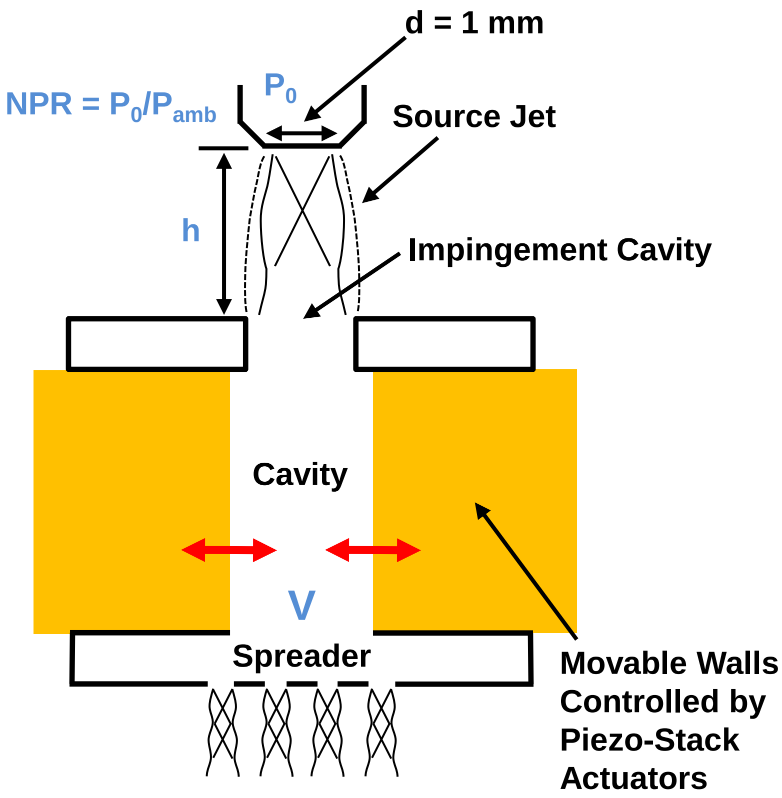
(d) Phase angle = 90°

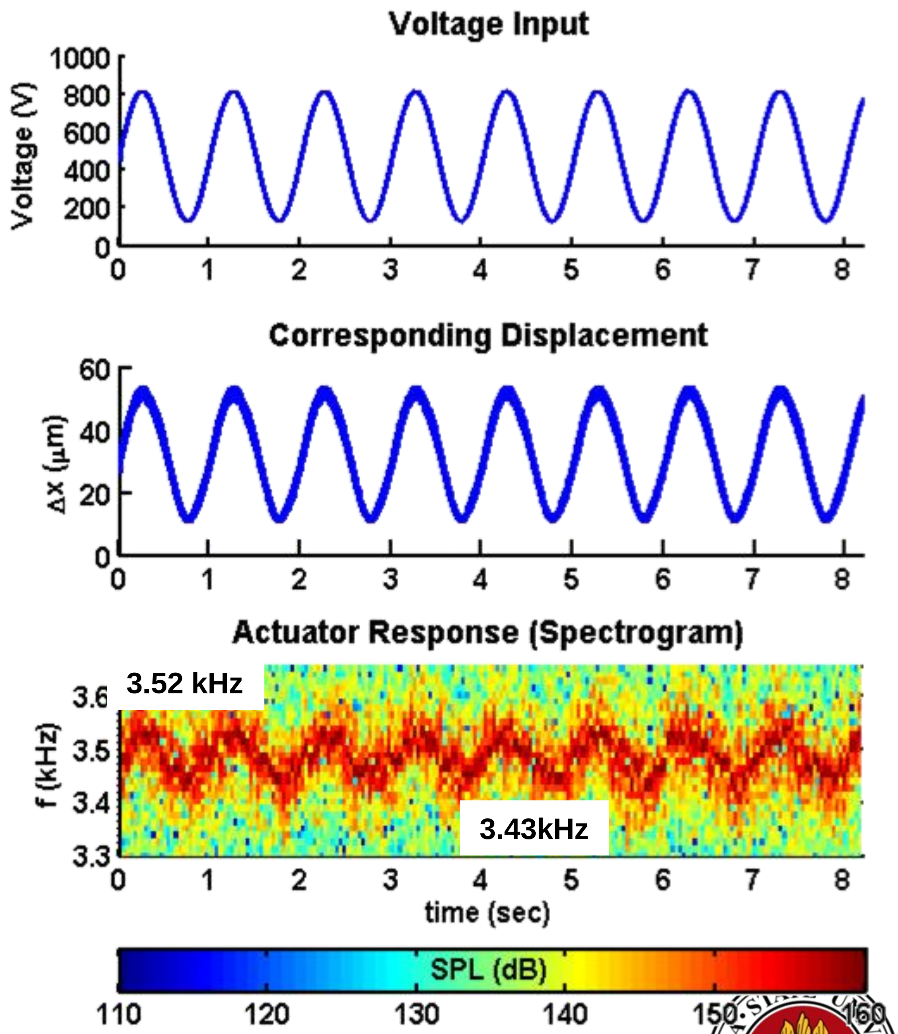
Color map represents normalized density, $\rho/\rho_{\mathbf{ambient}}$

