Minnowbrook VI, August 2009

Amplitude Scaling of Active Separation Control

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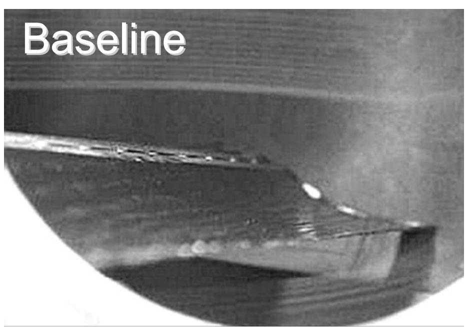
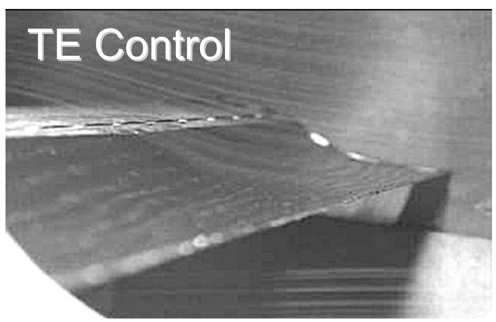
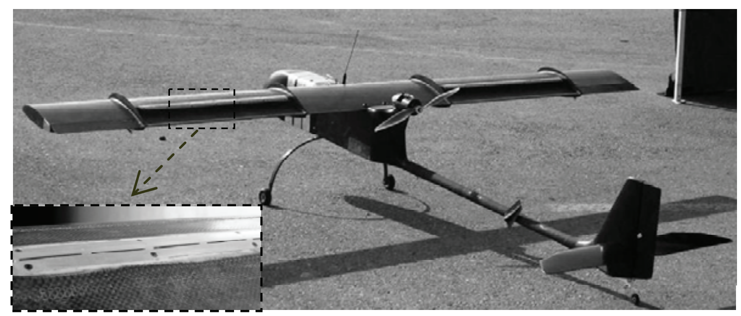


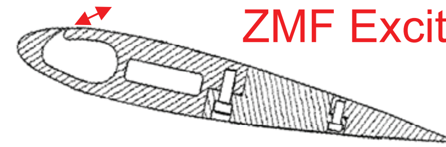


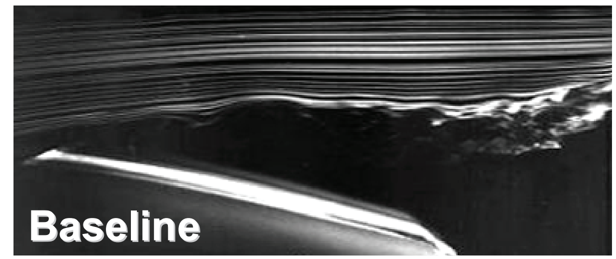


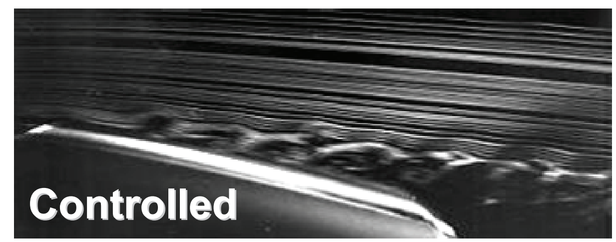
Acknowledgment:
I. Fono, G. Arwatz, T. Yehoshua, E. Ben-Hamou, I. Dayan
S. Pasteur, E. Nevo, Kronish, Blas, Meadow Aero Lab members

Motivation

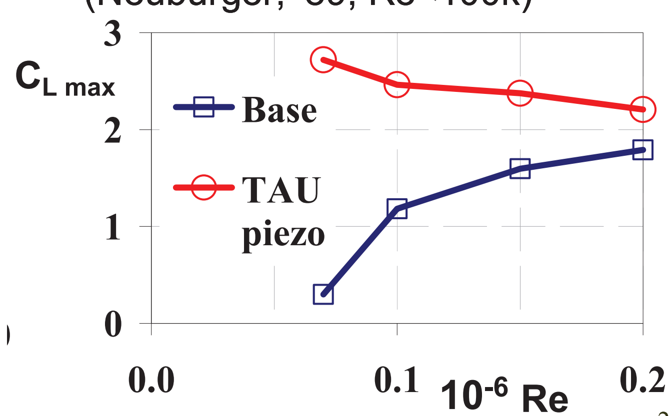
- **Active control of boundary layer separation leads to many benefits**
- **Frequency parameter: Strouhal (*F*⁺)**
- **Length scale under controversy**
- **Amplitude scaling?**
- **We use Cμ – historically, steady blowing**
- **But does it scale the data?**
- **Are there other parameters we should consider?**
- **We revisit here known and define 2 new amplitude scaling parameters**
- **Check their validity using low Re data ($Re<1x10^6$)**







(Neuburger, '89, Re<100k)



Amplitude scaling - 1

- **Velocity Ratio**

$$VR \equiv \frac{U_p}{U_e} \approx \frac{U_p}{U_\infty}$$

- **U_p- peak excitation velocity**
- **U_e- local external velocity**
- **U_∞- free-stream velocity**

- **Actuator Mach number over free-stream Mach number**
- **Implies linearity**

(Yehoshua)

Amplitude scaling - 2

- **Momentum coefficient**

$$C_\mu \equiv \frac{h}{c}\left(\frac{U_p}{U_\infty}\right)^2 = \frac{h}{c}(VR)^2$$

- **Ratio between (incomp., isoth.)**
  - **Excitation momentum (*h*=slot width)** hU_p^2
  - **Free stream momentum (*c*=chord)** cU_∞^2
- U_p **- peak excitation velocity**
- U_∞ **- free-stream velocity**
- ***h* – slot width, *c* – airfoil chord**
- **Follows steady-blowing concept**

(Yehoshua)

Amplitude scaling - 3

Reynolds # corrected momentum coefficient

- Ratio between
  - Excitation momentum $\approx hU_p^2$
  - BL momentum deficit $\approx \theta U_\infty^2$
- Laminar momentum thickness $\frac{\theta_{Lam}}{c} \approx \mathrm{Re}^{-0.5}$
- Turbulent momentum thickness $\frac{\theta_{Turb}}{c} \approx \mathrm{Re}^{-0.2} \Rightarrow \theta_{Turb} \approx c\,\mathrm{Re}^{-0.2}$

$$C_{\mu,\mathrm{Re}} \equiv \frac{h}{\theta}\frac{U_p^2}{U_\infty^2} \approx \frac{h(VR)^2}{c\,\mathrm{Re}^m} = \frac{h}{c}(VR)^2\,\mathrm{Re}^{-m}$$

(Yehoshua)

