Mini UAV's:
Can Active Flow Control
Do It All?

Avi Seifert

Department of Fluid Mechanics and Heat Transfer

Faculty of Engineering

Tel-Aviv University, Tel-Aviv, ISRAEL

What is "All"?

- **Eliminate Low Re Effects on Performance**
- **Control Attitudes and Provide Guidance**
- **Propulsion by Periodic Excitation**
- **No Moving Parts**

DARPA Proposal, Patent Pending, w/ Wygnanski & Greenblatt

Report Documentation Page

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15. SUBJECT TERMS

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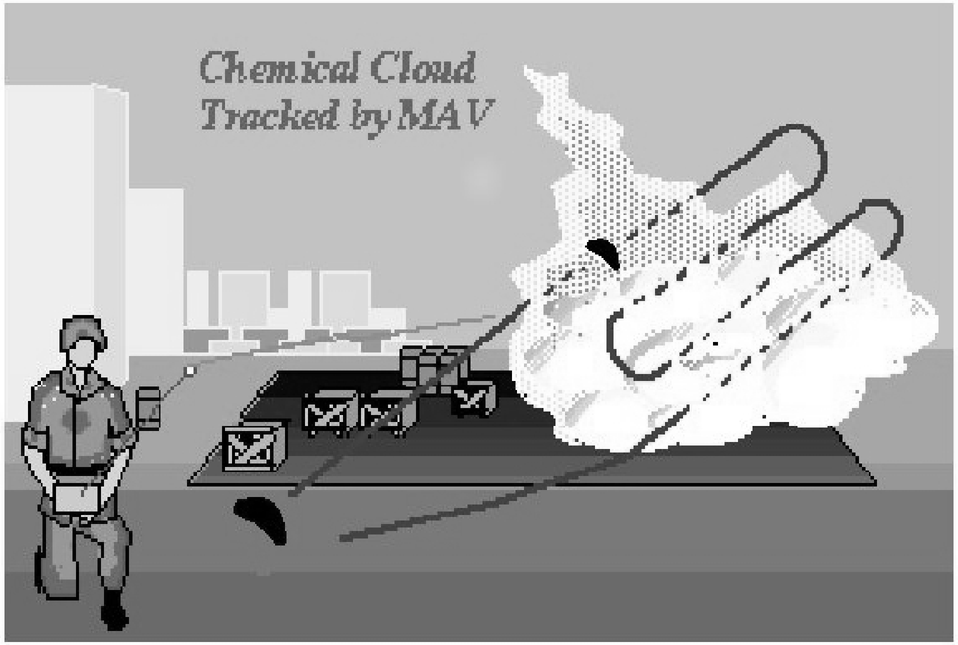
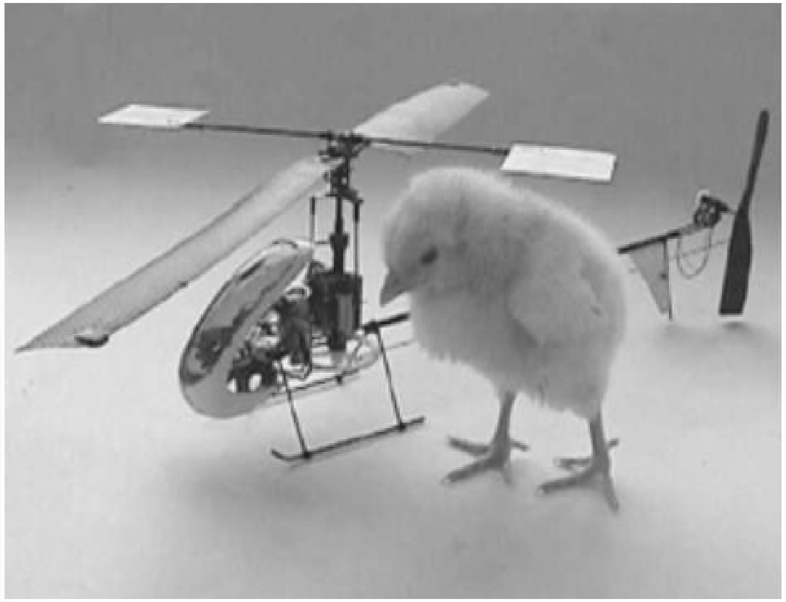
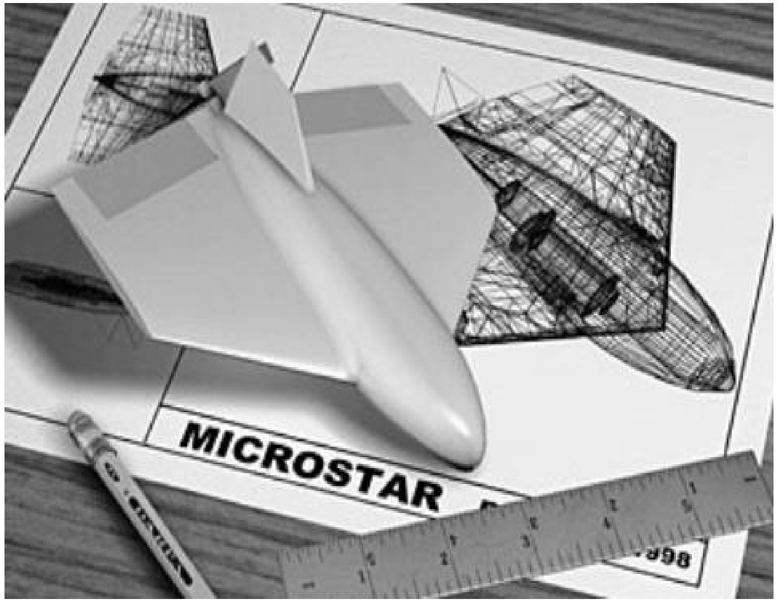
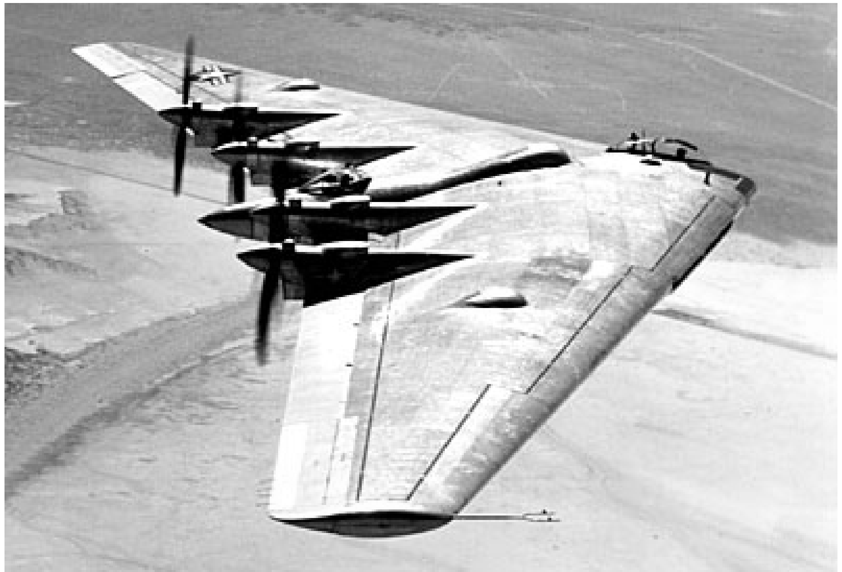
Mini UAV Controlled and Propelled by Periodic Excitation