REM Actuator:Simulations



SmartREM Actuator

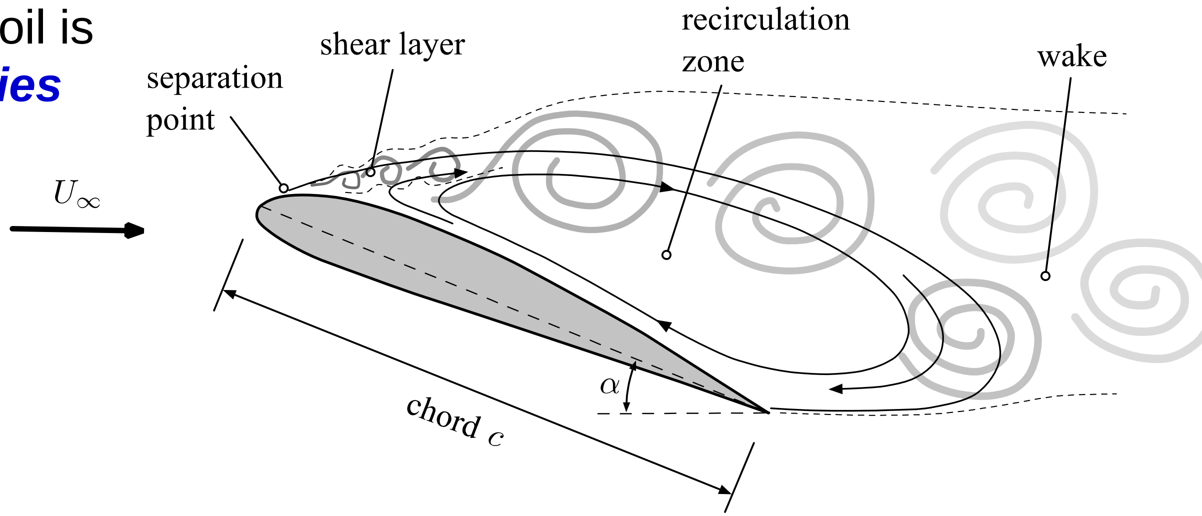




8/20/2012

Separated Flows (& Control of)*

- Separated flow past an airfoil is characterized by ***frequencies associated with the***
  - wake
  - shear layer (SL)
  - separation bubble (SB)
  - actuation (if applied)



- "Lock-on" describes when these components are the same or are harmonics
  - Harmonics could be evidence of non-linear interactions

- ***Effectiveness of a control strategy may be related to the presence of lock-on*** [Kotapati et al. 2001]

*** Courtesy: Cattafesta, Mittal & Rowley**

Parting Thoughts

Experiments

- Increasingly sophisticated, providing high-fidelity data
    - 2-D/Stereo/Tomo-PIV /(Plenoptic)

      => 2 component/3component/volumetric measurements
    - High-speed/time resolved and Phase conditioned
    - Synchronous: P, $\boldsymbol{V}$, ρ…
- They provide significant physical insight into flow physics.
- **Difficult and expensive to run; limited conditions**

Actuators

- A wider array of actuators with a range of control authority and bandwidth
    - Plasma Based (LAFPA, SJA, DBD); ZNMF (Synthtetic Jets); COMPAct, REM and more
    - **REM:** Simple, robust, scale-adapt/able, appropriate complexity & capability
        - *Smart* REM: 'on-the-fly' frequency control BUT more complex
- **Still unclear: "which actuator and under what conditions"**

Parting Thoughts

Simulations

- Increasingly sophisticated, provide high-fidelity data for increasingly complex flows
  - More rigorous validation using better experimental data
  - Good to excellent agreement (for some cases?)
- Provide physical insight into flow physics, provide properties not easily measured.
- **Difficult and expensive to run; limited conditions**
- **Rarely go beyond experimental conditions?**

As we Progress

- Simulations+Theory used to better explore flow dynamics;l arger range of conditions
- Provide guidance for active-adaptive control (that is *realistic/feasible*):
  - ***Temporal and Spatial*** requirements (freq., wavelength) for actuation and
  - ***Location*** *(where to best place them)*
  - ***Type*** of actuation: momentum, body force, thermal…
- Provide guidance for (sparse/minimal, practical) sensing requirements
- Help develop, simpler/low-order/…, *practical* models for closed-loop control
- **Plan experiments and computations together <u>from the start</u>**
  - We need to improve our communication skills