



Active flow control strategies using surface pressure measurements

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Motivation



Objectives of the present study



Results



Test case validation



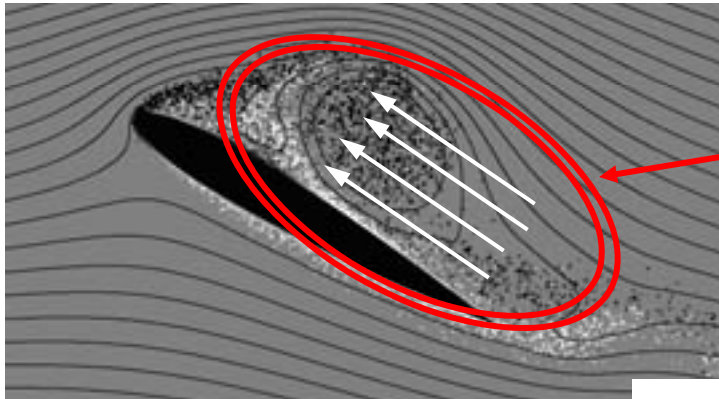
Questions

Motivation – Separation Control and Flow Management

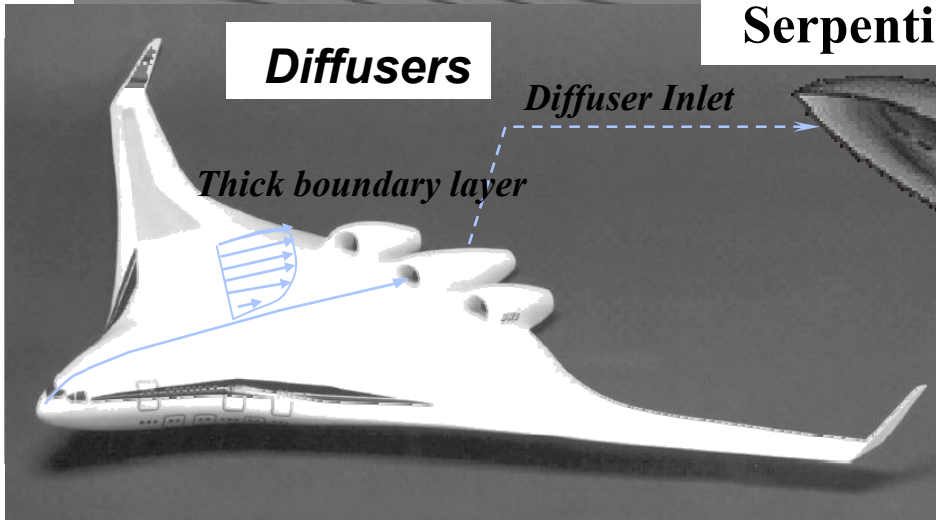
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Airfoils / Turbine Blades



Problem Zone / Area of Interest

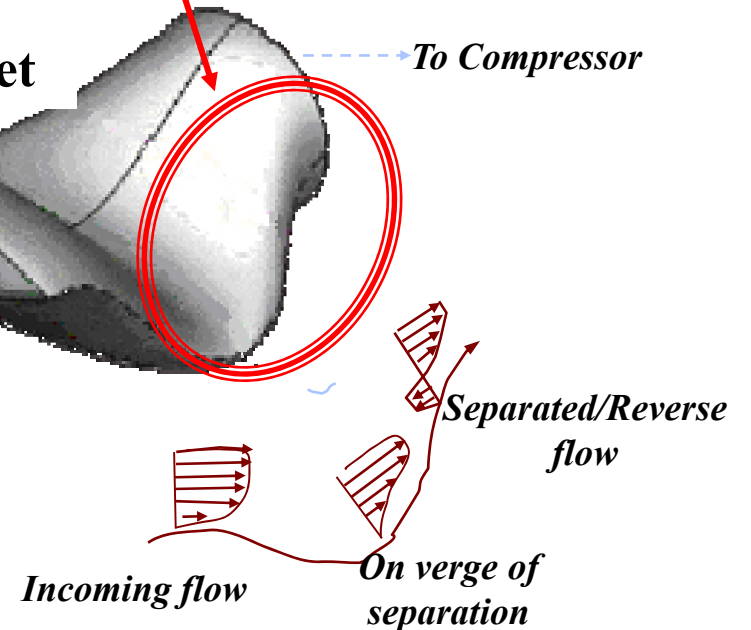


Diffusers

Diffuser Inlet

Blended Wing Body (BWB)

Serpentine Inlet



To Compressor

Separated/Reverse flow

Incoming flow

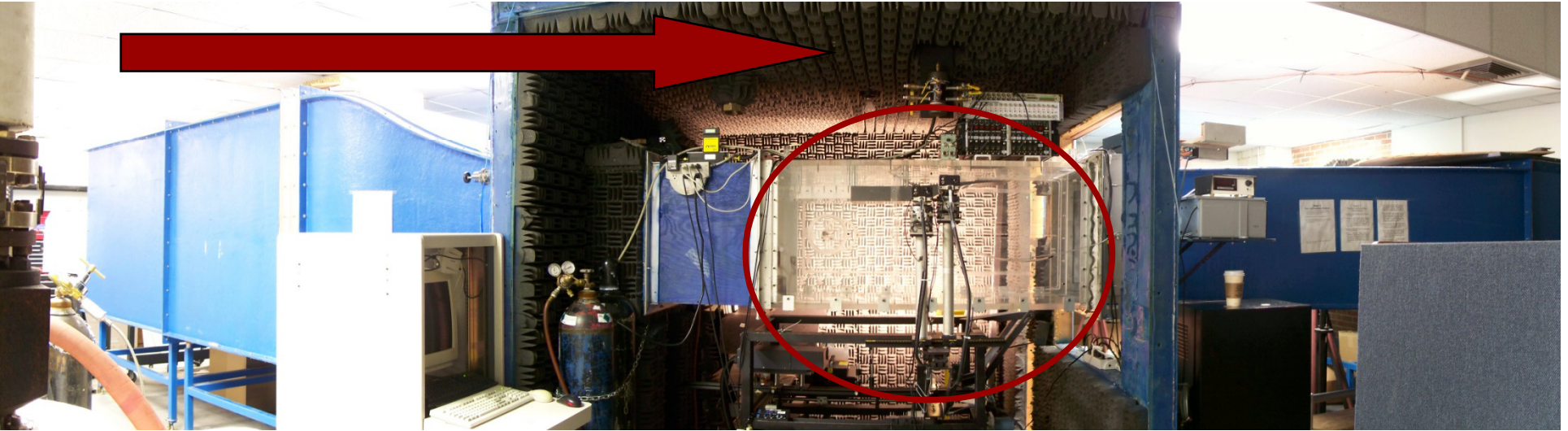
On verge of separation

NEED for efficient control devices !!

Objectives of the Present Study

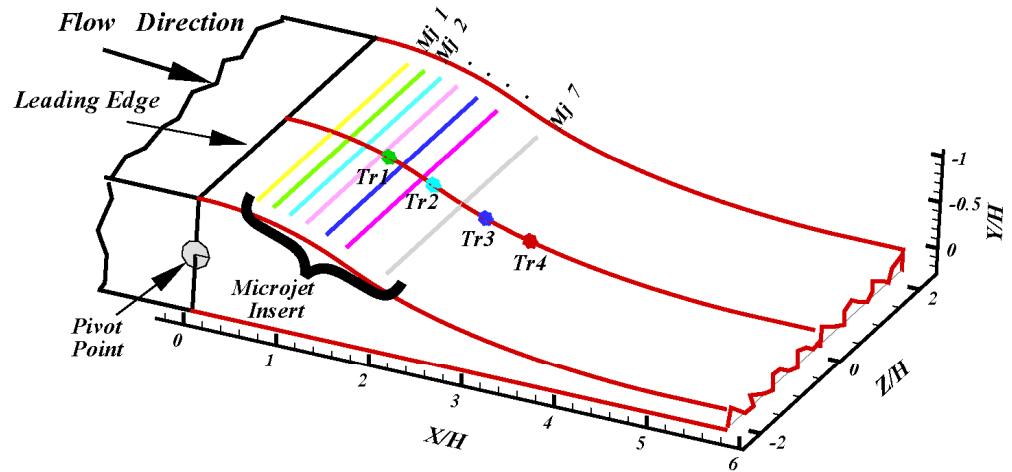
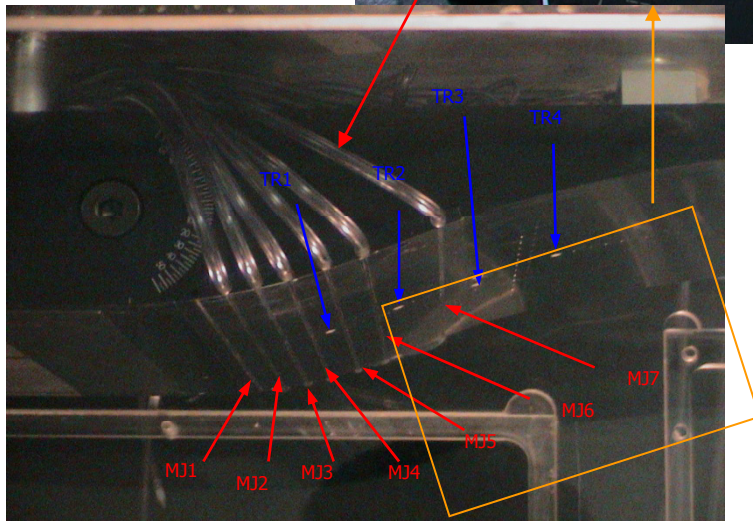
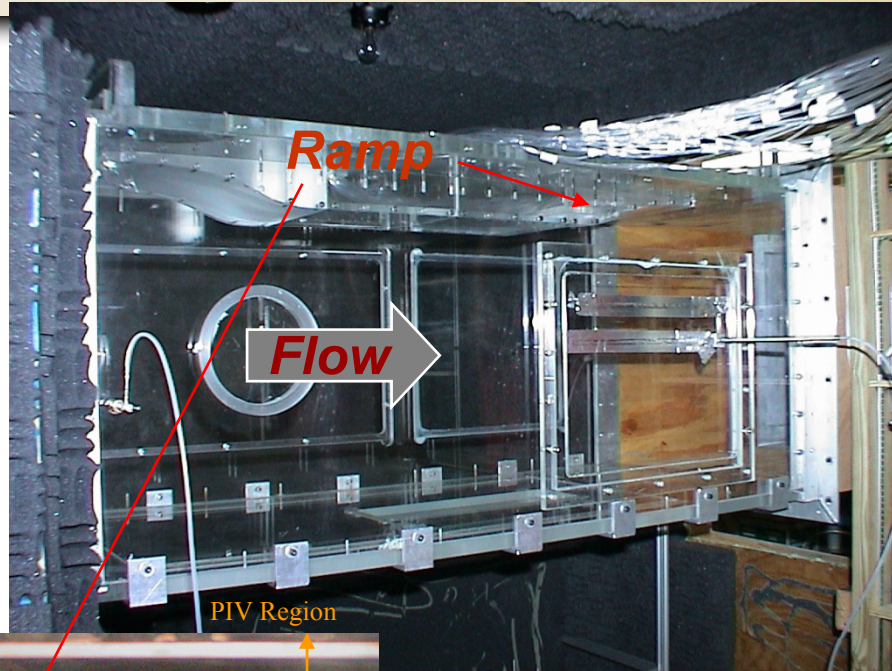
Evaluate the efficacy of Microjets