Vorticity-flux / Circulation - 4

- **Actuator's vorticity flux (blowing, half slot width)**

$$VF \approx \int_0^{T/2}\int_0^{h/2} \omega_z(y,t) U_p(y,t)\,dy\,dt$$

$$VF \approx \int_0^{h/2}\int_0^{T/2} U_p(y,t)\frac{dUp(y,t)}{dy}dt\,dy$$

$$VF \approx \frac{U_p^2}{h}\frac{hT}{4} \approx \frac{U_p^2 T}{4} \approx \frac{U_p^2}{4f}$$

- **Kutta-Zhukovsky**

$$C_L = \frac{\rho_\infty U_\infty \Gamma}{1/2\rho_\infty U_\infty^2 c}$$

- **Circulation**

$$\Gamma = cC_L U_\infty$$

- **Vorticity-flux coefficient**

$$C_\Gamma \equiv \frac{Slot\_Vorticity\_Flux}{Baseline\_Circulation} \approx \frac{U_p^2 T}{4\Gamma_{Baseline}}$$

$$C_\Gamma \approx \frac{U_p^2 T}{4cC_L U_\infty} = \frac{1}{4C_L}\left(\frac{U_p}{U_\infty}\right)^2 \frac{1}{S_t} = \frac{(VR)^2}{4C_L S_t}$$

Frequency corrected VR - 5

- Nagib et al (2006)
- Proposed to scale AFC effect on lift using

$$H \equiv \frac{U_p / U_\infty}{\sqrt{fc/U_\infty}} = \frac{VR}{\sqrt{S_t}}$$

- Velocity ratio
- Strouhal number

- For large separated regions
- Low frequencies
- Problematic at $f \rightarrow 0$ …

(Yehoshua)

Amplitude Scaling Options

- **Velocity ratio (VR)**

$$VR \equiv \frac{U_p}{U_e} \approx \frac{U_p}{U_\infty}$$

- **Strouhal weighted VR (Nagib et al, 2006)**

$$H \equiv \frac{VR}{\sqrt{S_t}}$$

- **Momentum coefficient**

$$C_\mu \equiv \frac{h}{c}(VR)^2$$

- **Reynolds corrected C_μ**
  - ***m=0.2 (Turb.), m=0.5 (Lam.)***

$$C_{\mu,\mathrm{Re}} \equiv \frac{h}{c}(VR)^2\ \mathrm{Re}^m$$

- **Vorticity flux coefficient**

$$C_\Gamma \equiv \frac{(VR)^2}{C_L S_t}$$

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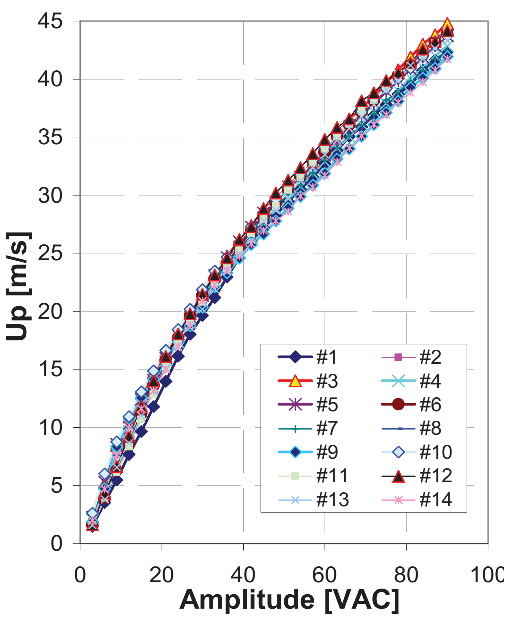
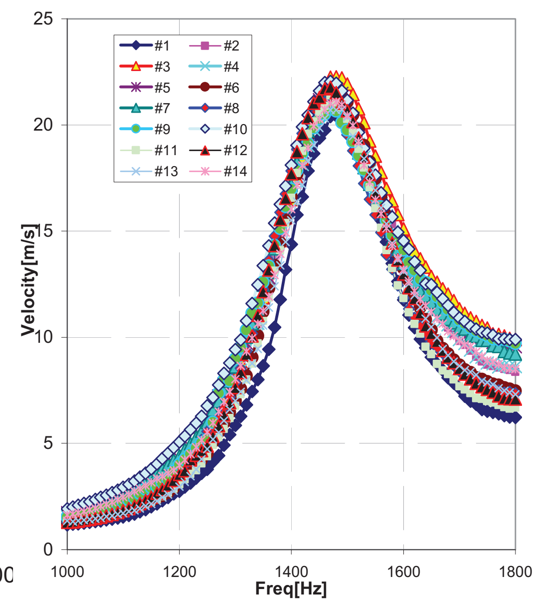
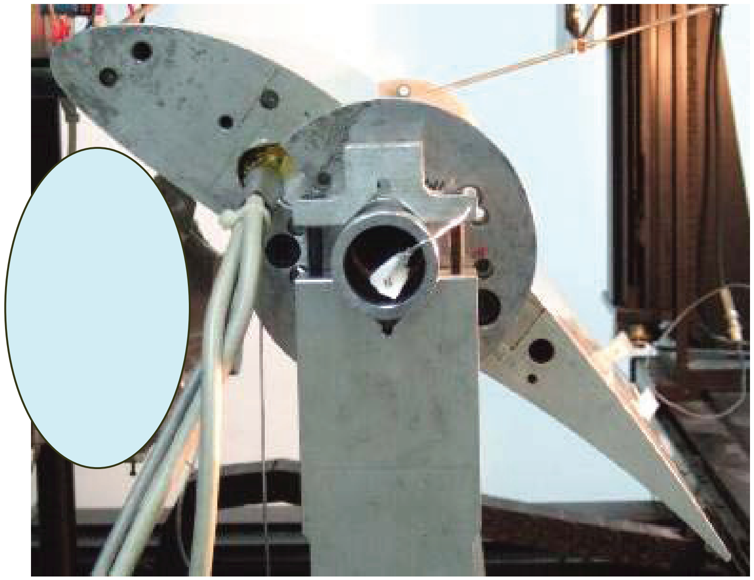
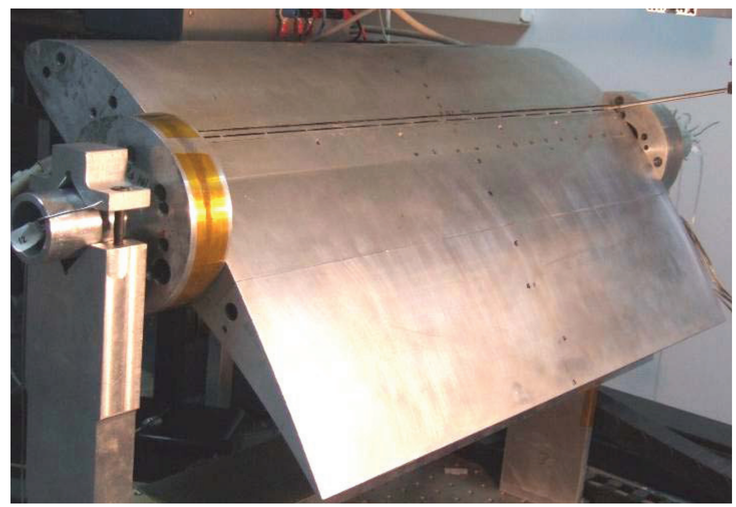
IAI-Pr8-40 Airfoil AFC Testing