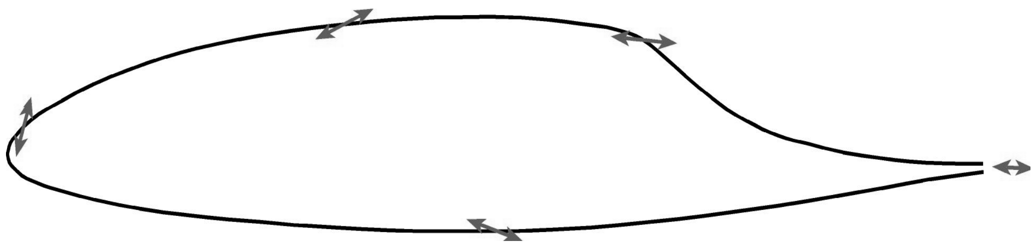


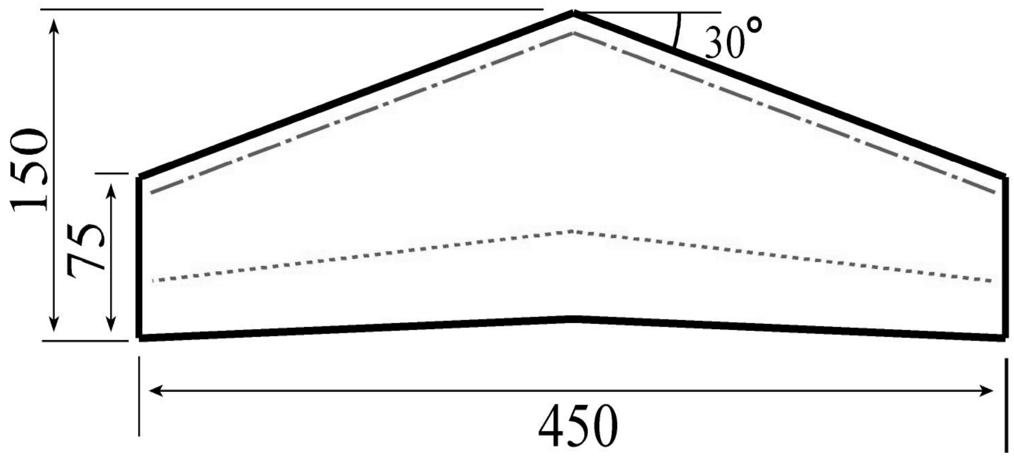






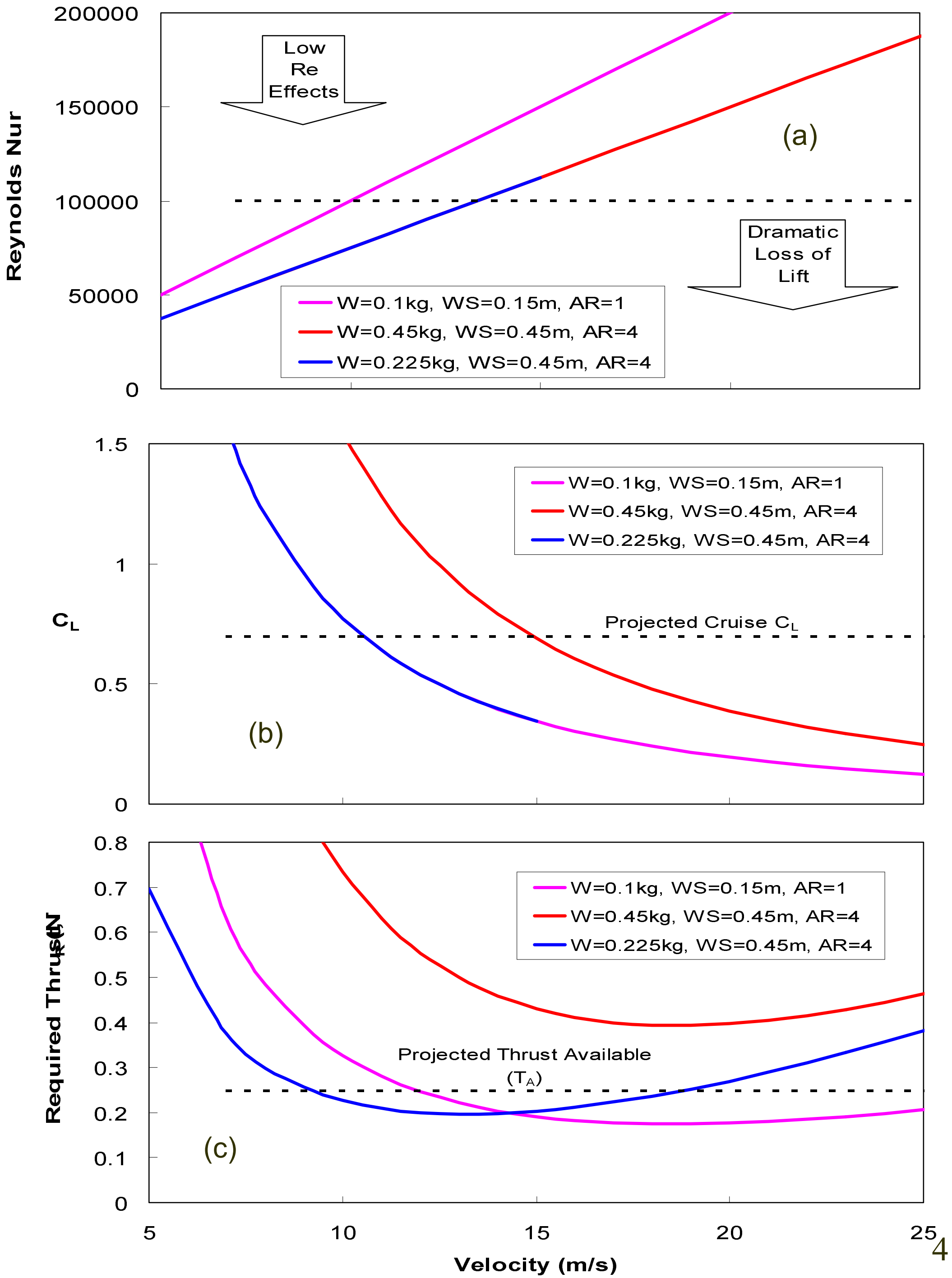
Proposed mUAV Configuration – No Moving Parts



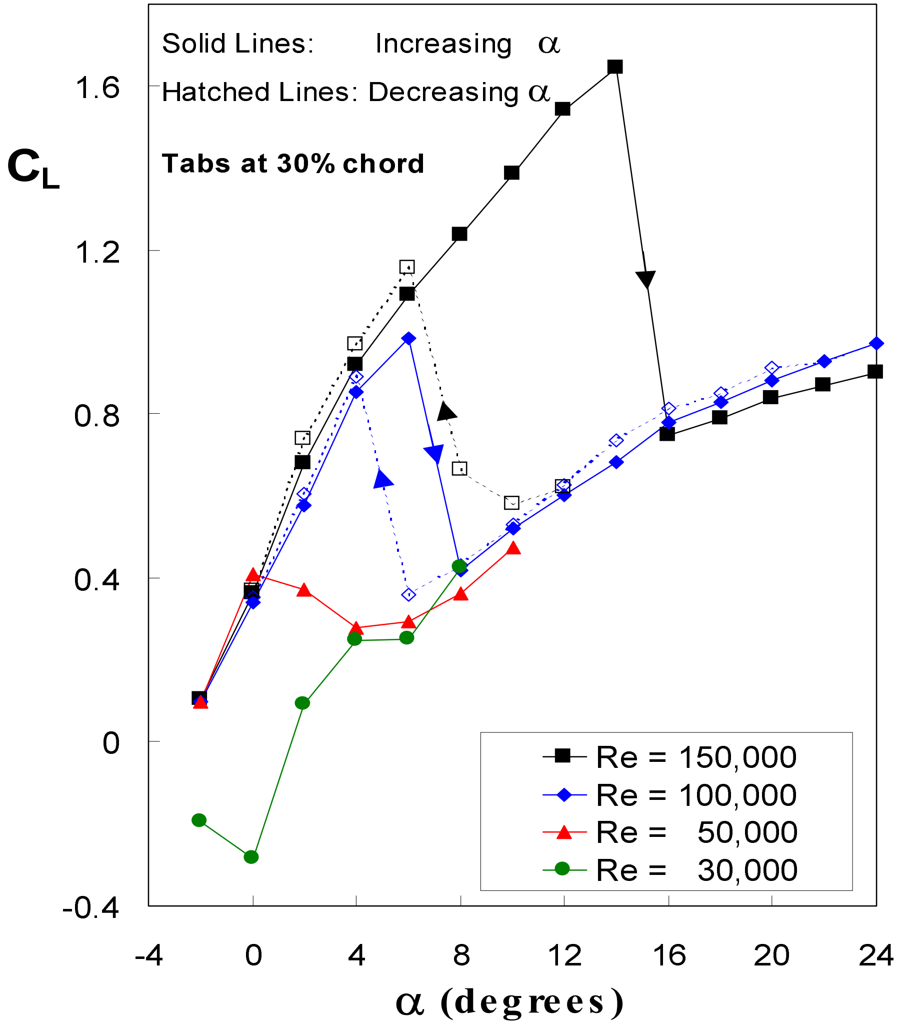


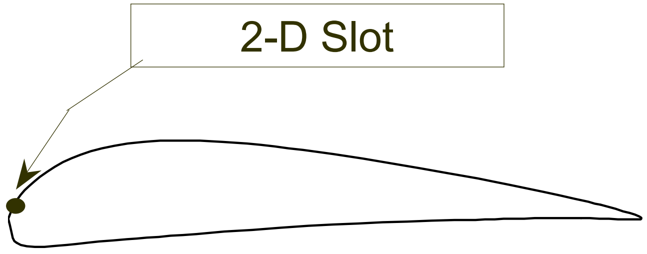
Wing profile considered for the proposed mUAV.
Zero Pitching Moment – when Flow fully attached.
Form-thrust capability (Glauert, Goldschmied)
Arrows indicate possible actuator placement
Plan-view of the “flying wing” mUAV configuration considered in the proposal

Basic micro and mini UAV performance comparison (Root chord of 15 cm)



Low Re Effects on C_L of the PR8/flap airfoil

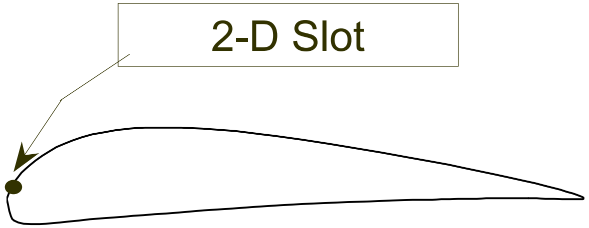


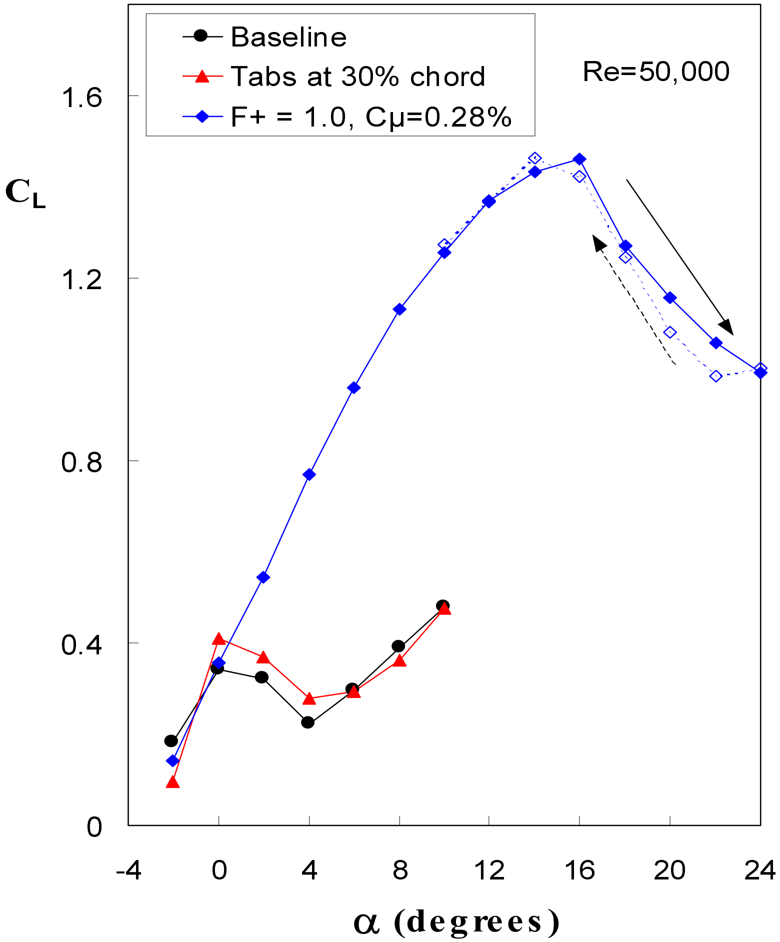


Flap element of the PR8 airfoil

(Greenblatt and Wygnanski, 2001)

Effect of tabs and AFC at low Reynolds numbers





(Greenblatt and Wygnanski, 2001)

Non dimensional frequency

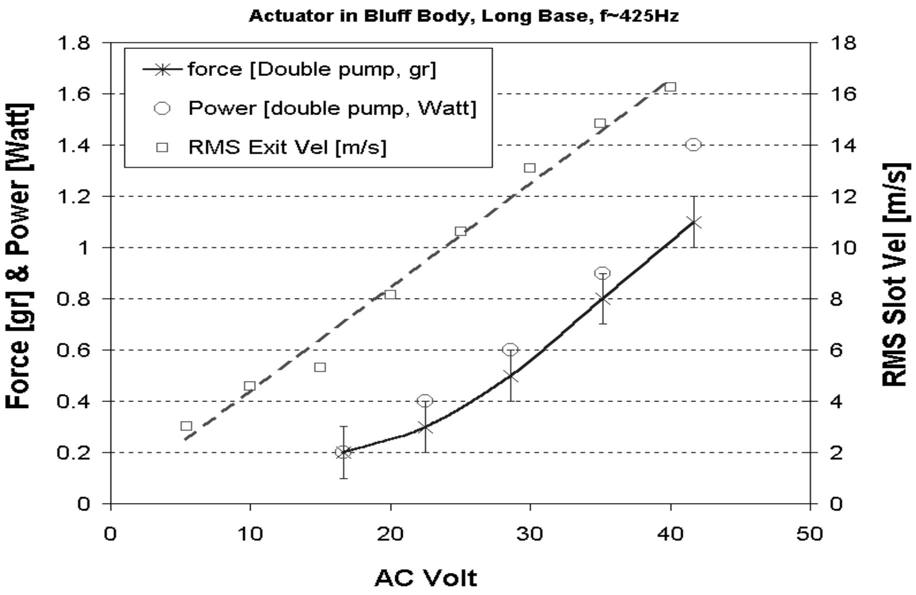
$$F^{+} \equiv \frac{f \cdot C}{U_{\infty}}$$