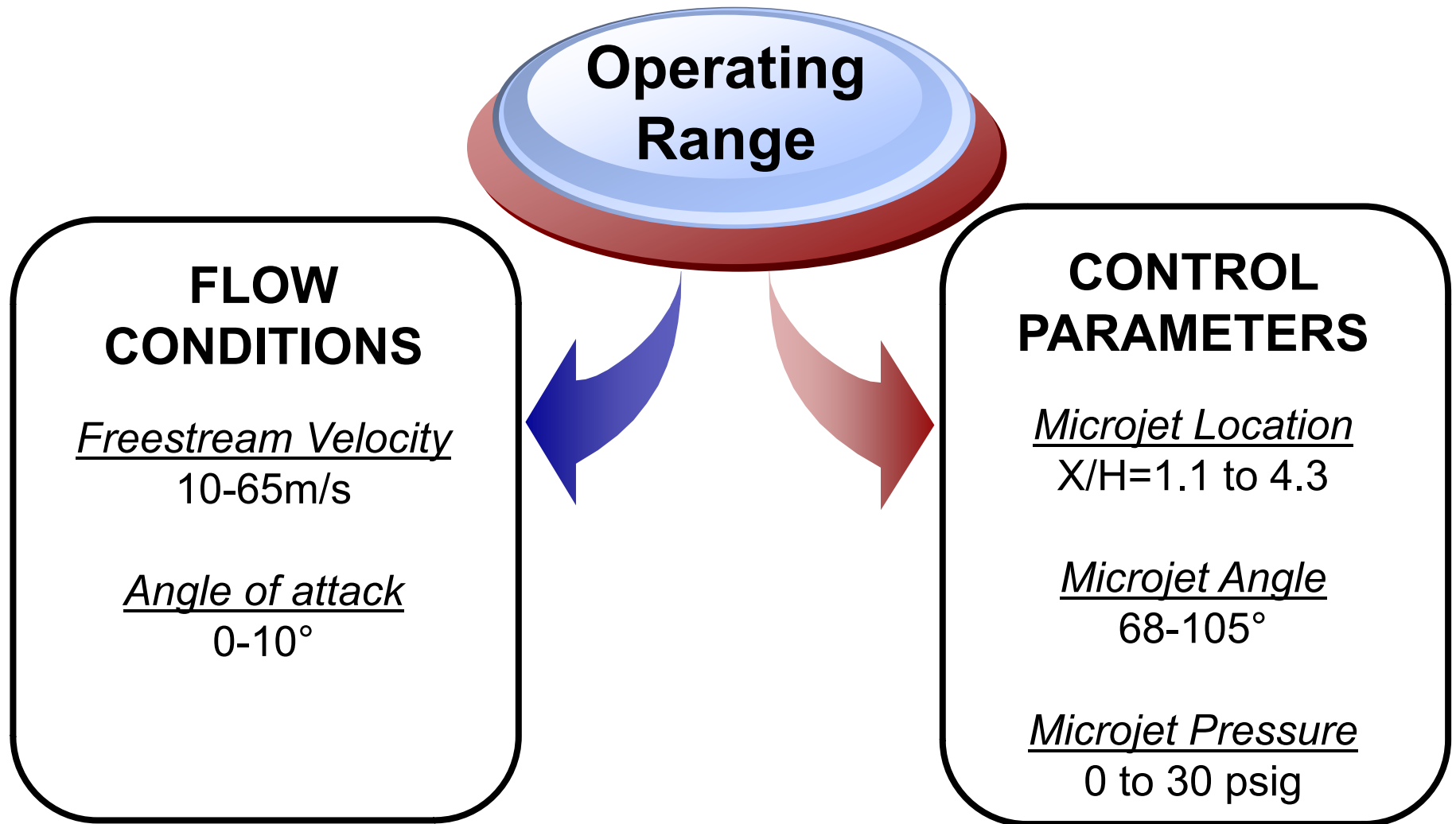
- Can we *eliminate/minimize* flow separation?
- Is the flow *unsteadiness* reduced?
- *Guidelines for an active control*
 - *Search* for an appropriate sensor.
 - Examine for means to develop a *flow model* for identifying the state of flow over the surface
 - Guidelines toward future development of a *Simple and Robust* control methodology.



Wind Tunnel

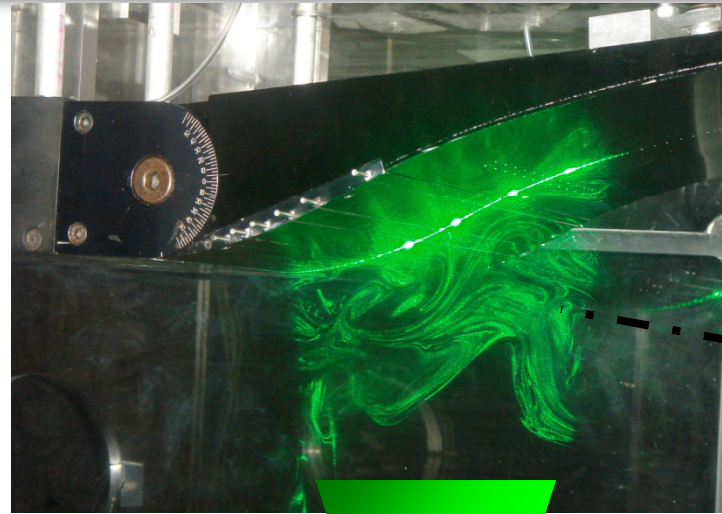
- **Subsonic Closed-Loop Wind Tunnel**
- **Freestream Velocity: 10 – 65 m/s**
- **Test Section:**
 - **24" x 24" x 48"**
 - **Excellent Optical Accessibility**



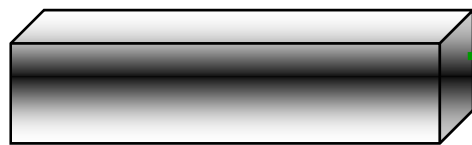


Incoming B.L. turbulent: At $U_{\infty} = 40\text{m/s}$, $Re_{L.E.} = 1.2 \times 10^6$

Particle Image Velocimetry (PIV)