- Chord 360mm, span 609mm
- Actuator at x/c=0.38
- Shallow angle, downstream excitation
- 14 segmented, individually controlled
- Piezo actuators ($f_{Helmholtz}$=1460Hz)
- Slots: 0.9mm by 40mm
- Power: 1.7w per actuator at 100vac



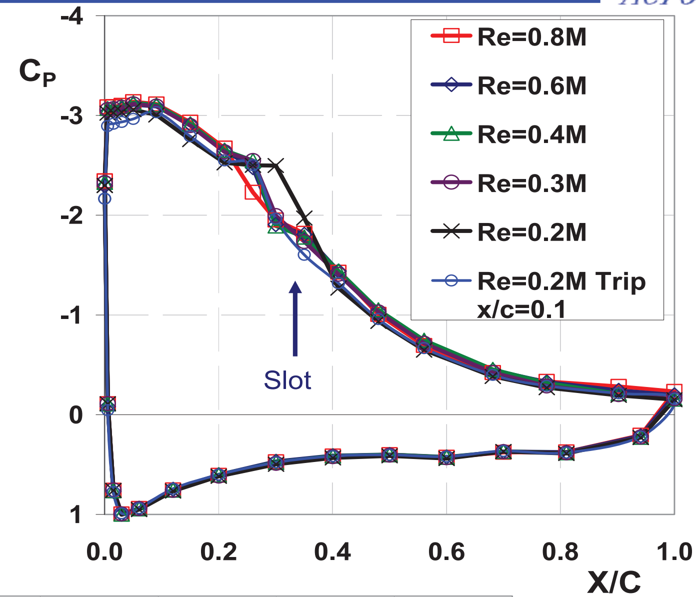


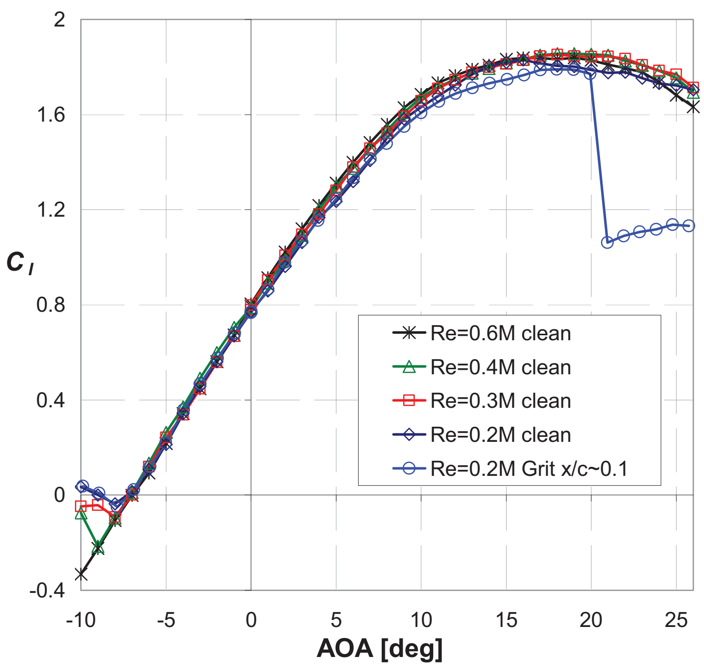


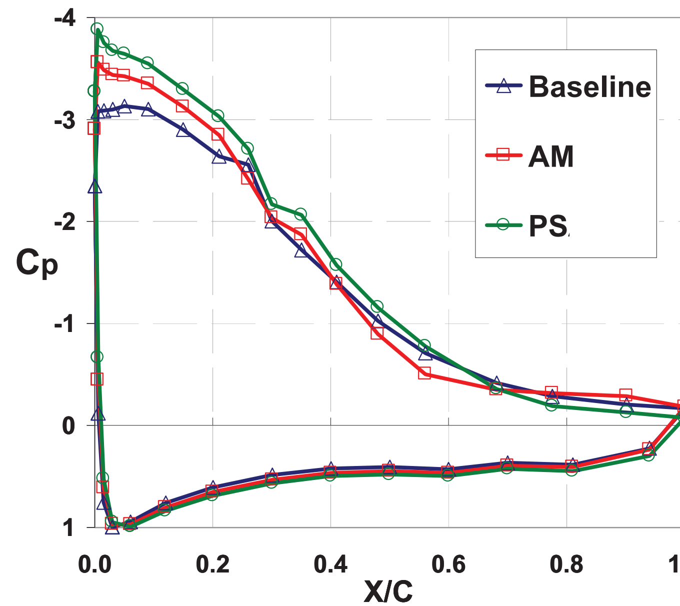


IAI-Pr8-40 Baseline

- Thick, Efficient, Low Re airfoil
- Mild, trailing edge stall
- Chord 360mm, span 609mm
- Actuator at x/c=0.38
- Shallow angle, downstream excitation
- 14 segmented, individually controlled
- Piezo actuators ($f_{Helmholtz}$=1460Hz)
- Slots: 0.9mm by 40mm