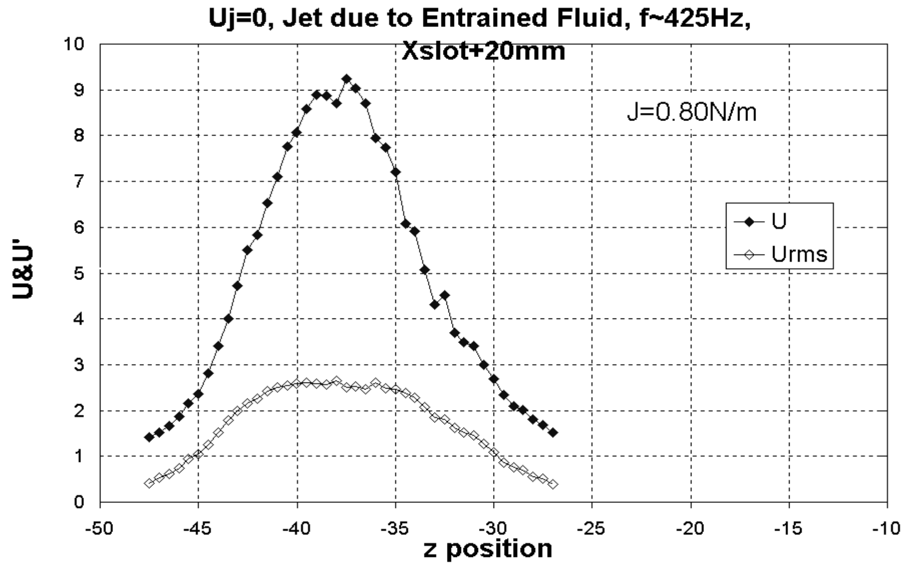
Oscillatory momentum coefficient

$$C_{\mu} \equiv \frac{\langle u` \rangle^{2} A_{slot}}{\frac{1}{2} U_{\infty}^{2} A_{wing}}$$

f=modulating or actuators frequency
C=root chord
U_{∞}=free stream velocity
A_{wing}= wing area
A_{slot}
<u`>=excitation velocity fluctuations

Oscillatory Momentum Generator

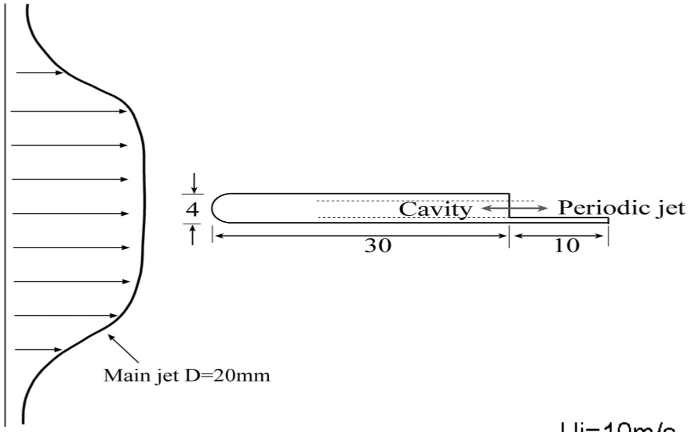


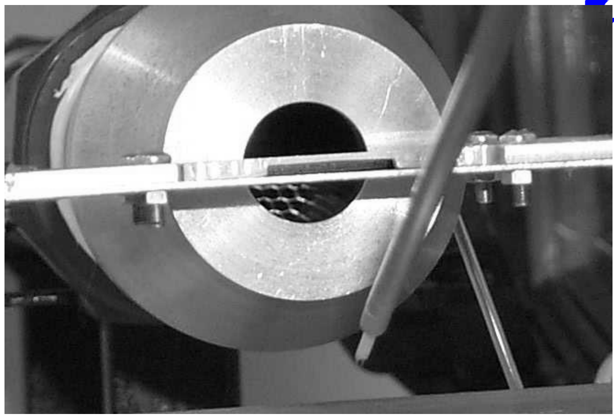


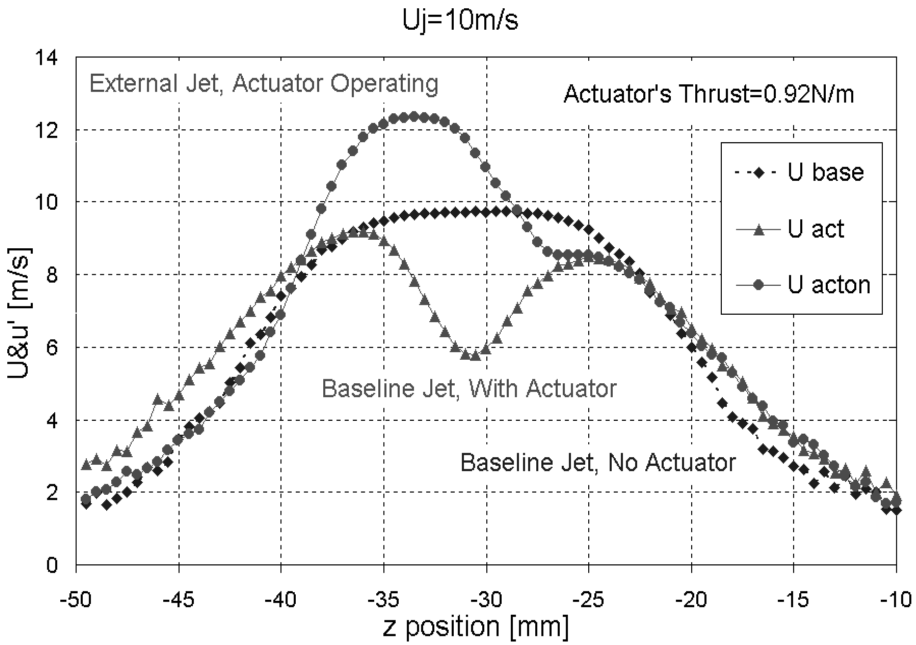
Performance of the actuator model shown above.
Force and required power (left ordinate) and RMS of slot exit velocity (right side ordinate).

Mean and RMS velocity due to flow entrained by periodic excitation in the absence of jet flow.

Oscillatory Momentum Generator







Velocity profiles showing actuator effect on Jet flow. Blue – jet without actuator, Red – passive Actuator, Green – operating actuator.

Summary – mUAV Activities

- Rugged, No Moving Parts mUAV (45cm, 225gr) proposed
- Real Low Re Effective Operation (10m/s) using AFC
- Available TAU Piezo cavity Installed Actuators
-
- Controls Aspects (later)
- Guidance (at work)

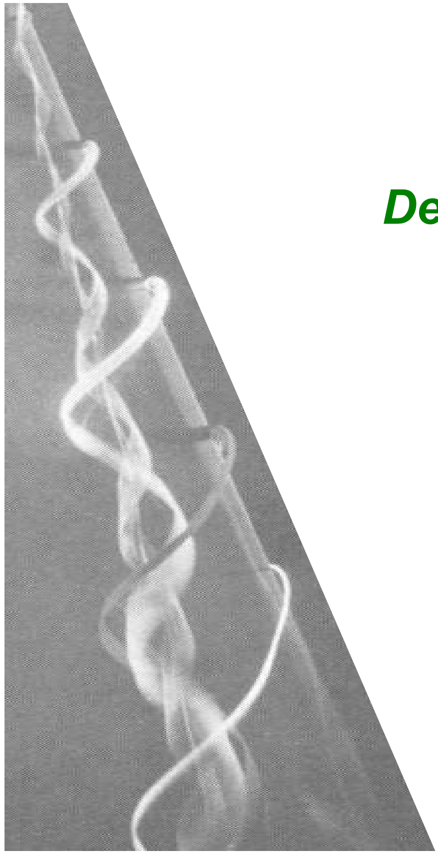
Active Flow Control of a Delta Wing at High Incidence using Segmented Piezoelectric Actuators

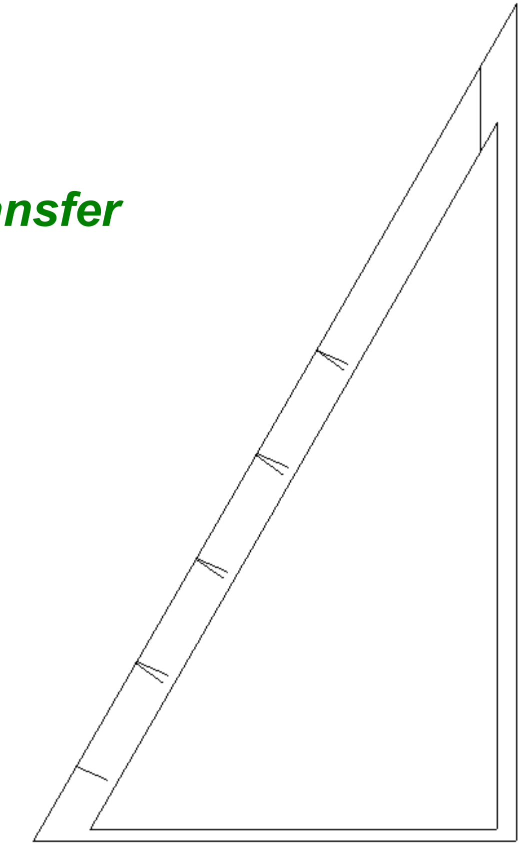
S. Margalit (M.Sc. Student)

Faculty of Mechanical Engineering

Department of Fluid Mechanics and Heat Transfer

Tel-Aviv University





Background & motivation

- The Delta wing is used in jets planes, space shuttle and missiles
- Problematic maneuvering at low speed, high angles of attack
- Vortices → Lift (at high angles of attack)
- Vortex breakdown → stall, loss of control

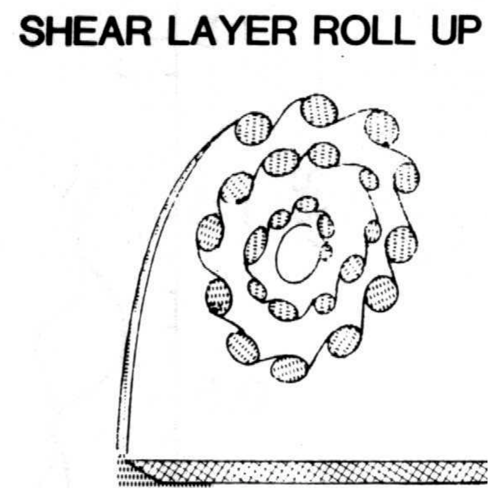
- Previous work :
  - Mechanical add ons , fixed or non fixed
  - Steady suction/blowing
  - Mass-less periodic excitation :
    - Does not alter external shape
    - No complex devices, No Plumbing
    - Fast response
    - Energy efficient

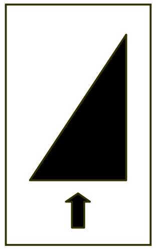
Our idea: A "2D" approach to a 3D problem

<u>**Previous periodic excitation from the leading edge**</u>

- **[Gad-el-Hak & Blackwelder 1987]**
- **[Bachar & Wygnanski 1997]**
- **[Guy et al 1999 , Siegel et al 2001]**

- **small vortices that shed from the leading edge roll up to form a large vortex.**
  [Payne & Nelson],[Gad-el-Hack & Blackwelder 1987]





Rear view of lateral cross section

shed small vortices → strengthen the primary vortex

The objective of the investigation

- Identify the optimal excitation parameters,
  by measuring the aerodynamic forces & moments, using a balance

- Understand the mechanisms of control effectiveness, using pressure and PIV data.