Laser Sheet

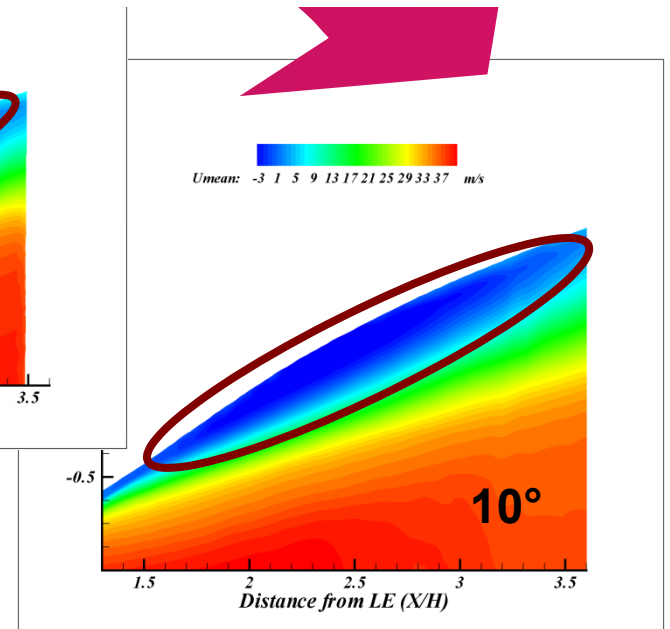
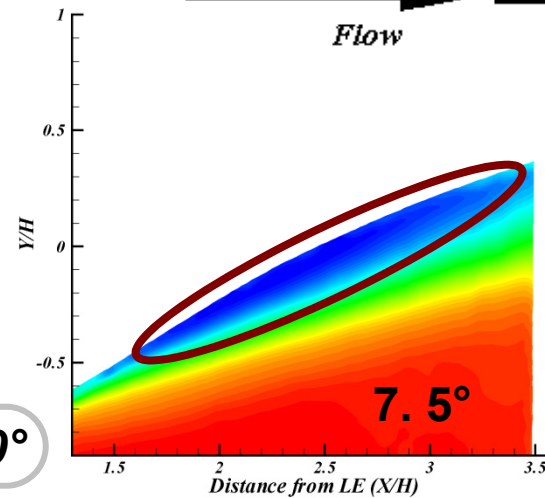
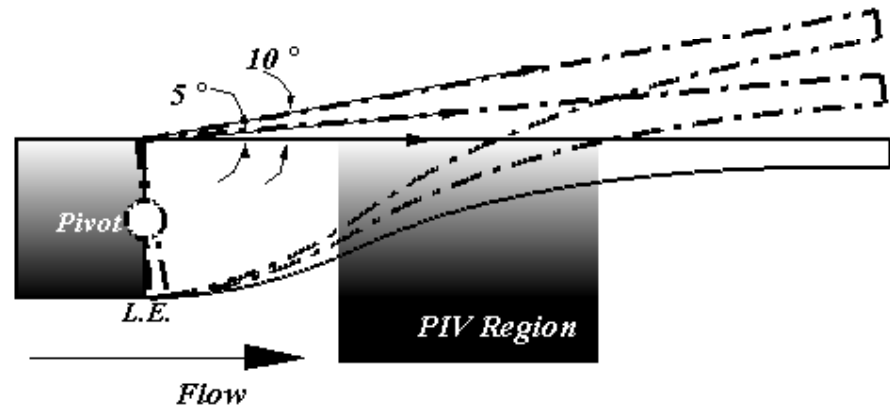
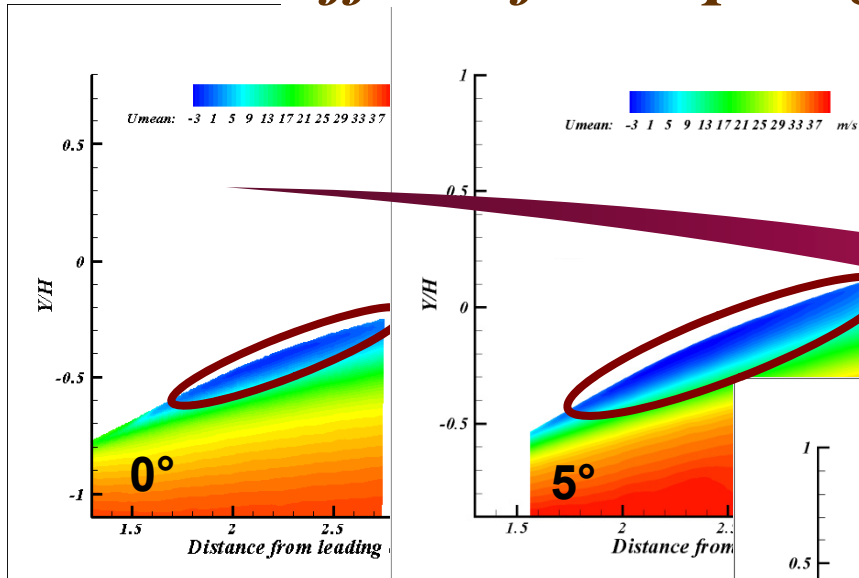


ND-YAG Pulsed Laser



Laser Optics

Effect of Ramp Angle, No Control, $U_\infty = 40\text{m/s}$

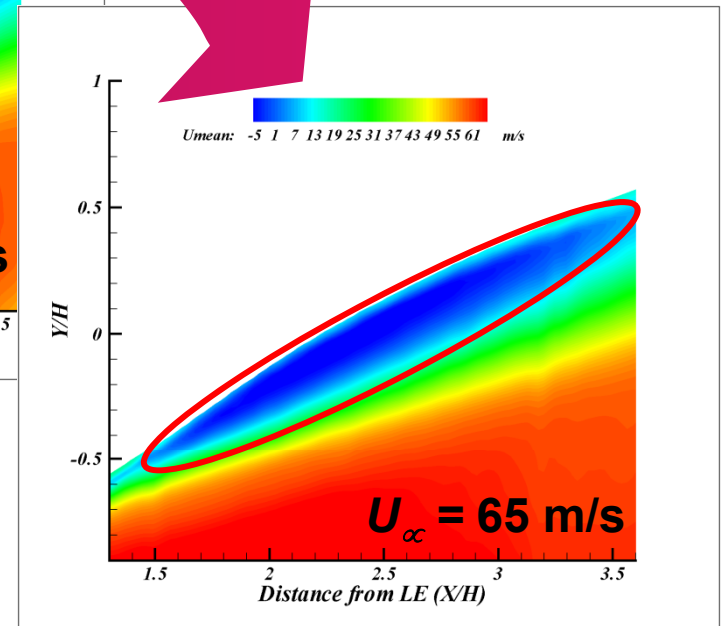
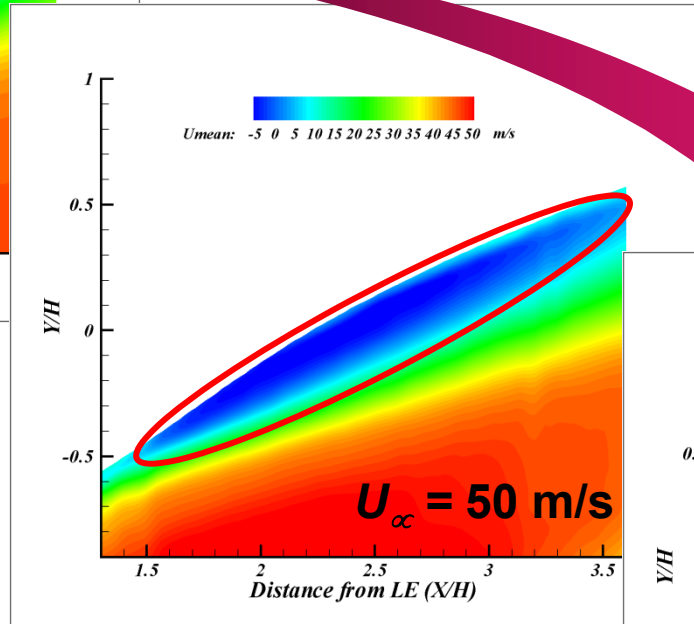
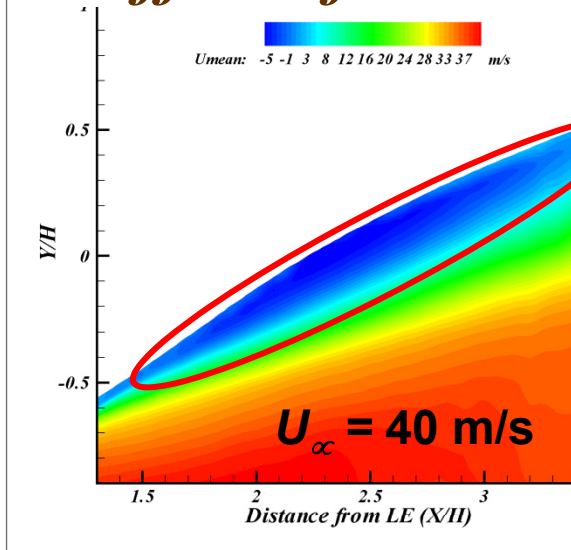


Separation region increases with increasing Angle of Attack...

$\Delta X \sim 1/3^{\text{rd}}$ of Ramp length for 10°

Separation location moves upstream with increasing AOA...

Effect of Free-stream Velocity, No Control, Ramp Angle = 10°



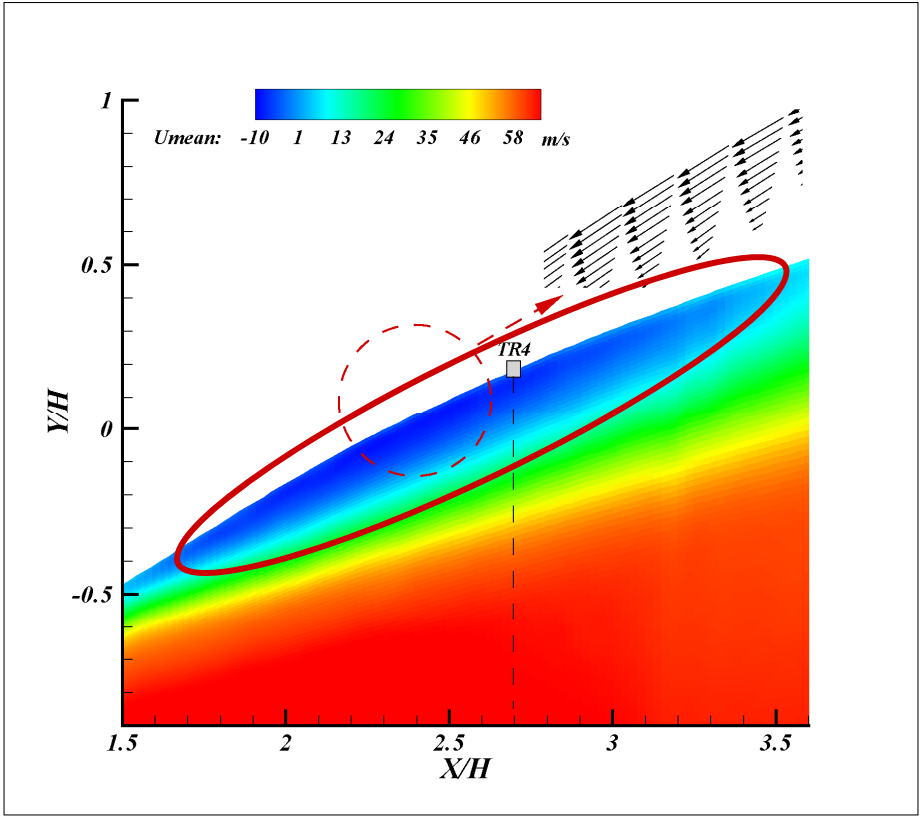
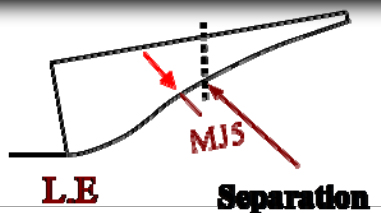
Separation extent remains same with Free-stream velocity...