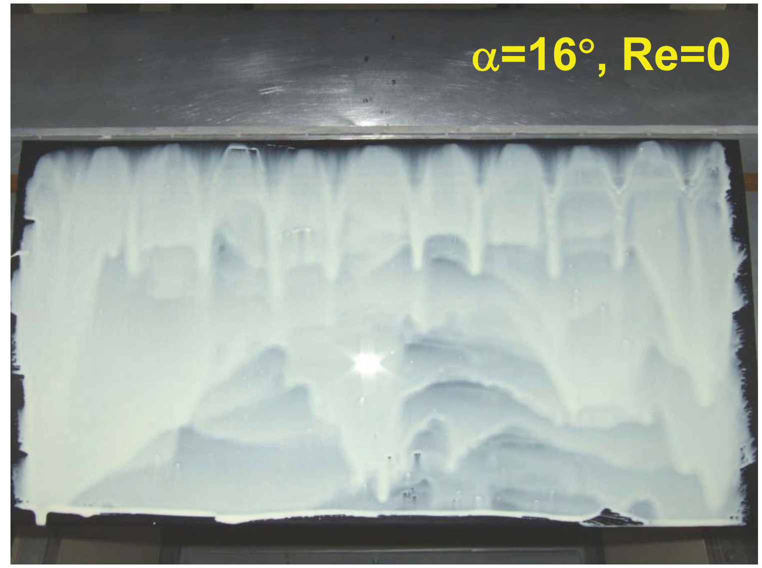


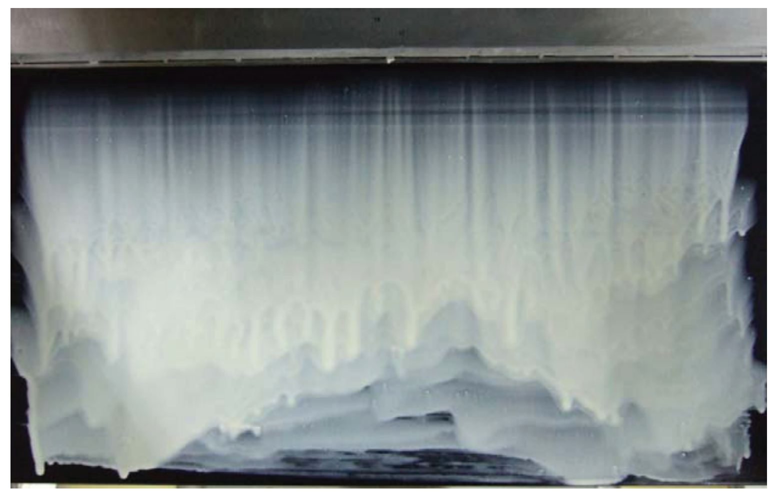


IAI-Pr8-40 Controlled

- Actuator at x/c=0.38
- Shallow angle, downstream excitation
- 14 segmented, individually controlled
- Piezo actuators ($f_{Helmholtz}$=1460Hz)
- Slots: 0.9mm by 40mm

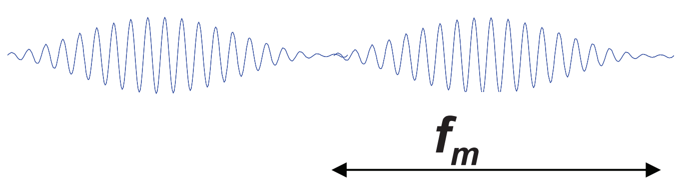
- Two modes of operation:
- Pure sine, Anti-phase, F^+>10
- AM, In-phase, F^+~1
- Control of TBL separation
- Conducted amplitude scans at otherwise fixed conditions
- Scale lift increment vs amplitude





α=16°, Re=0.3M

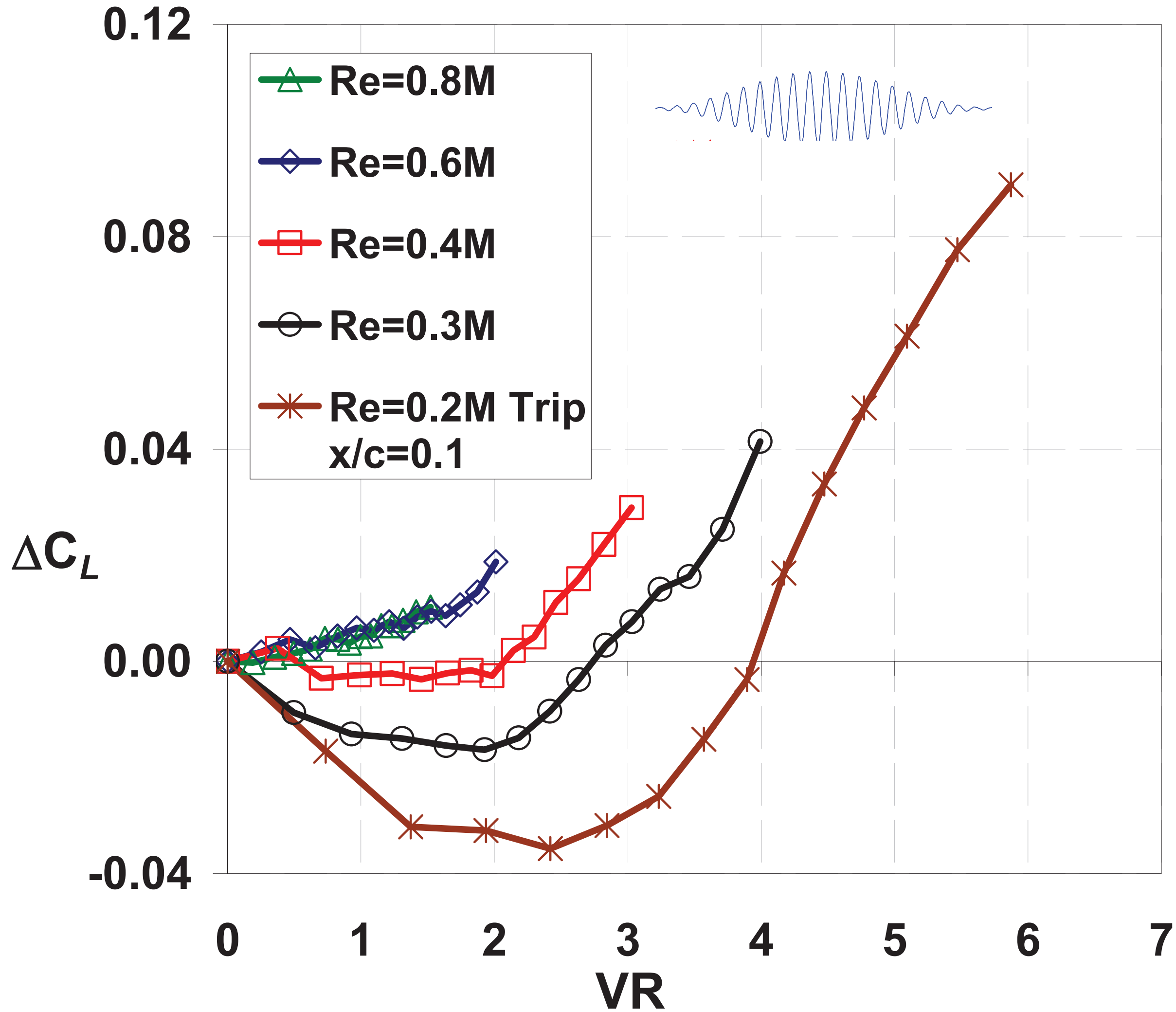
AM



Low Frequency Amp Scaling

- Velocity ratio (VR)