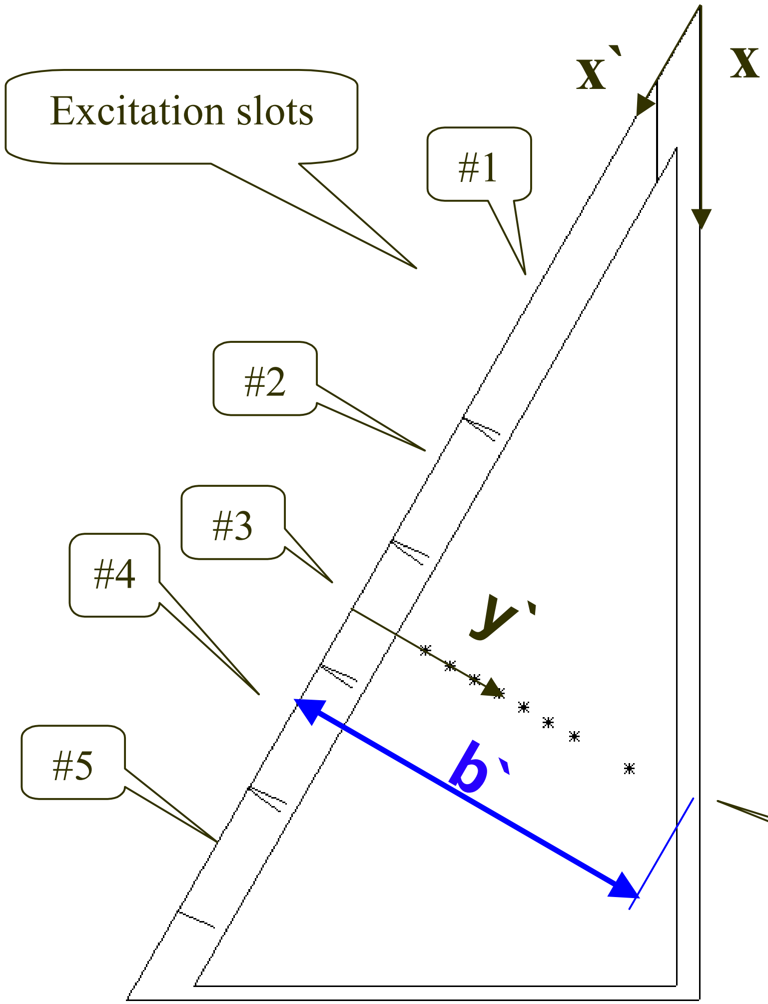
Questions of research

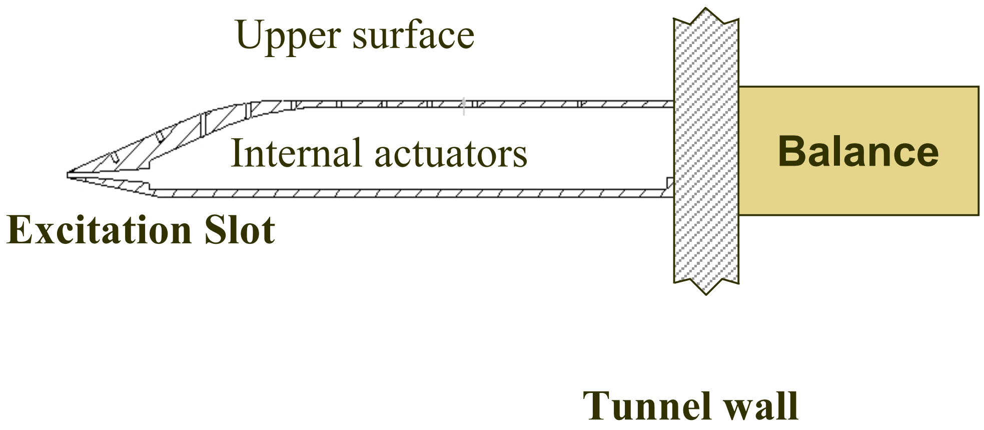
- Is the vortex breakdown delayed, is the vortex strengthened, or perhaps something else all together?

- What is the effect of the wind tunnel boundary layer?

- What is the Effect of Reynolds number?

The Delta wing and actuators slots



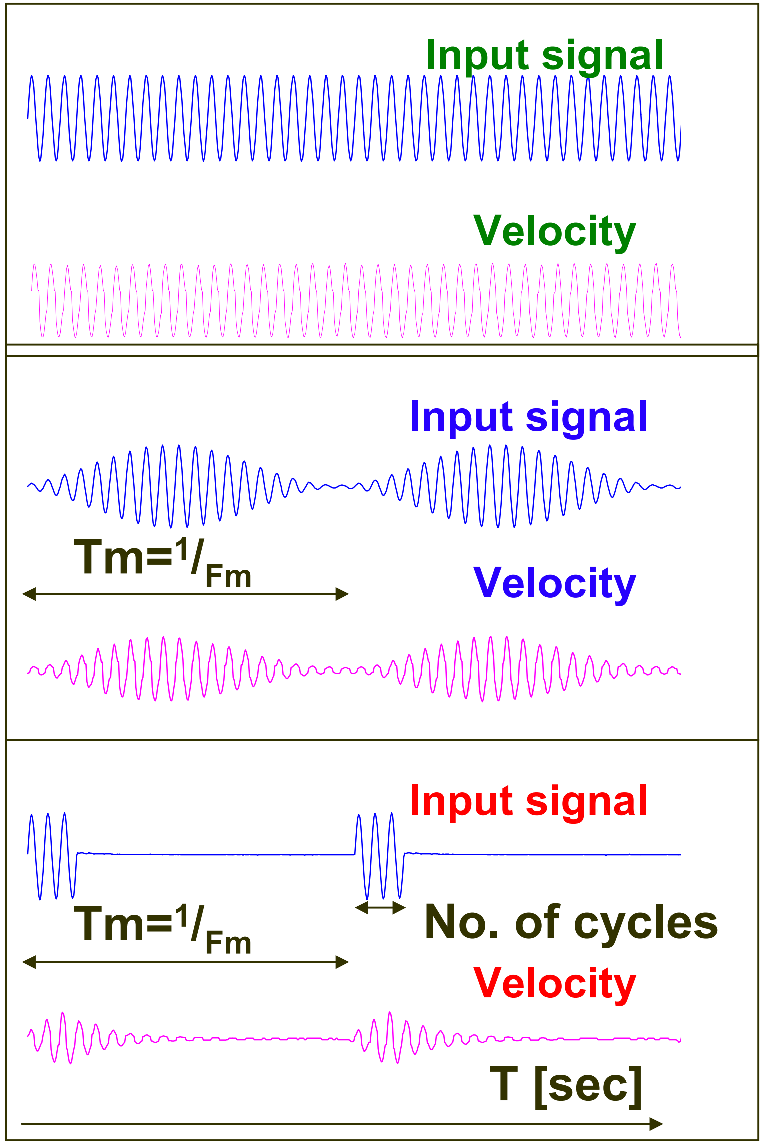


Excitation waveforms

Pure Sine

AM
(Amplitude Modulation)

BM
(Burst Mode)
[Used by Amitay et al 1998]



Non dimensional frequency

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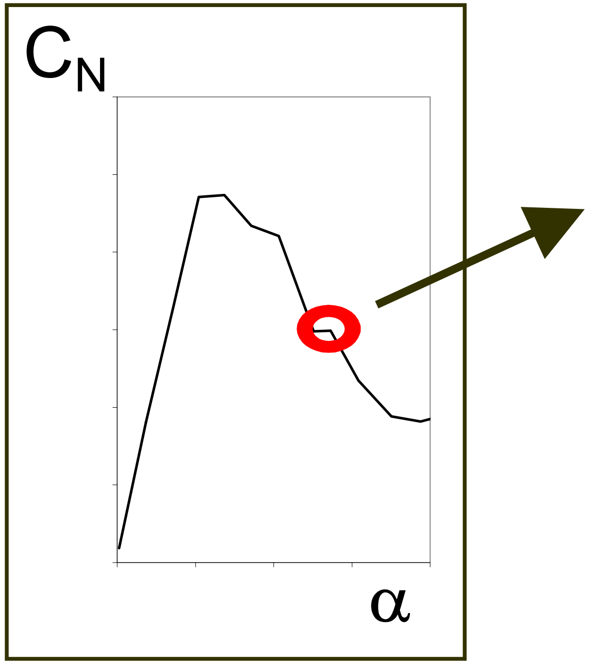
Oscillatory momentum coefficient