Magnitude of reverse flow velocity increases with Free-stream velocity...

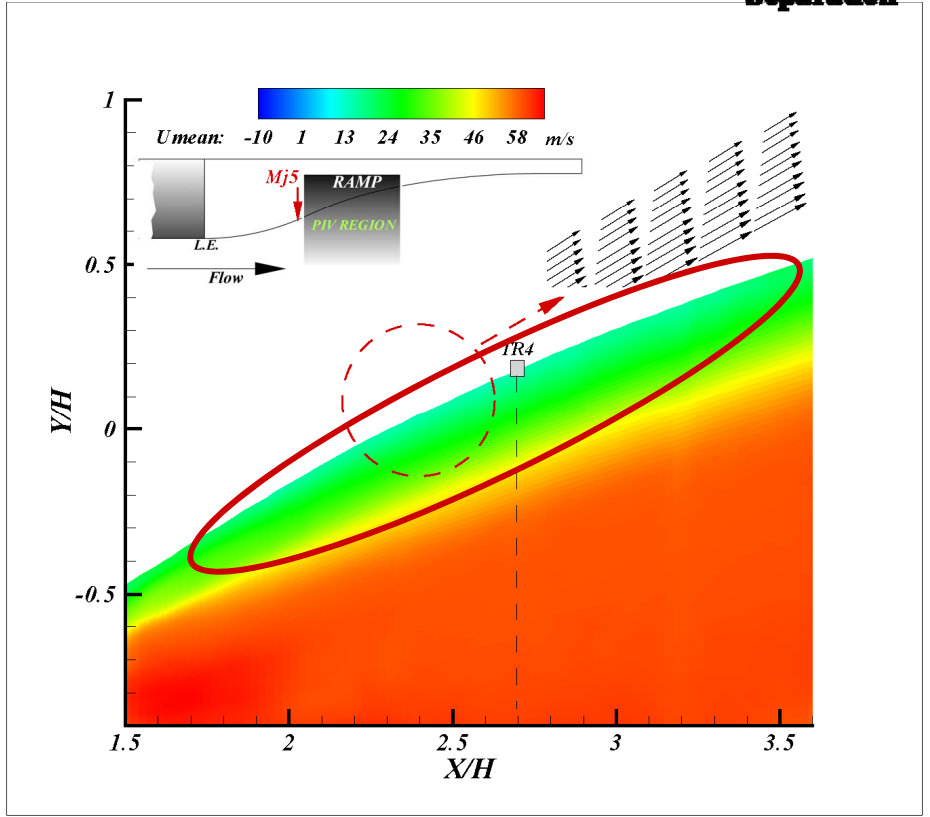


Control Efficacy for the Largest Separation Case

Ramp Angle = 10° , $U_\infty = 65\text{m/s}$



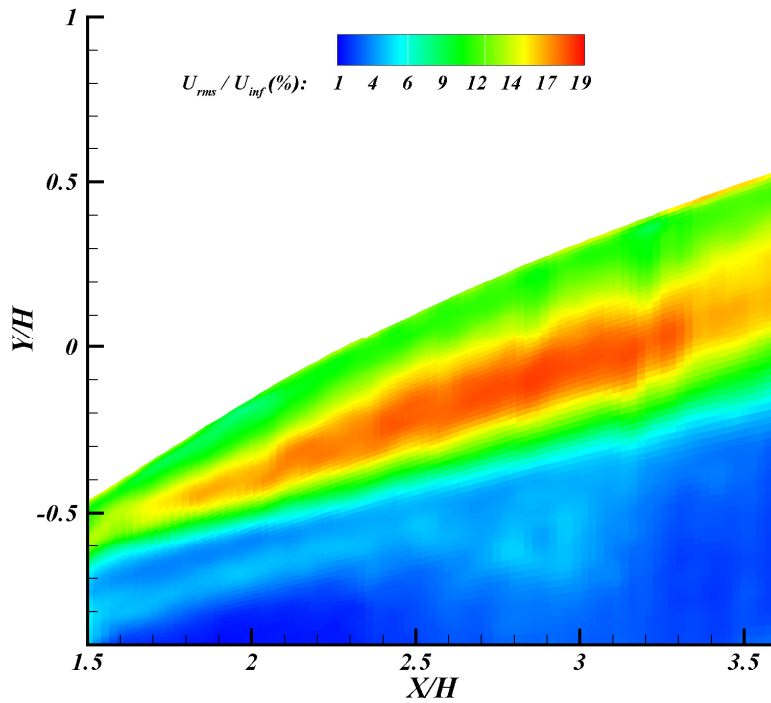
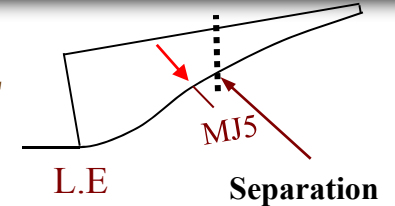
No Control



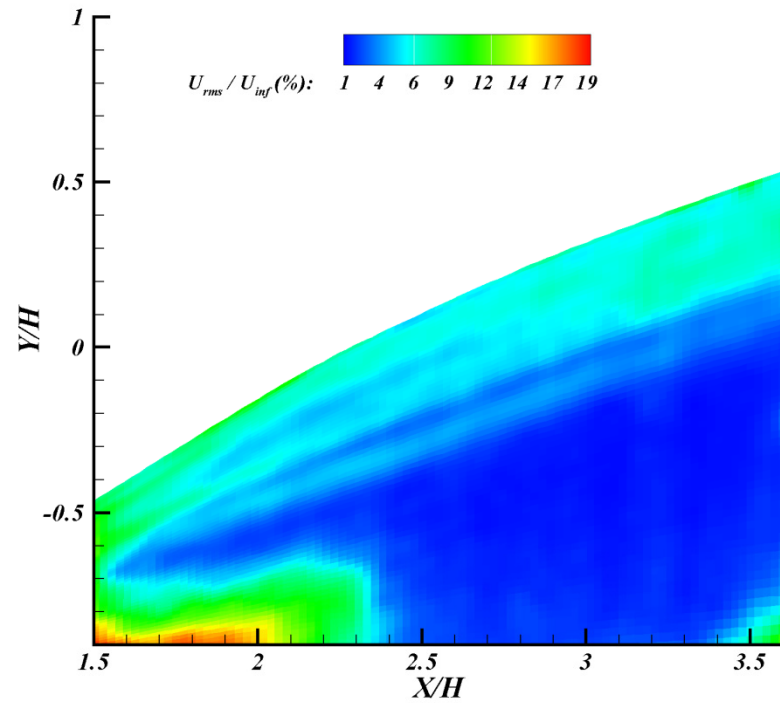
MJ5, 90°, 25psig

Unsteadiness – with and without control

Root Mean Square Velocity, U_{rms}
Ramp Angle = 10° , $U_\infty = 65\text{m/s}$



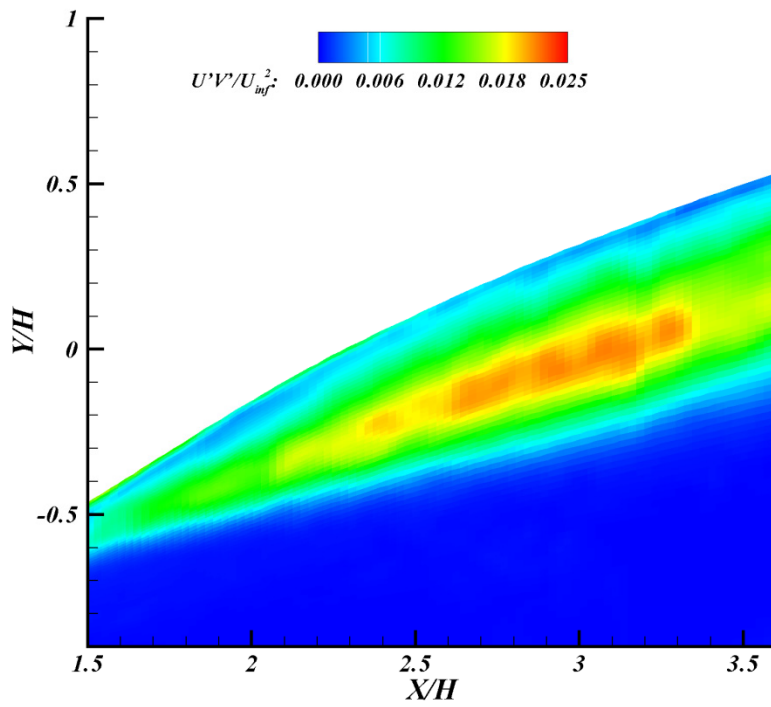
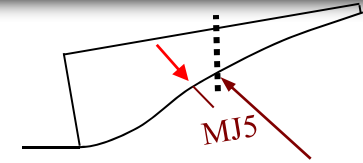
No Control