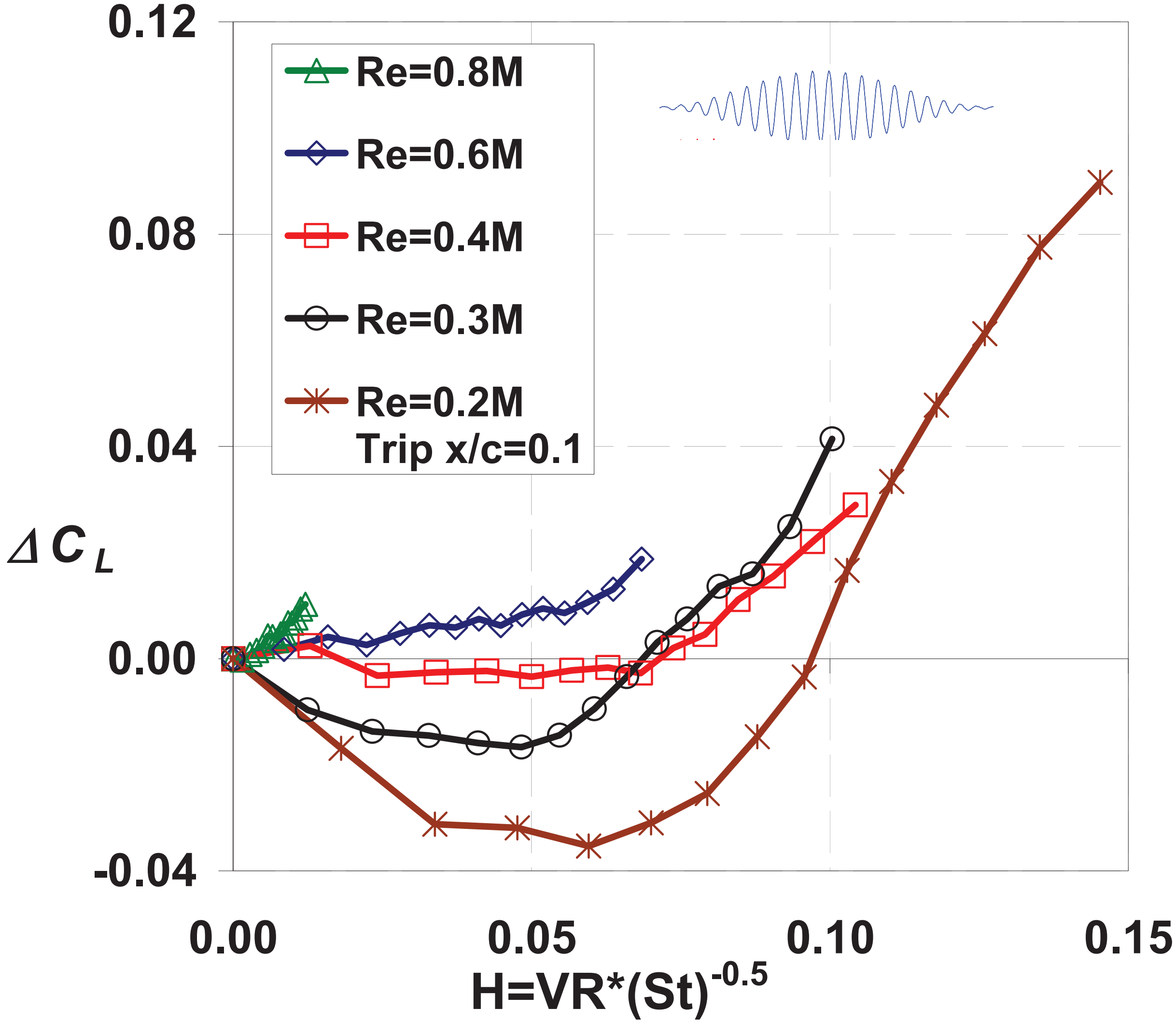
α=16°, AM, F+=1



Low Frequency Amp Scaling

- St corrected VR

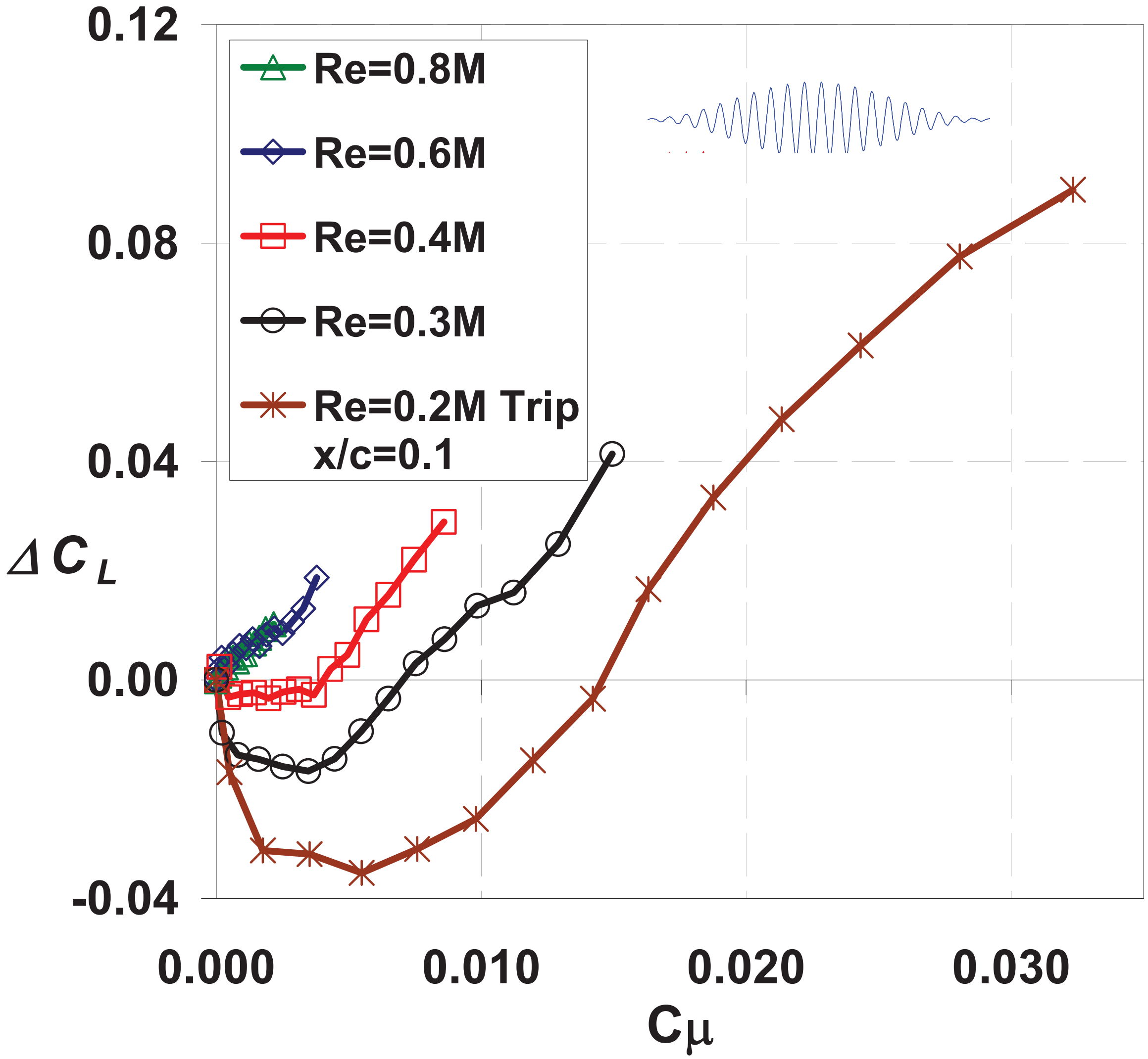
α=16°, AM, F+=1



Low Frequency Amp Scaling