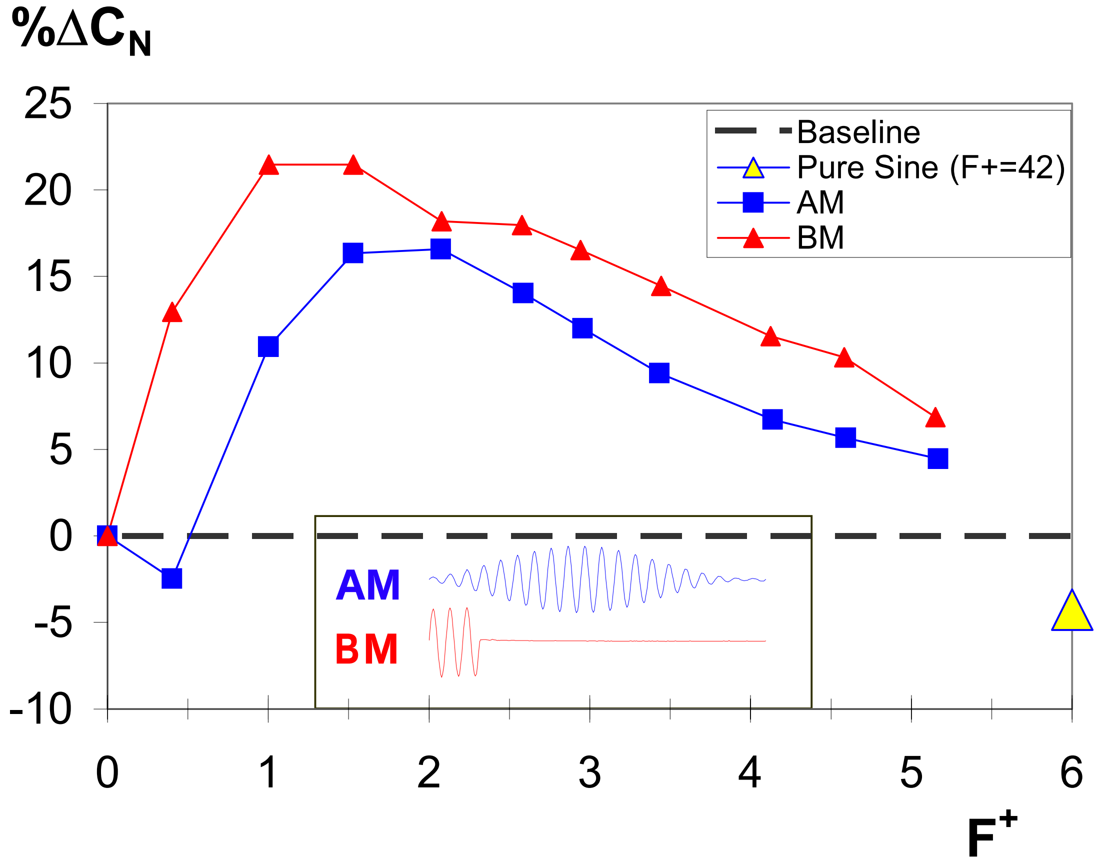
$$C_{\mu} \equiv \frac{\langle u` \rangle^{2} A_{slot}}{\frac{1}{2} U_{\infty}^{2} A_{wing}}$$

f=modulating or actuators frequency
C=root chord
U_{∞}=free stream velocity
A_{wing}= wing area
A_{slot}
<u`>=excitation velocity fluctuations

Delta Wing - Frequency effect: AM and BM

- BM → larger enhancement
- BM→ wider frequency response
- Sine →Negative effect





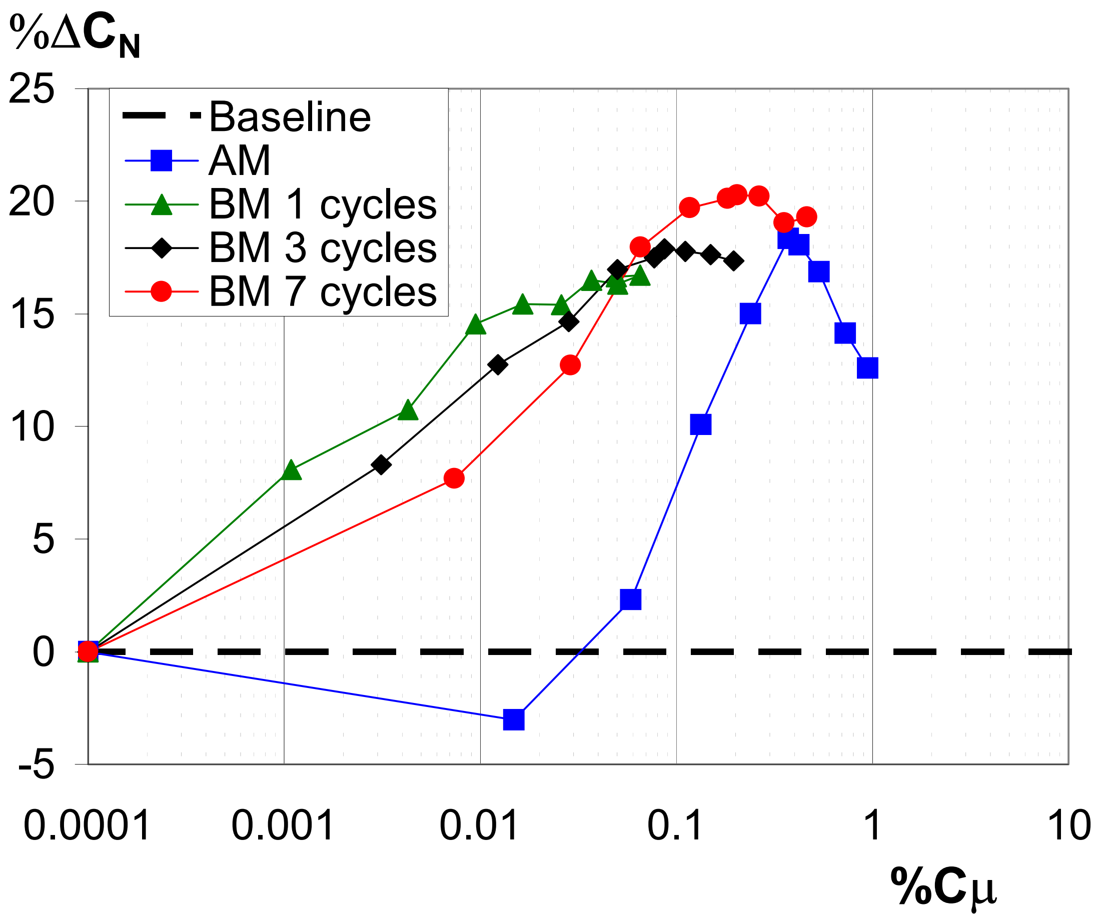
Excitation voltage 75 volt.

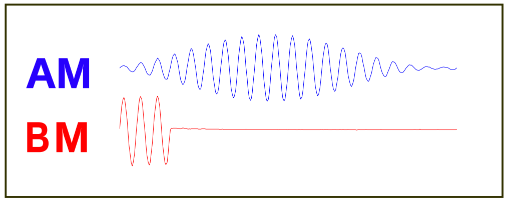
AM: $C\mu$=0.41%; BM: 3 cycles $C\mu$ increase with F^+.

Re=234k, angle of attack 37.8°

Excitation Momentum effect : AM & BM

- **BM is more effective than AM at much lower input**
- **BM responses at extremely low input**
- **Restitution at exit peak velocity of the order of the free stream.**



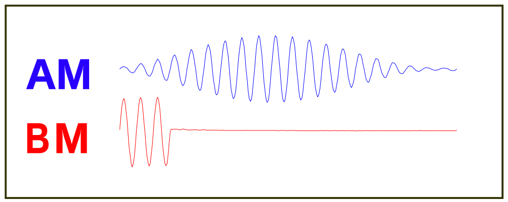


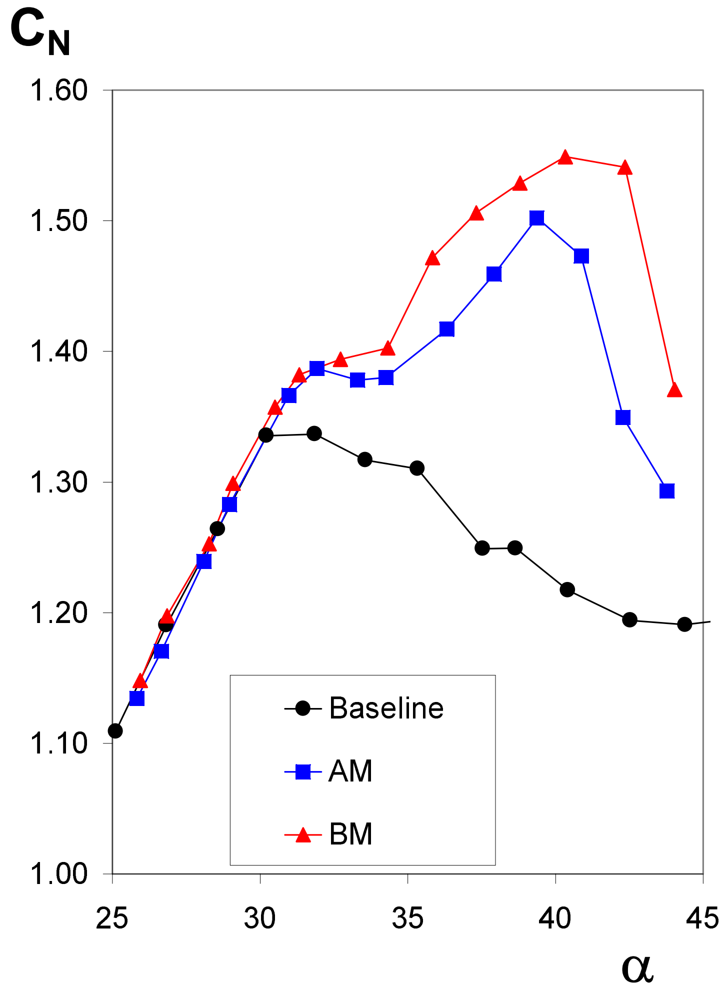
Excitation: BM: $F^{+}=2.0$, $C\mu$ changed by amplitude.

Re=234k, angle of attack 37.8°

Normal force vs. angle of attack: AM&BM

- BM enhances normal force by up to 27%
- BM excitation momentum is an order of magnitude less than AM
- The "dent" was improved

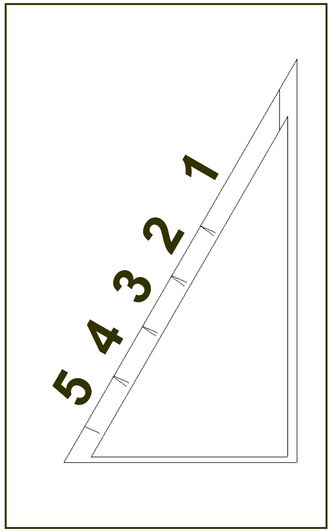


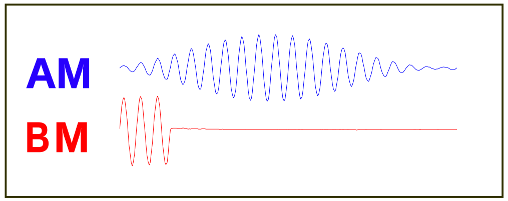


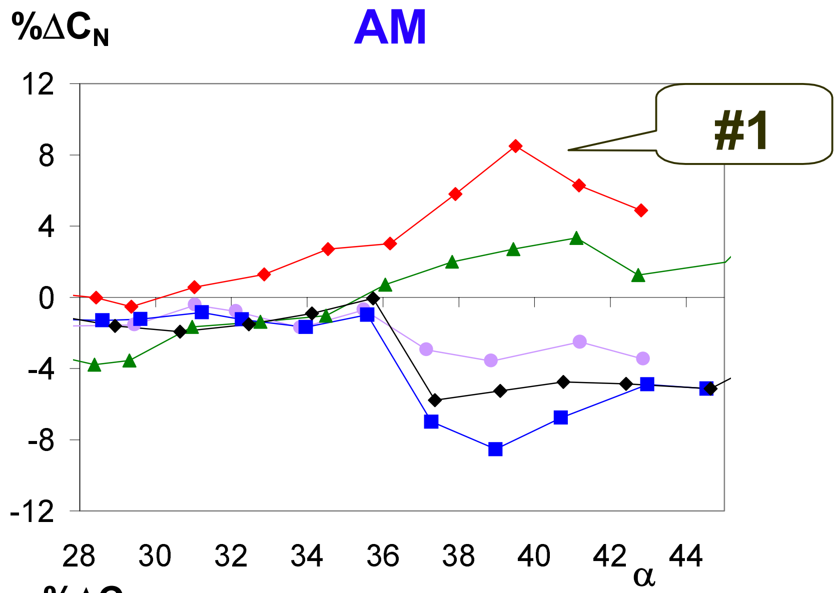
Excitation: AM: F^+=2.0, $C\mu$ 0.41%.
BM: F+=1.0, $C\mu$=0.03%.
Re=234k