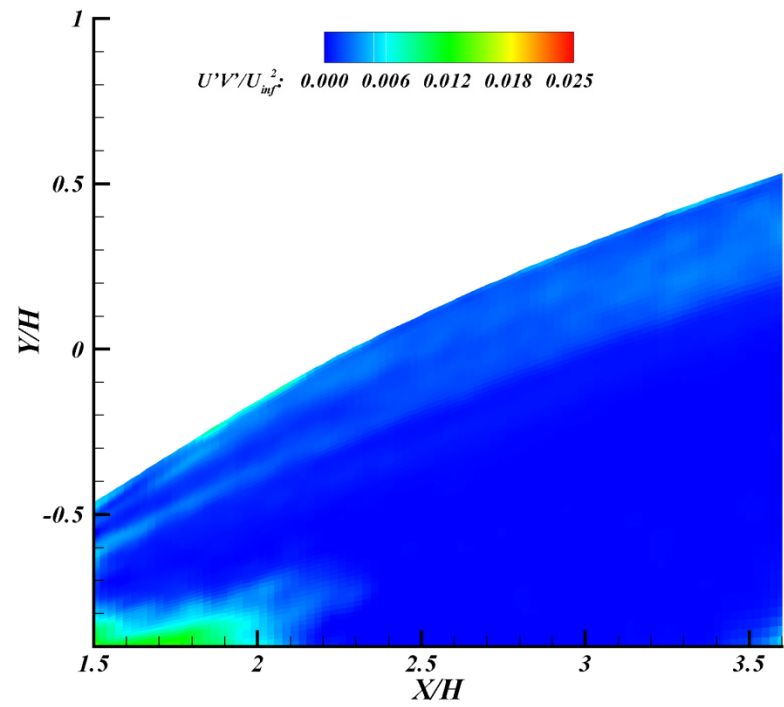
MJ5, 90° , 25 psig

Peak unsteadiness reduced by 70%

Turbulent Shear Stress, $U'V'$
Ramp Angle = 10° , $U_\infty = 65\text{m/s}$



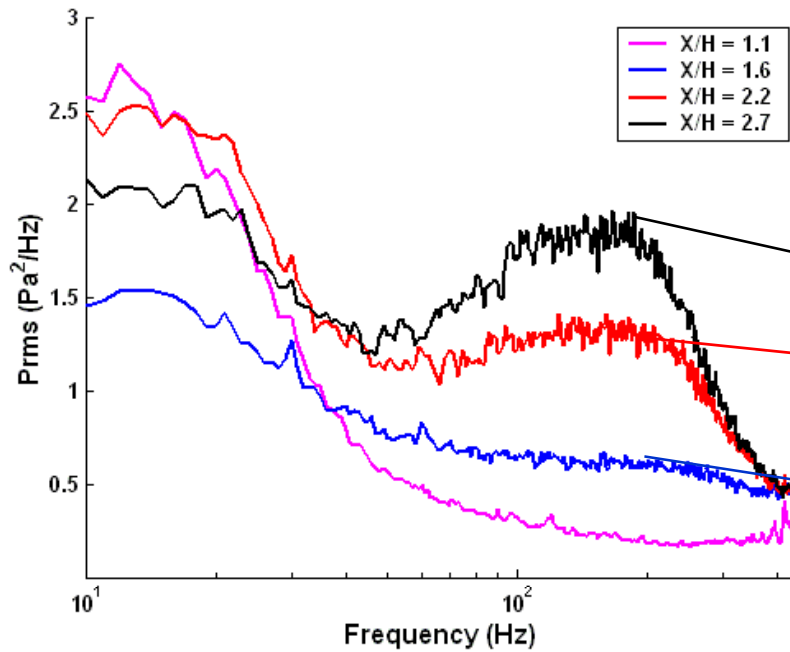
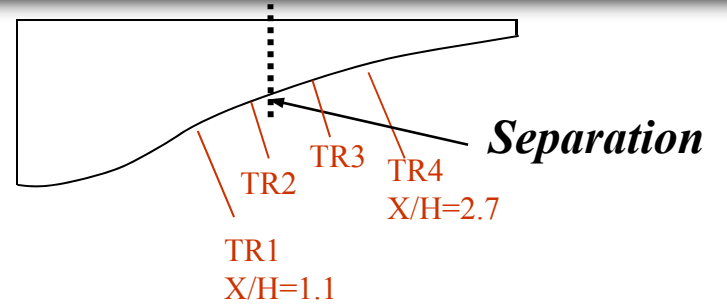
No Control



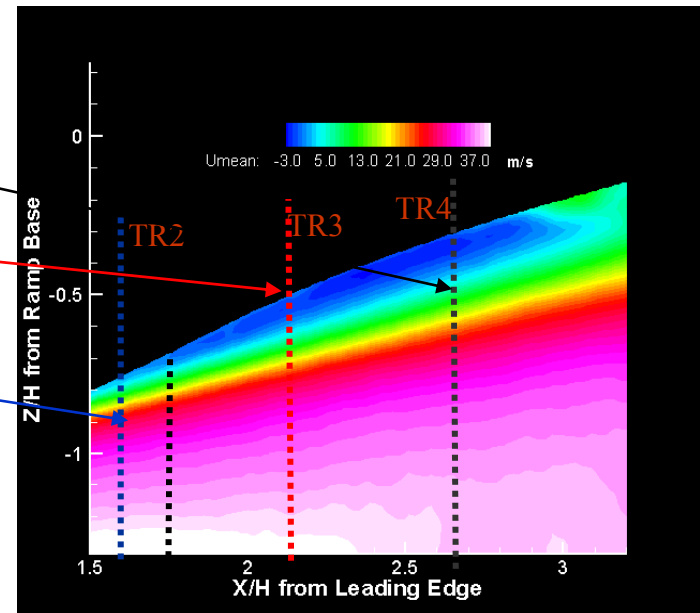
MJ5, 90° , 25 psig

Unsteady Pressure, P' in Flow-field

Ramp Angle = 5° , $U_\infty = 40\text{m/s}$



Spatial Pressure spectra @ 40m/s



Corresponding Streamwise Locations

Substantial Increase in P_{RMS} across separation !!

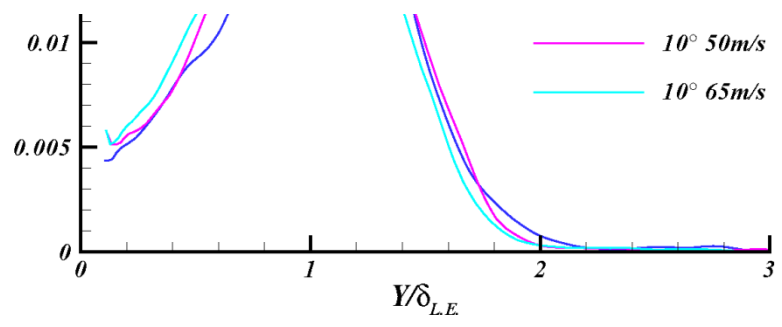
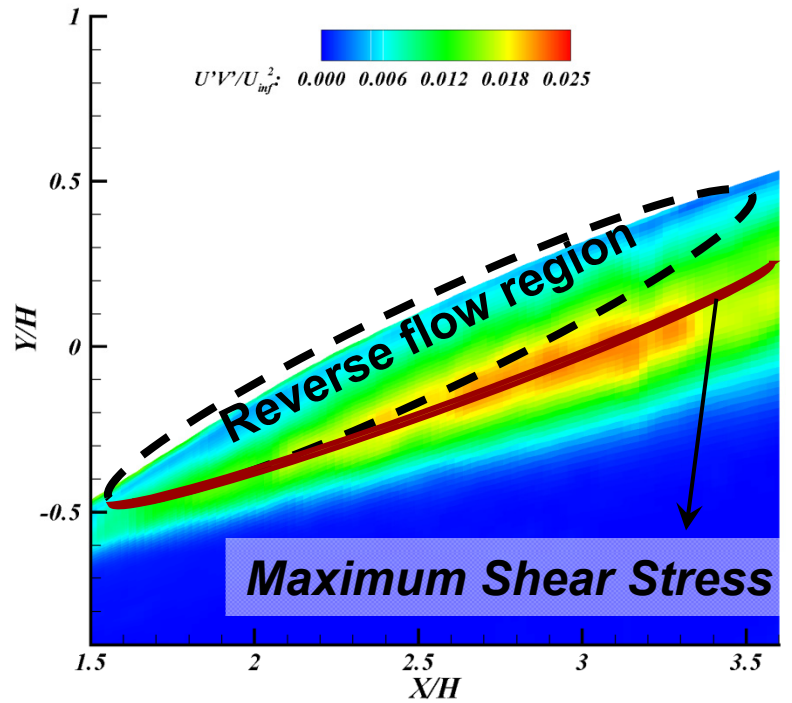
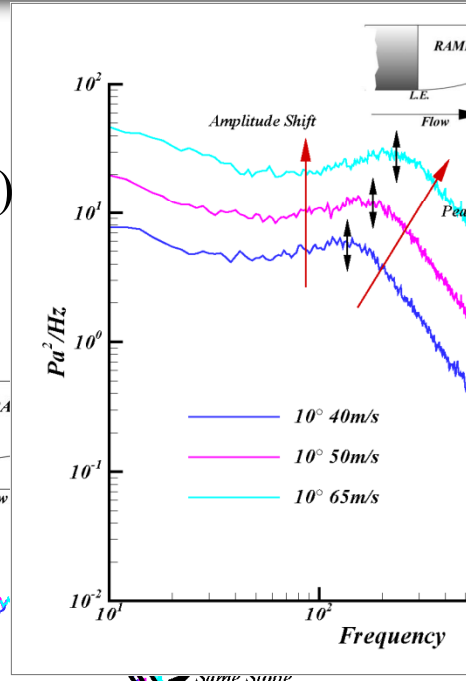
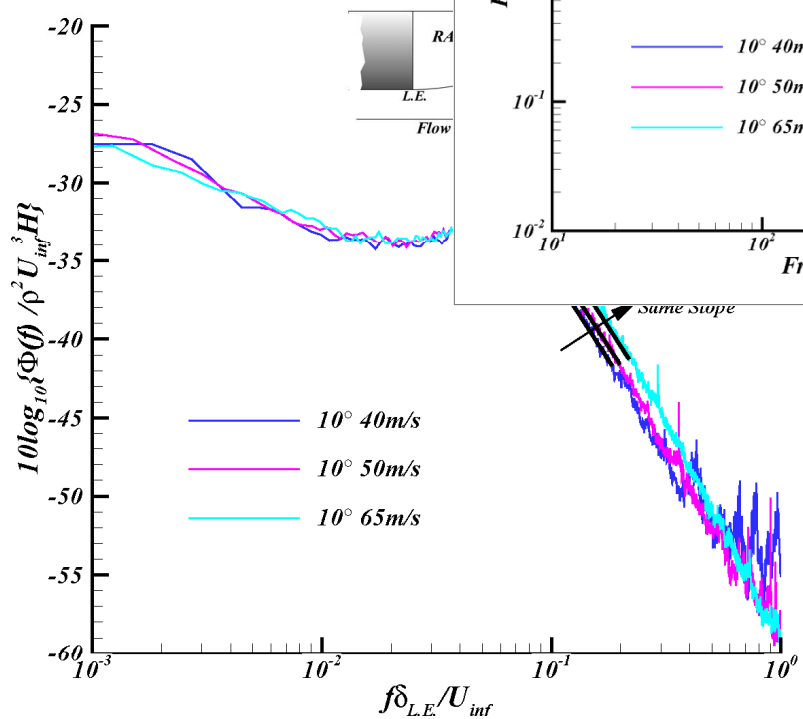
Effect of Freestream Velocity