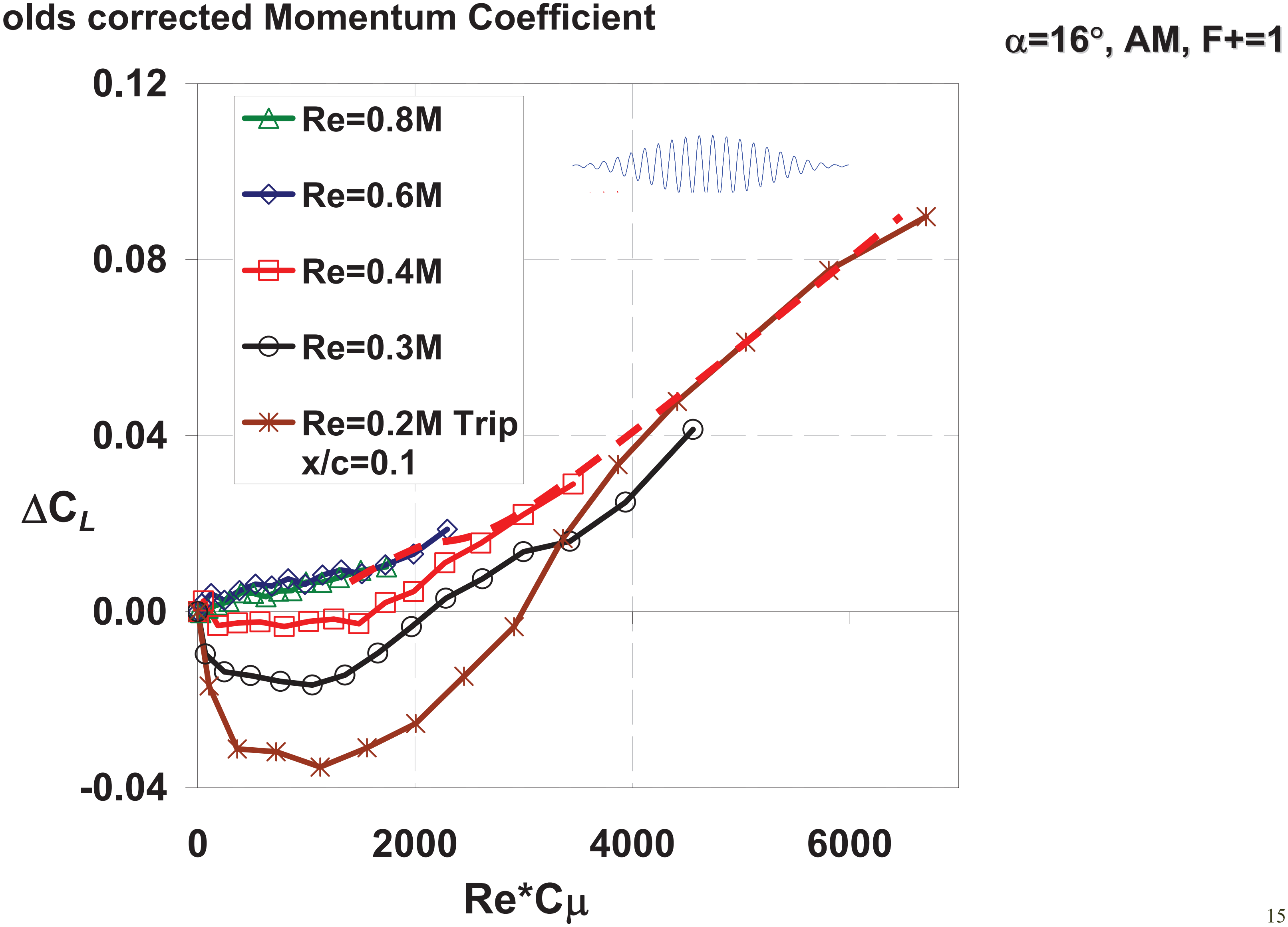
- Momentum Coefficient

α=16°, AM, F+=1



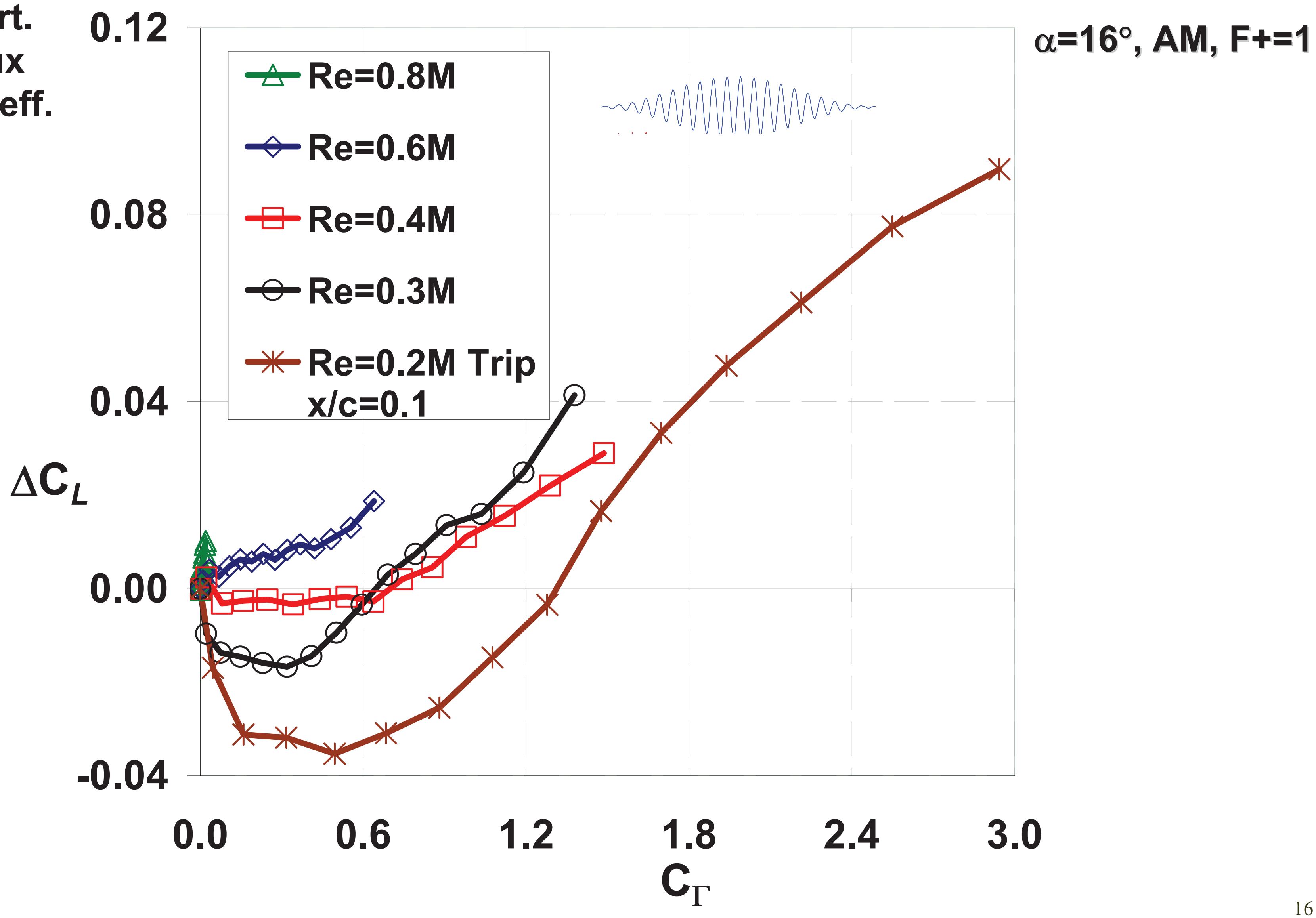
Low Frequency Amp Scaling

- Reynolds corrected Momentum Coefficient