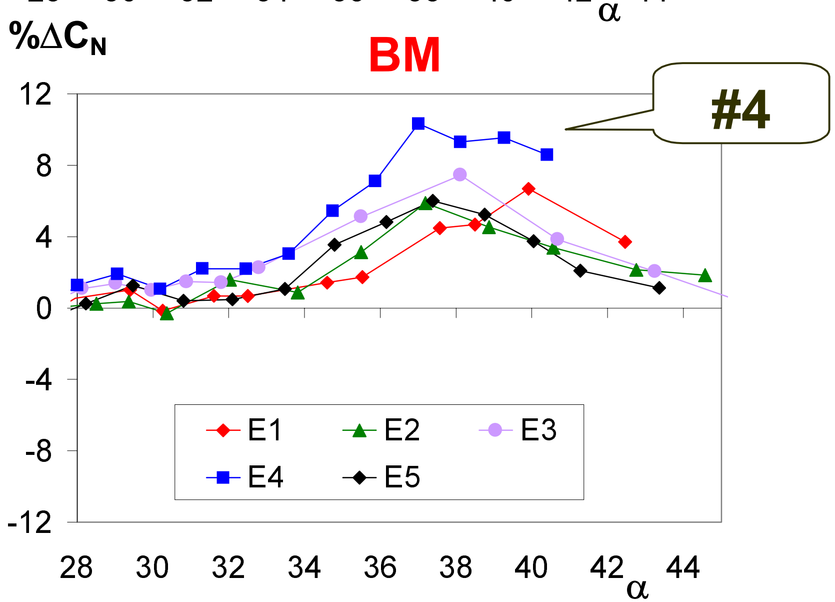
Delta Wing -Separate activation of actuators

- AM most effective near apex
- BM most effective close to trailing edge
- At AM slots 3-5 degrade C_N
- Beneficial for rolling control







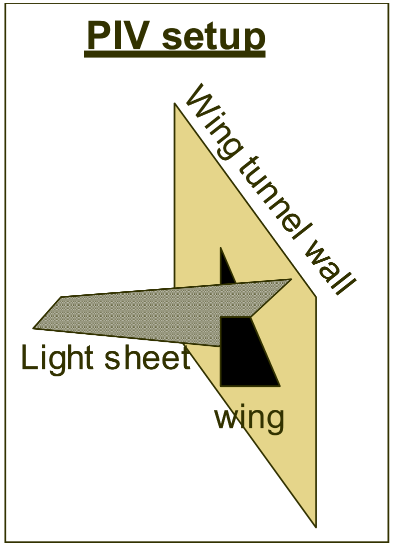


Excitation: AM,F^+=2.0, $C\mu$=0.19%

BM, 3 cycles,F^+=1.0, $C\mu$=0.006%

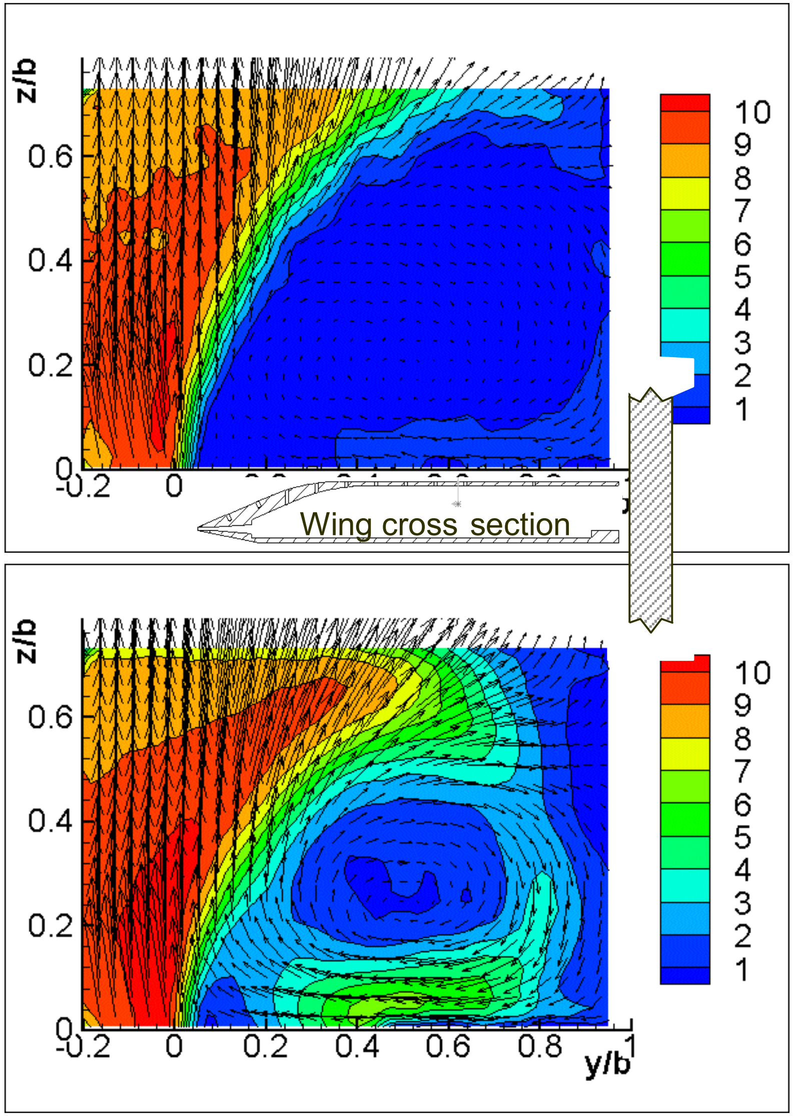
Delta Wing - Cross stream Velocity (PIV) at X/C=0.6

- **Shear layer→ closer to wing**
- **Stagnant bubble → vortical flow**
- **Velocity enhancement**



Baseline

BM Excitation
Avg of 8 phases



PIV avg of 100 image pairs
Angle of attack 37.8º
Re=234k
Excitation: BM, F+=1.0, Cμ=0.003%.

Delta Wing - Summary

- Installation of Piezo actuators in very tight space
- Generation of Low Frequency Excitation through Amplitude Modulation and Burst Mode and Non-linear Interaction
- O(10^{-2}) Saving in Energy due to VERY Low Duty Cycle
- Control and Guidance Aspects

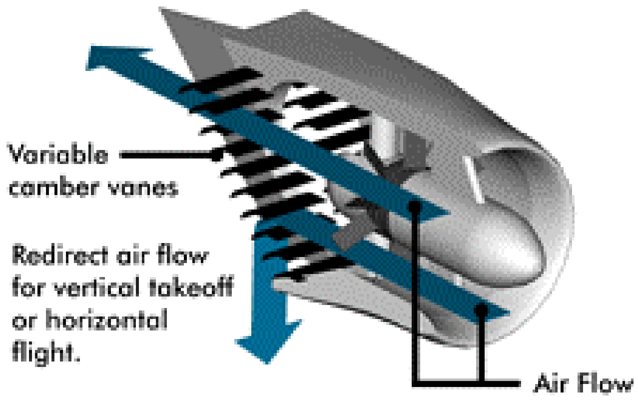
Closed-loop Vectoring Control of a Turbulent Jet Using Periodic Excitation

Aerolab

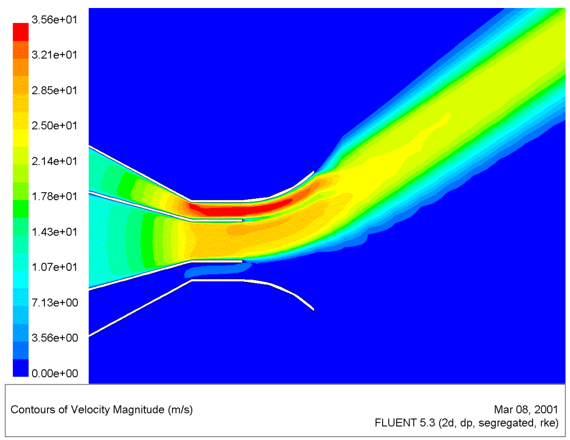
D. Rapoport (M.Sc. Student)

Background

- **Mechanical strategies pros & cons:**
  - ✓ **Significant engine jet deflection angles**
  - ✖ **Weight and Thrust penalty**
  - ✖ **Slow response**



- **Fluidic strategies pros & cons :**
  - ✓ **Fast response (bandwidth around 50 Hz).**
  - ✓ **No moving parts.**
  - ✖ **Moderate deflection angles.**