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$$f^+ = (f \delta_{L.E.}) / U_\infty$$

$$10 \log(\Phi(f) / \rho^2 U_\infty^3 H)$$



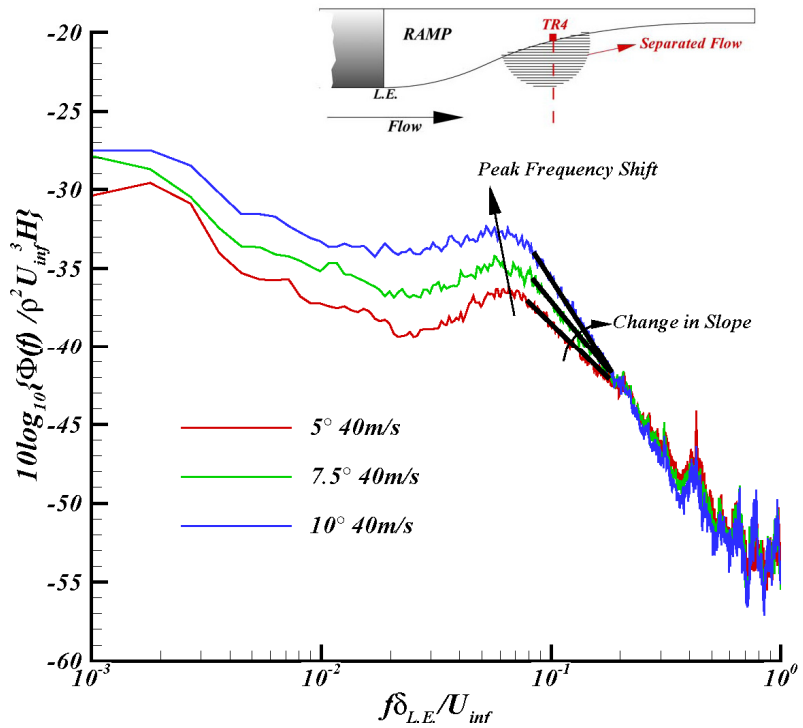
Non-dimensionalized Pressure Spectra

Non-dimensionalized shear stress

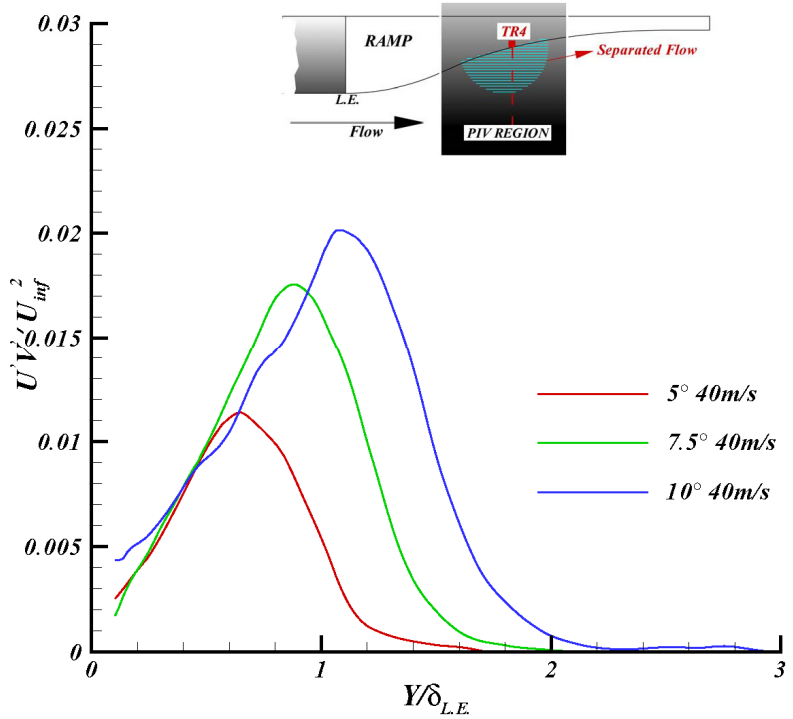
Dependence on Angle of Attack

Angle = 5°, 7.5°, 10°

$U_\infty = 40 \text{ m/s}$



Non-dimensionalized Pressure Spectra



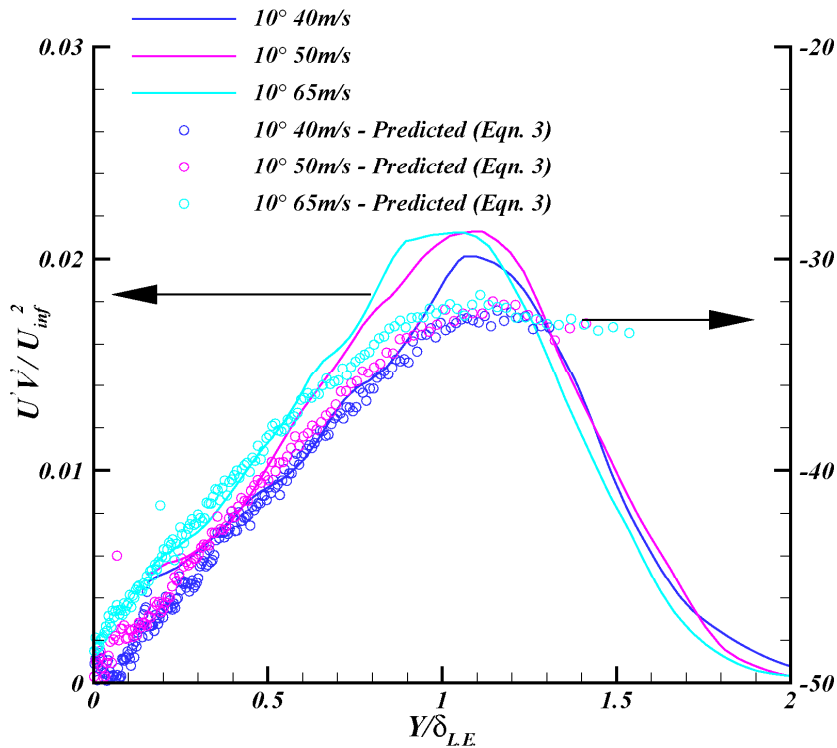
Non-dimensionalized shear stress

Developing a Sensor model

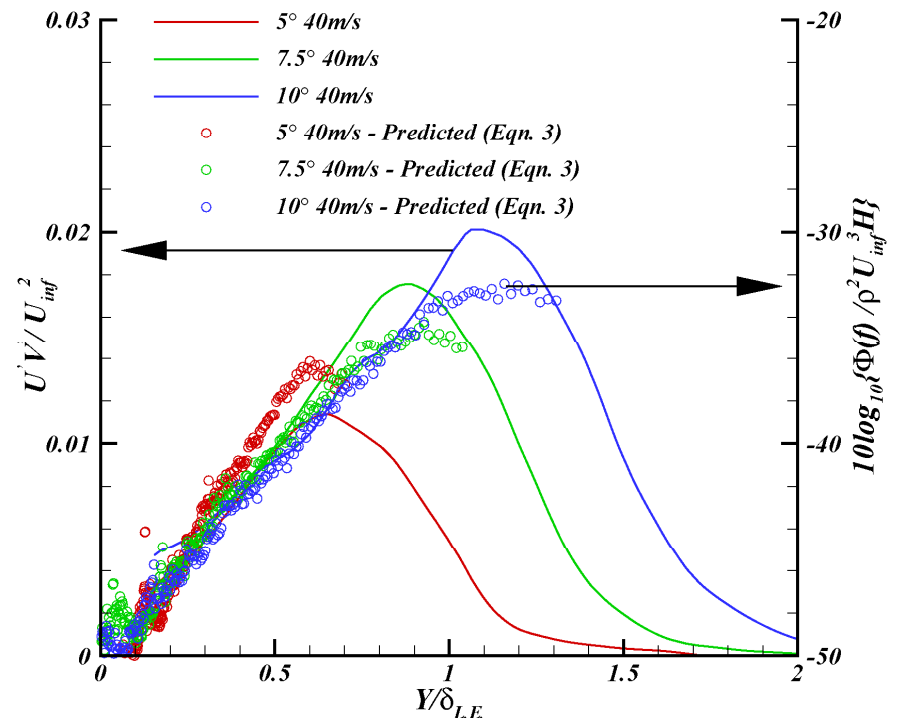
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$$\frac{Y}{\delta_{L.E}} = \log(\text{slope}) \left[\log \left(\sqrt{\frac{1}{J_s}} \times \text{slope} \right) \right] + 0.25$$