Low Frequency Amp Scaling

- Vort. Flux Coeff.



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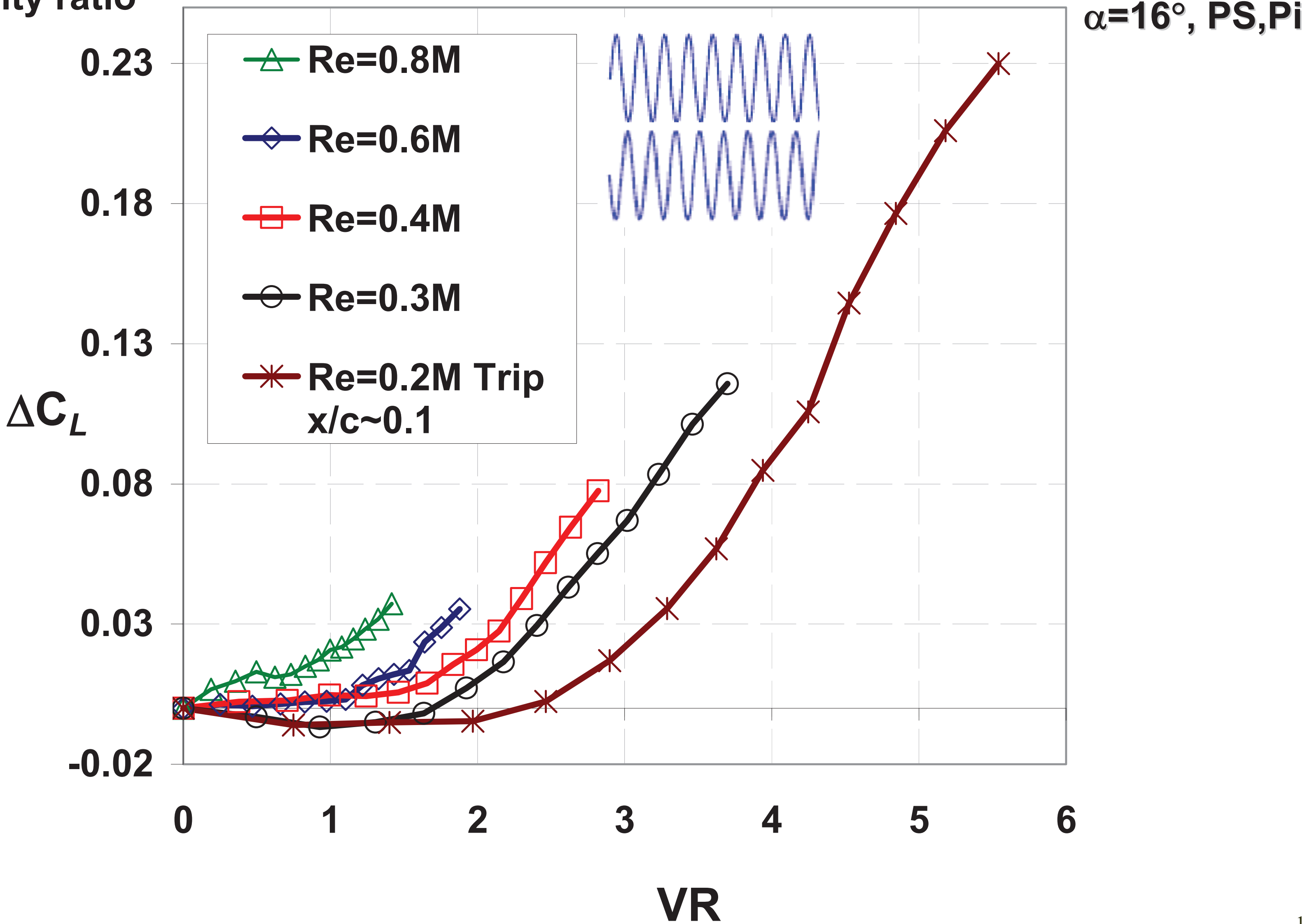
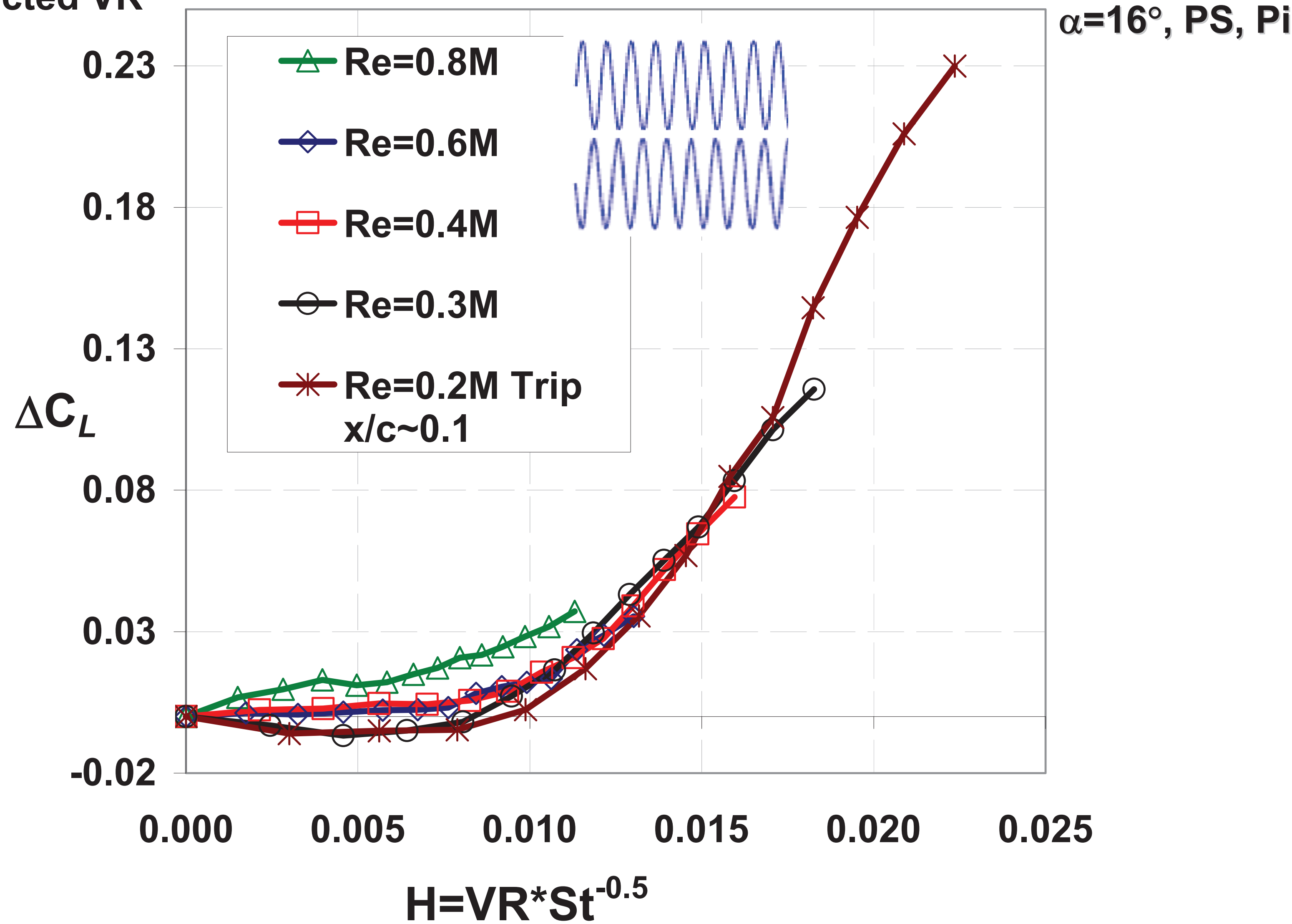
High Frequency Amp Scaling