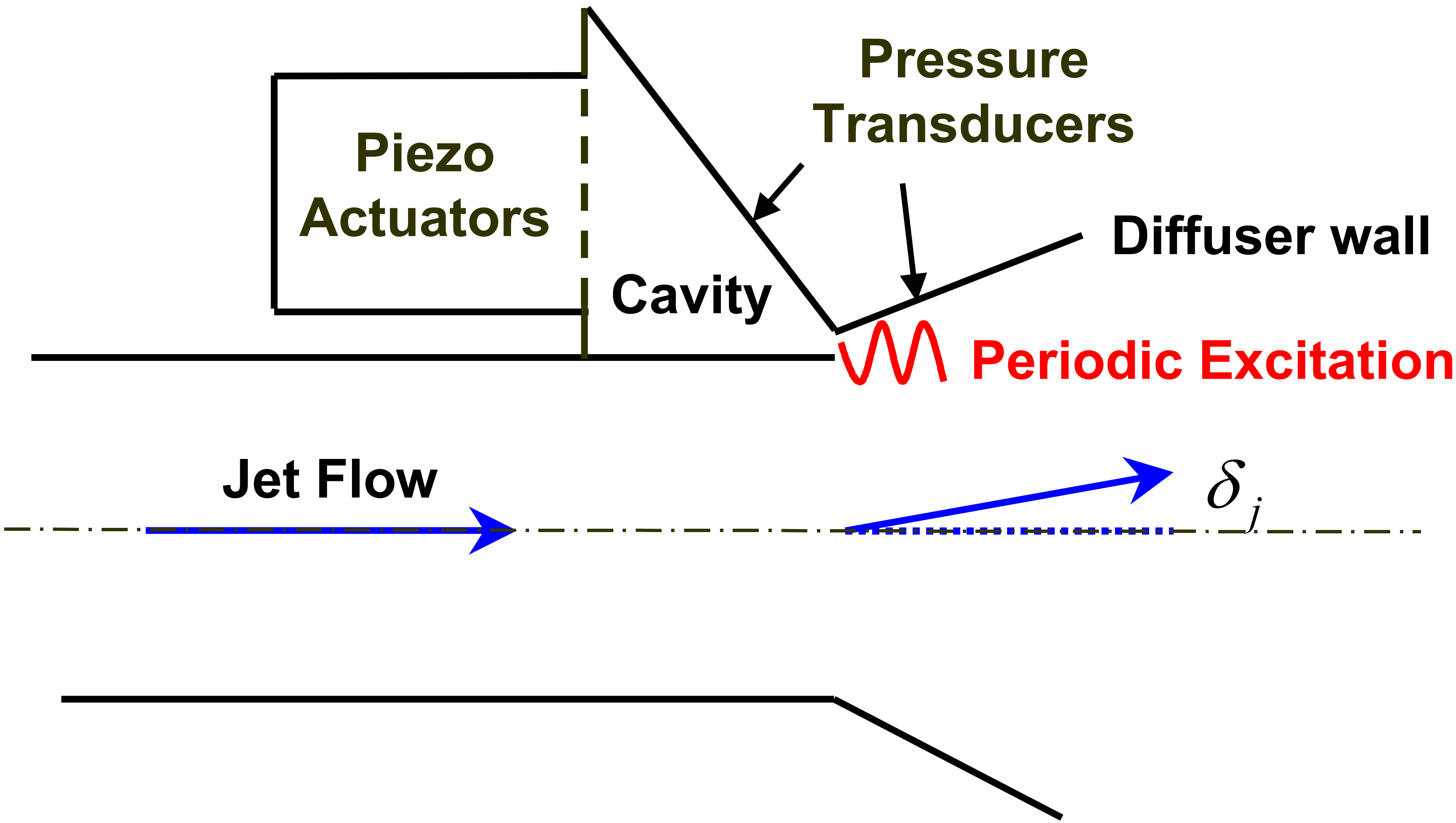
Motivation – Jet Vectoring

- Applications for fluidic jet vectoring
  - Gust alleviation
  - Engine out performance
  - mUAV Guidance

- Closed-loop control motivation
  - Enabling fast and smooth transitions between stationary deflection angles
  - Maintaining desired vectoring angles under varying system conditions

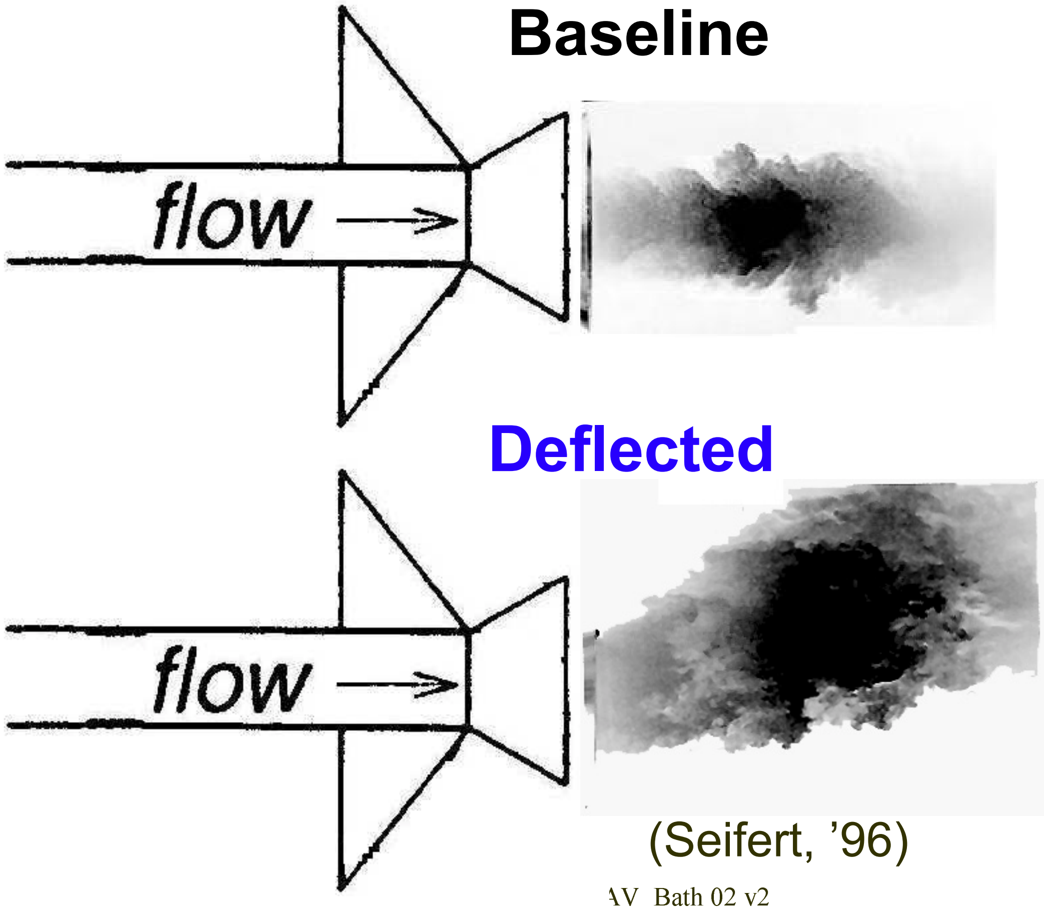
Experiment

Axis-symmetric Circular Jet, Diffuser, Excitation



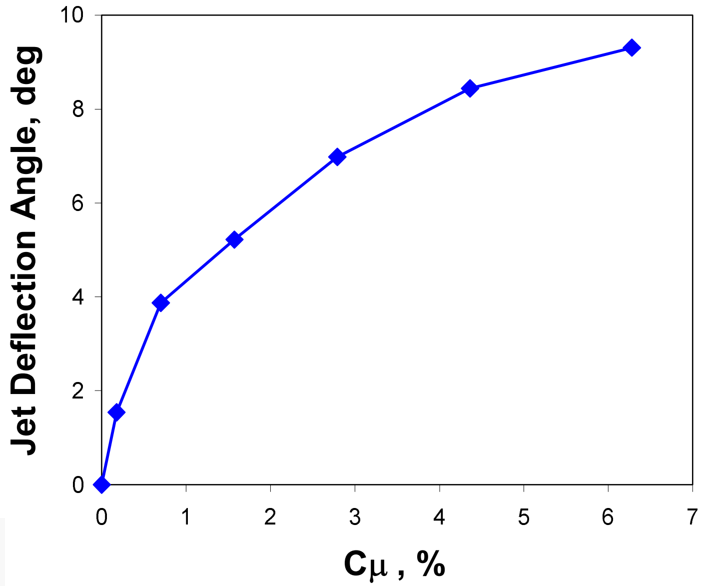
Jet Vectoring using AFC

- **Jet vectoring using periodic excitation acting only on the upper quarter of the jet circumference:**



(Seifert, '96)

Data from current setup

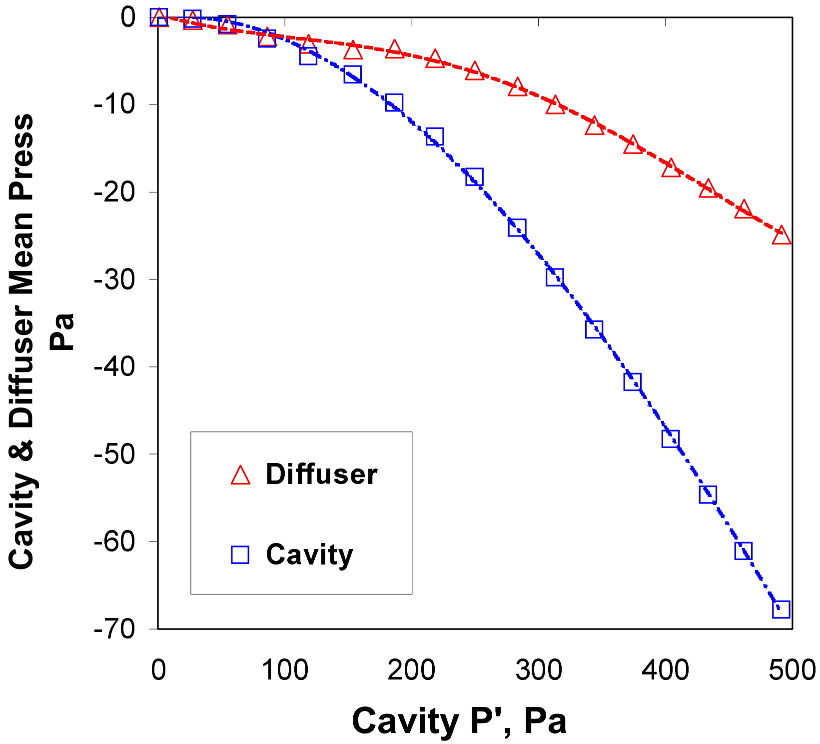


$$C_\mu \equiv \frac{j'_{slot}}{J_{jet}} = \frac{\rho A_{slot} u'^2_{slot}}{\rho A_{jet} U^2_{jet}}$$