Freestream Velocity variation

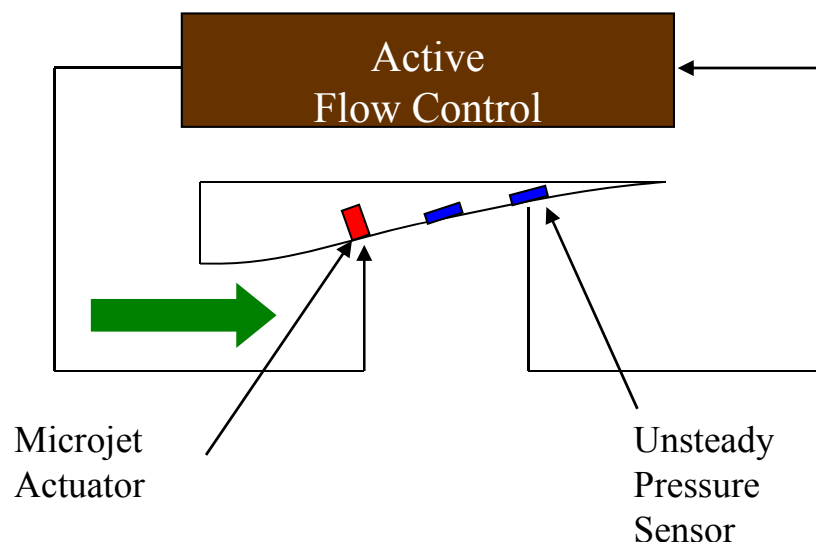


Angle of Attack dependence

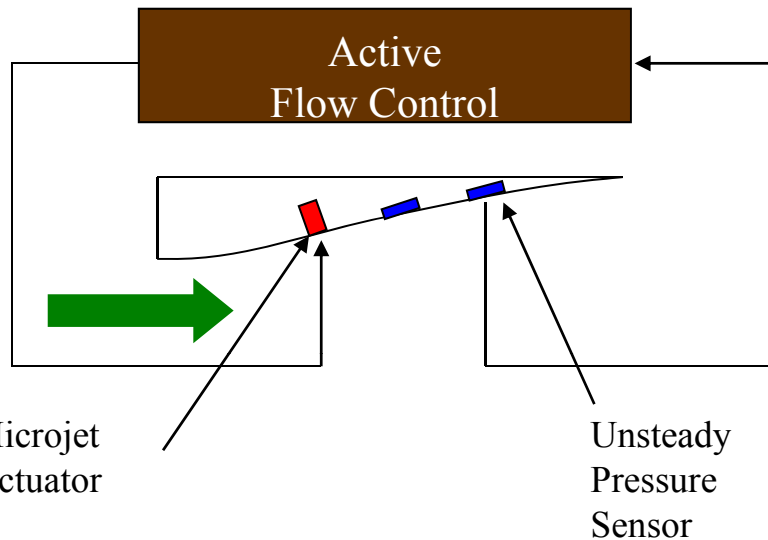
A reasonably good estimate of the peak unsteadiness location can be obtained by unsteady surface pressure measurements

Advantages of the proposed 'Virtual Sensor'

- Relatively **simple and fast estimations of flow conditions** above the surface
=> Faster ID of appropriate control parameters
- **Increased sensitivity** of the pressure measurements (Narrow frequency range to use)
- Control approach can be '**hard-wired**' or be '**software controlled**'
- Provides a proportional **control knob**
 - Can be used as part of an outer-loop for '**Overall System optimization**'



**Proposed
Control Schematic**



Requirements

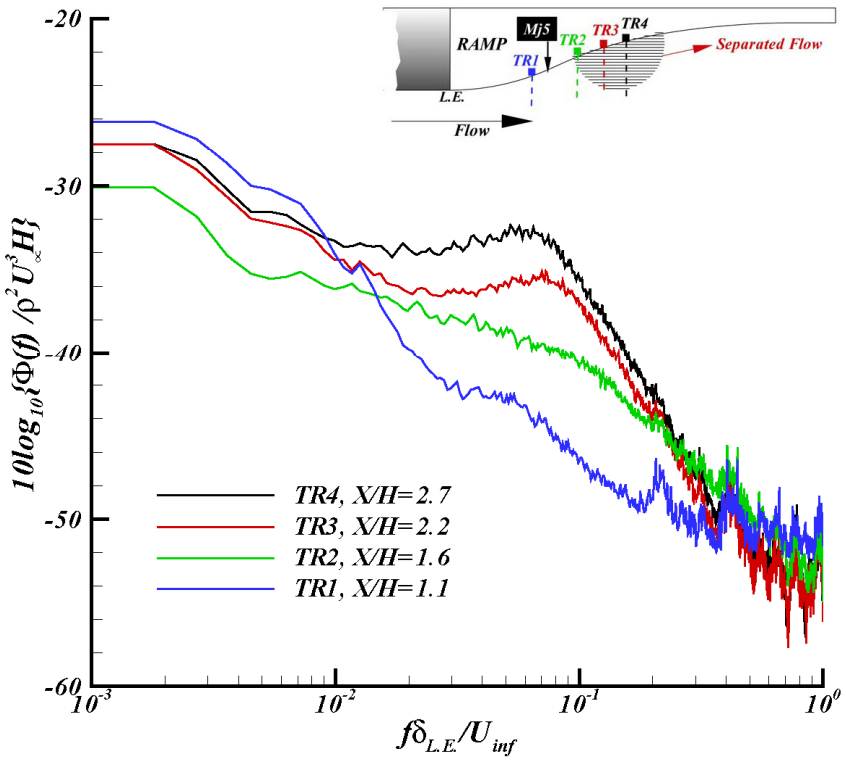
- Known *Geometry & Actuator Locations*
- *Jet trajectory* (based on C_{μ})
- *Unsteady pressure measurements*

Steps for Control Approach

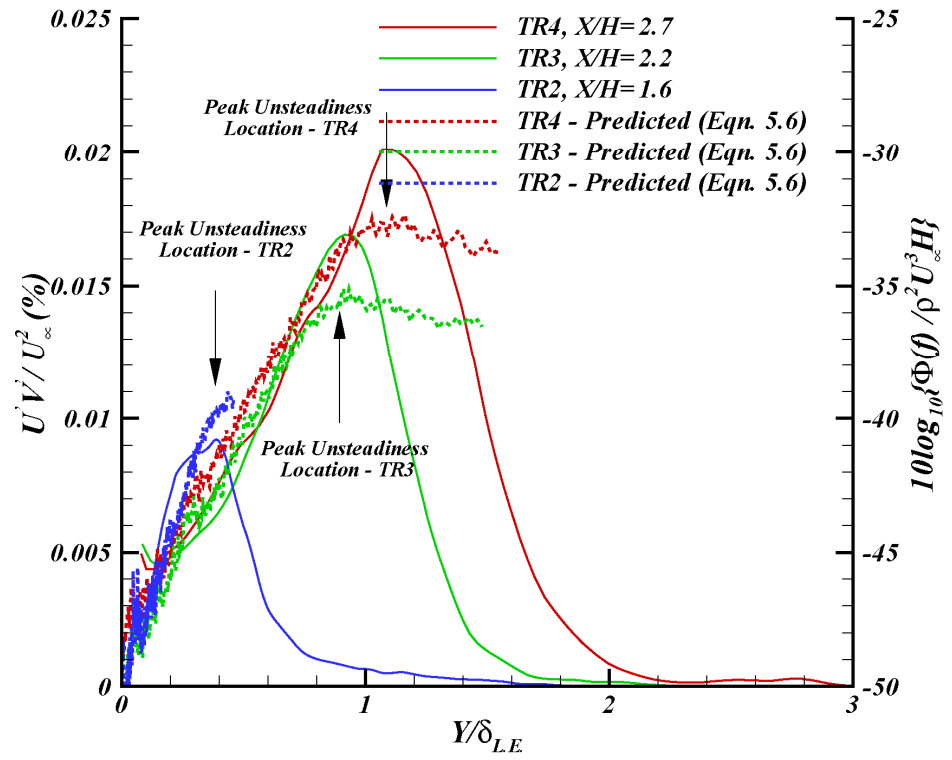
- Obtain $P'(f)$
- Transform to identify **peak unsteadiness location** (Y/δ to be affected)
- Use known geometry to **identify the location of microjets available** (X_i)
- Determination of C_{μ} based on X and Y for **optimal effect**.