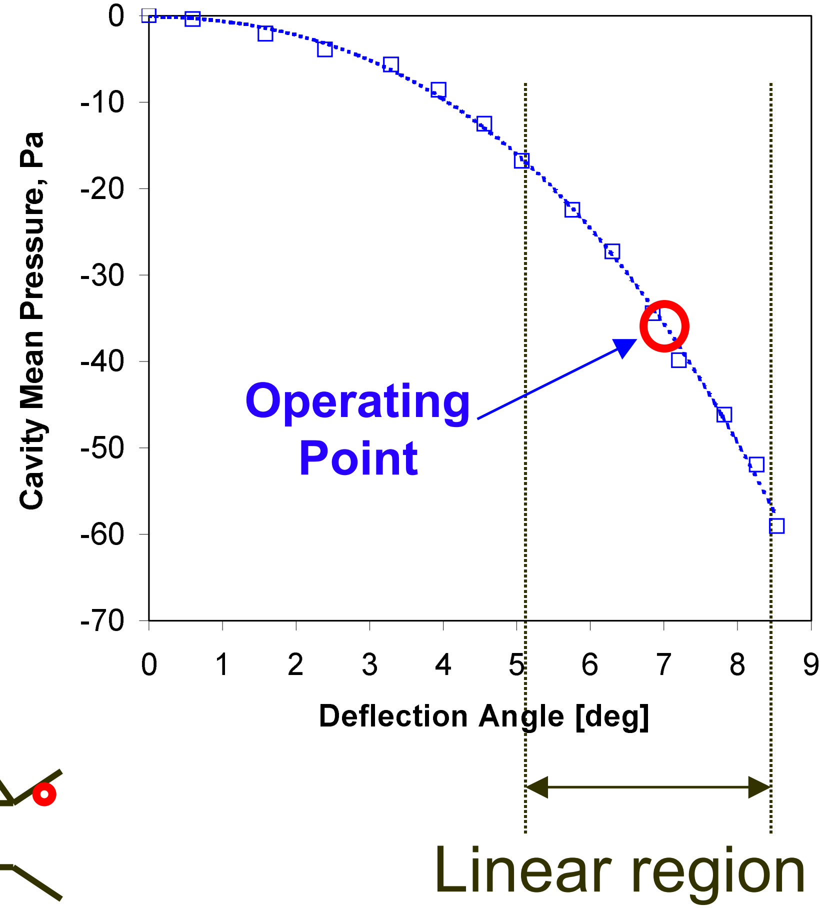
Less Sensitive to F^+

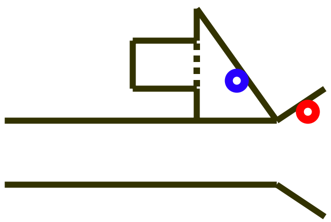
Static Measurements

Cavity and Diffuser Mean Pressures vs. p'



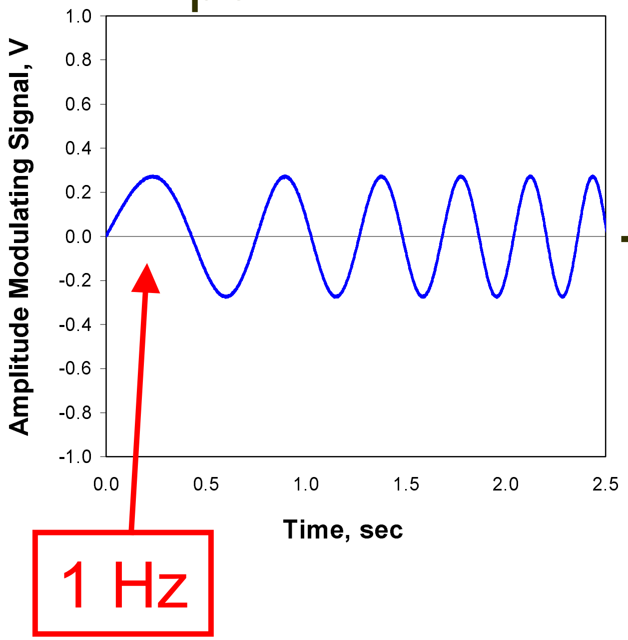
Cavity Mean Pressure vs. Jet Deflection Angle



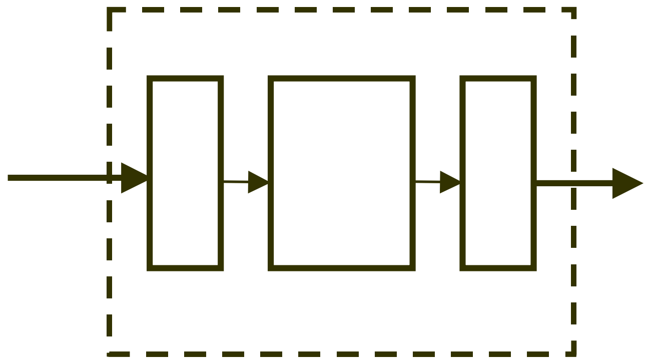


Plant's Model Identification (Freq. Sweep 1-90Hz)

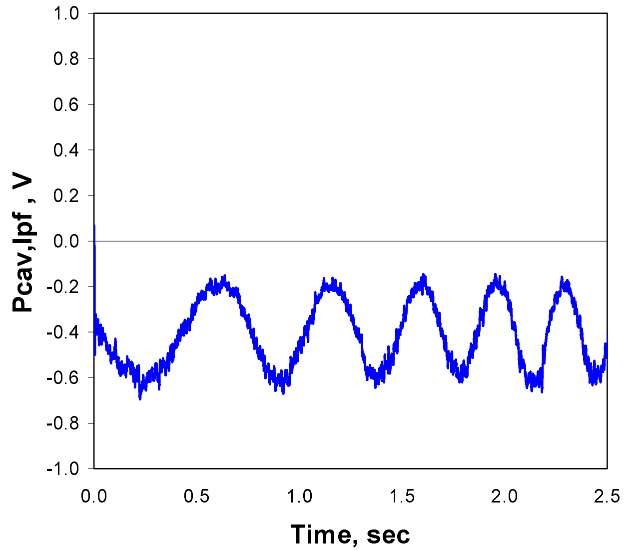
Input



Plant

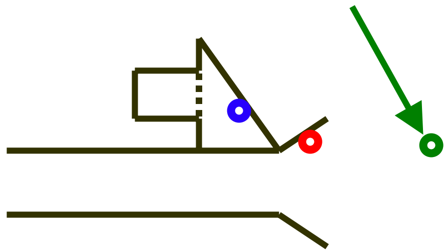


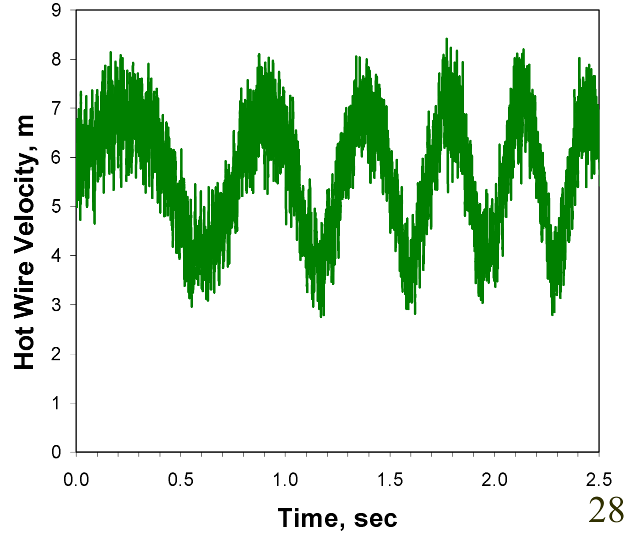
Output (LPF Cavity P)



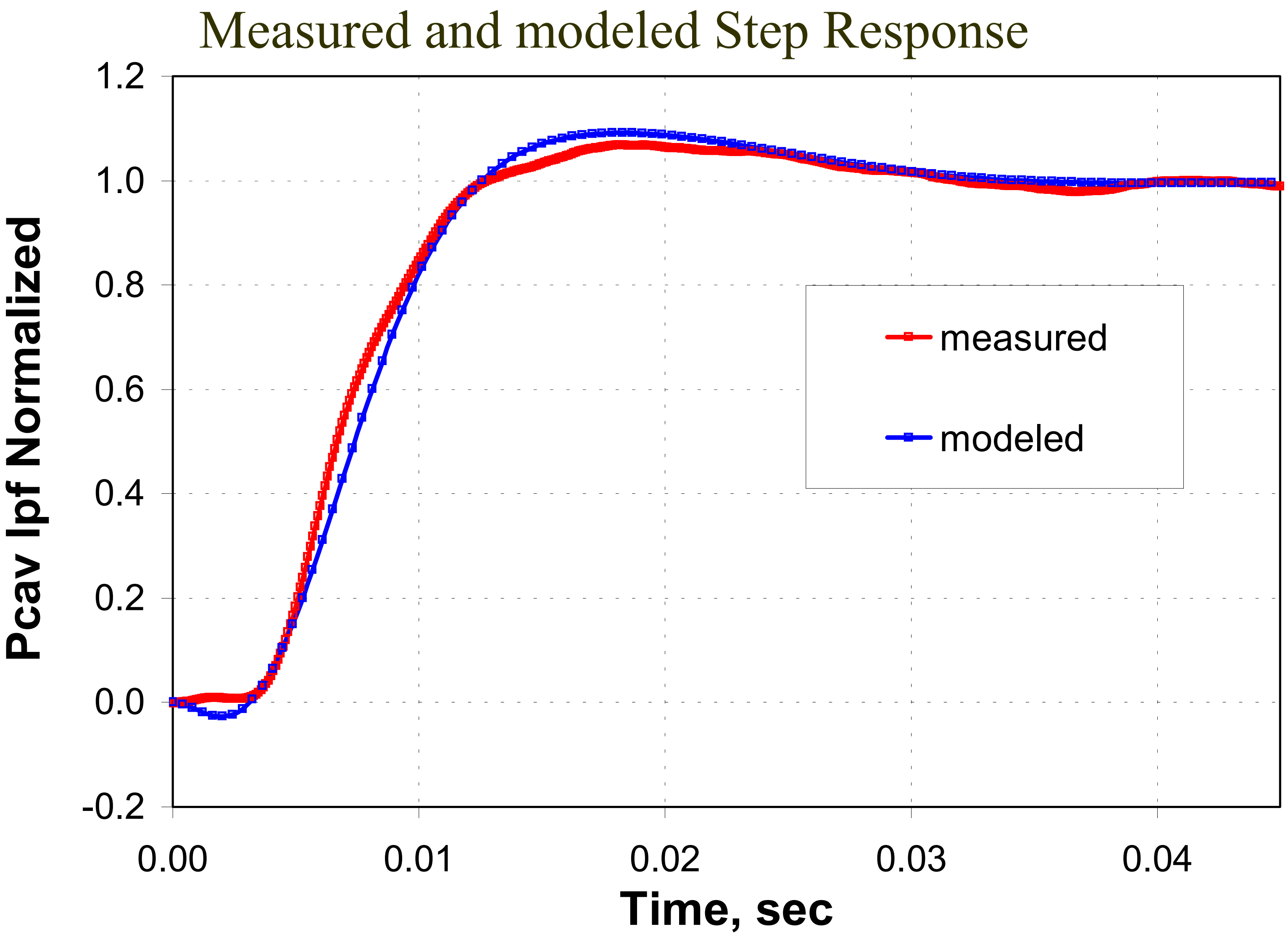
First 2.5 sec

HW Measurement
In the Shear Layer





Closed–loop Step Response



Jet Vectoring Control - Summary

- **Closed-loop LINEAR jet vectoring Control:**
  - Using Only one Sensor @ Actuator's Cavity for:
    - Health Monitoring
    - System INPUT
    - Jet Deflection Indicator (to close the loop)
  - Zero steady-state error
  - Small overshoot (less than 10%)
  - Bandwidth ≈ 50Hz ($S_{td} \approx 0.17$)
- **The Linear Controller performs reasonably well over the entire range of deflection angles (outside the design envelope)**