Validation of the proposed model – Test Case

Ramp Angle = 10°, $U_\infty = 40\text{m/s}$



Non-dimensionalized Pressure Spectra

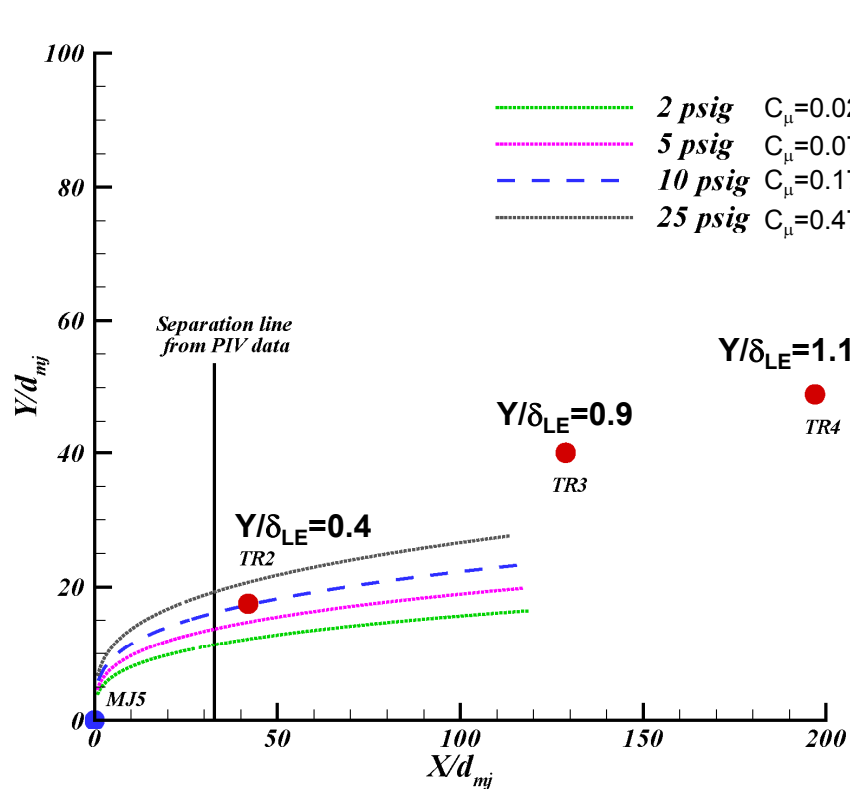


Estimated shear stress profile

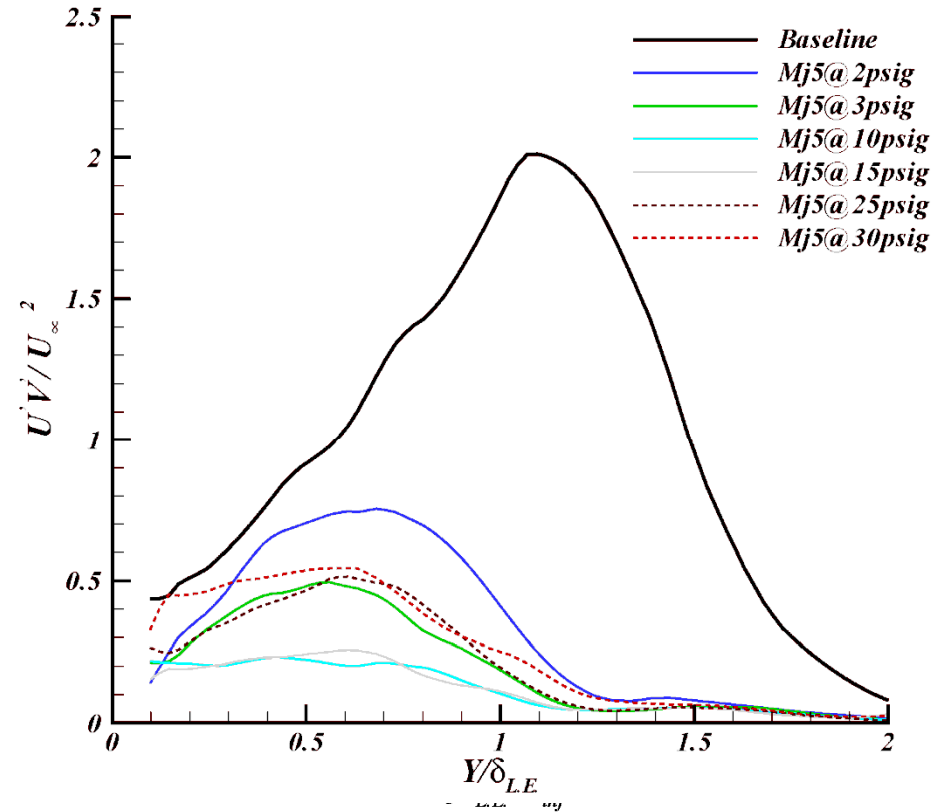
Ramp Angle = 10°, $U_\infty = 40\text{m/s}$; Microjet: MJ5, 90°

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Location of Unsteadiness mapped with Microjet location and Jet Trajectory



Response on the flow-field

Separation Control using Microjets

Effectiveness of Microjet Control

- Completely eliminated separation with very low mass flux
- More than 70% reduction in unsteadiness
- Makes flow nominally 2-dimensional

Use of Unsteady Surface Pressure for Active Flow Control

- Flow properties well reflected in the pressure spectra
- Relatively faster control schemes can be developed

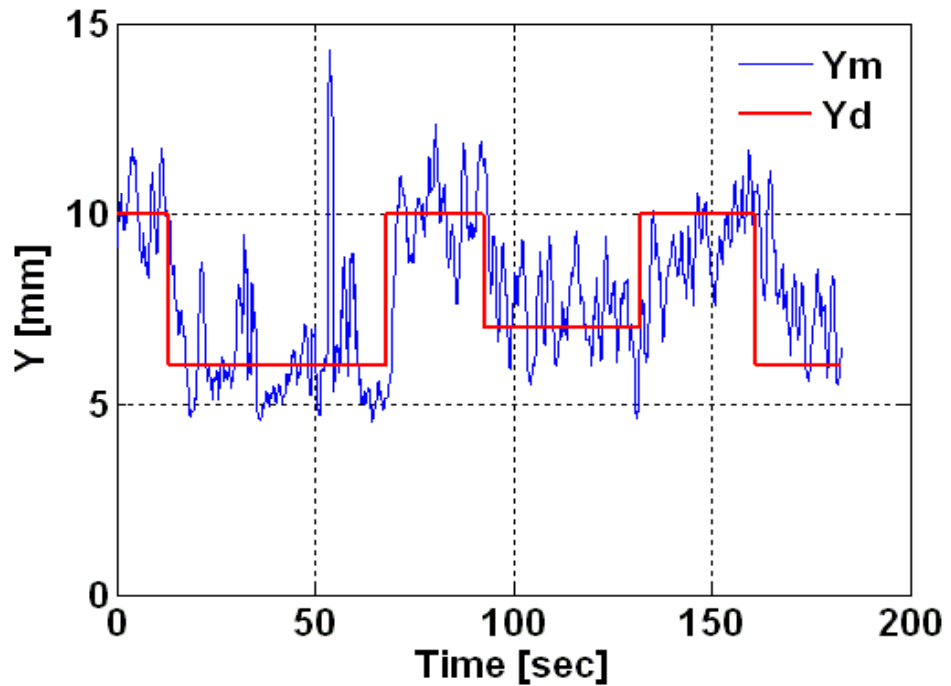
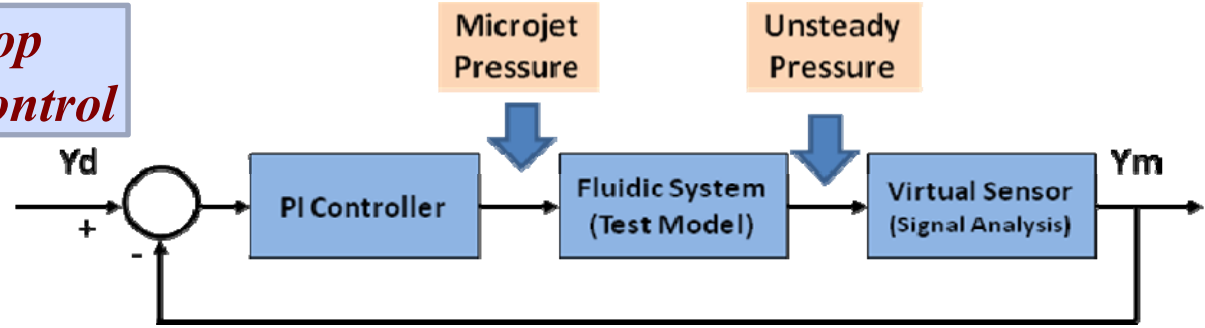


Questions ?

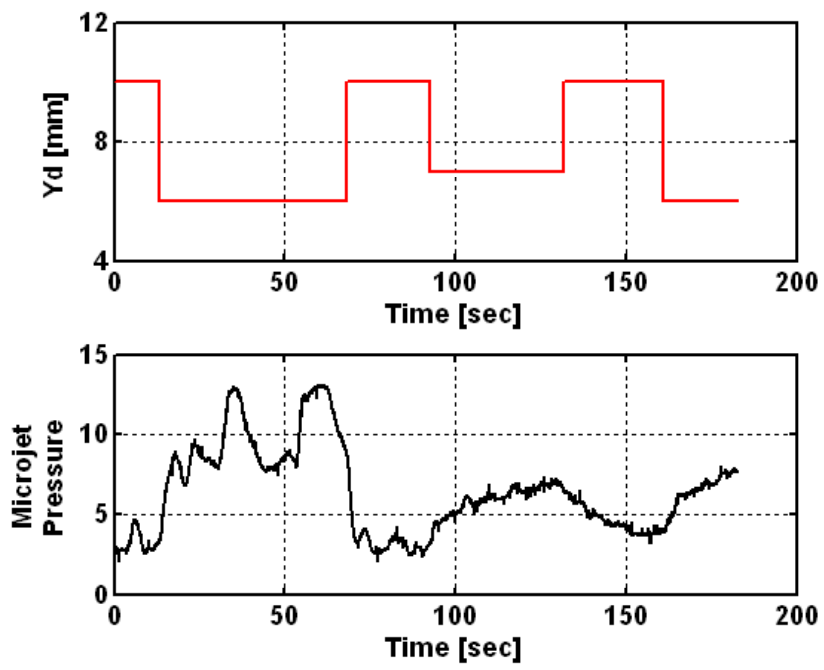
Closed Loop Tracking

Collaborators: Oscar Y. Chuy, E. Collins

Closed Loop Separation Control



Tracking the degree of separation



Commanded Microjet pressure