- Velocity ratio



High Frequency Amp Scaling

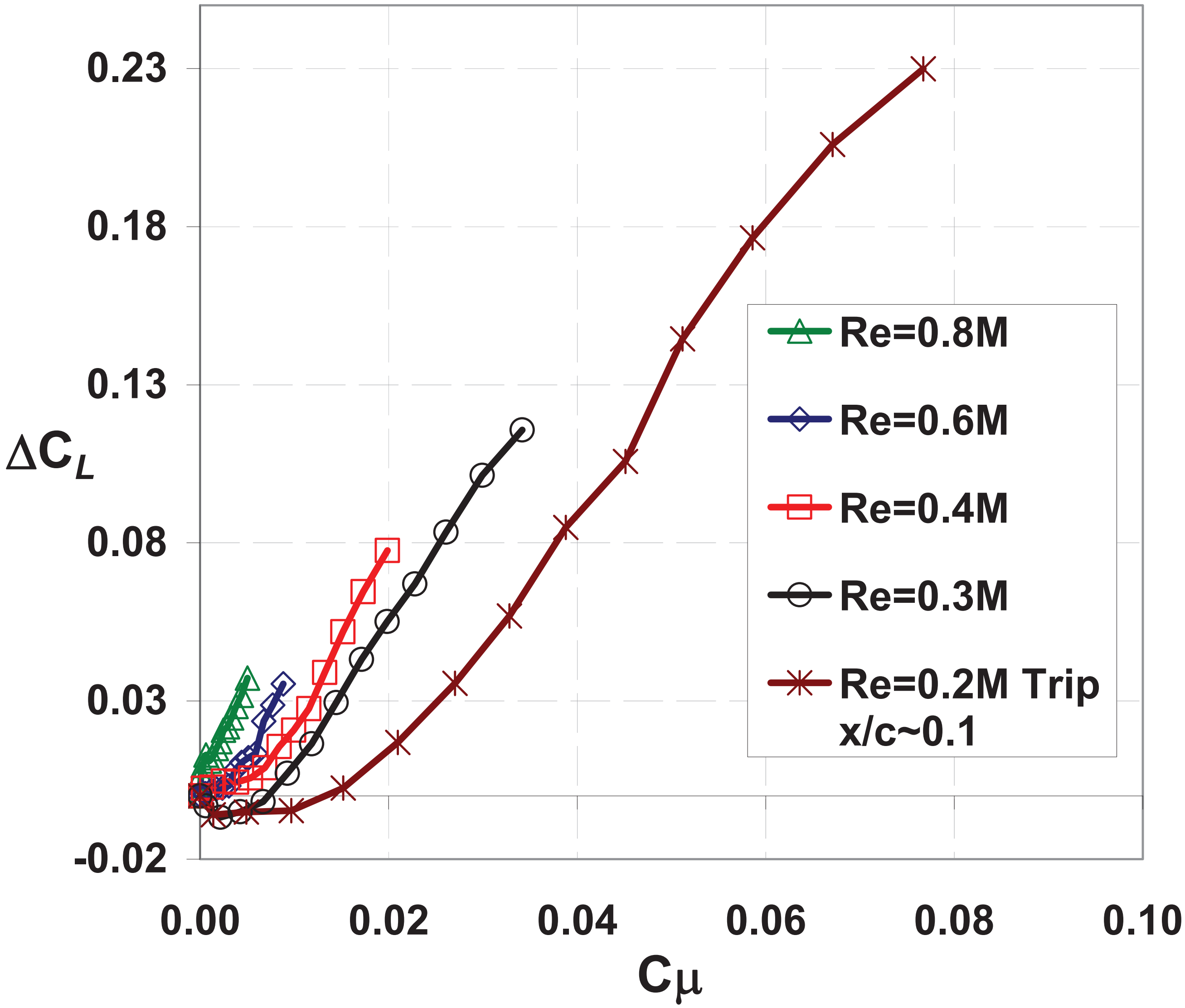
- St corrected VR

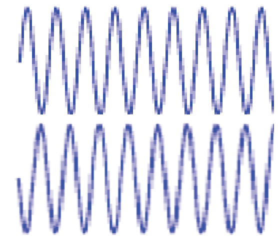


High Frequency Amp Scaling

- Cμ

α=16°, PS, Pi





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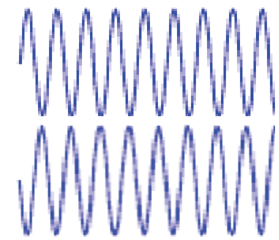
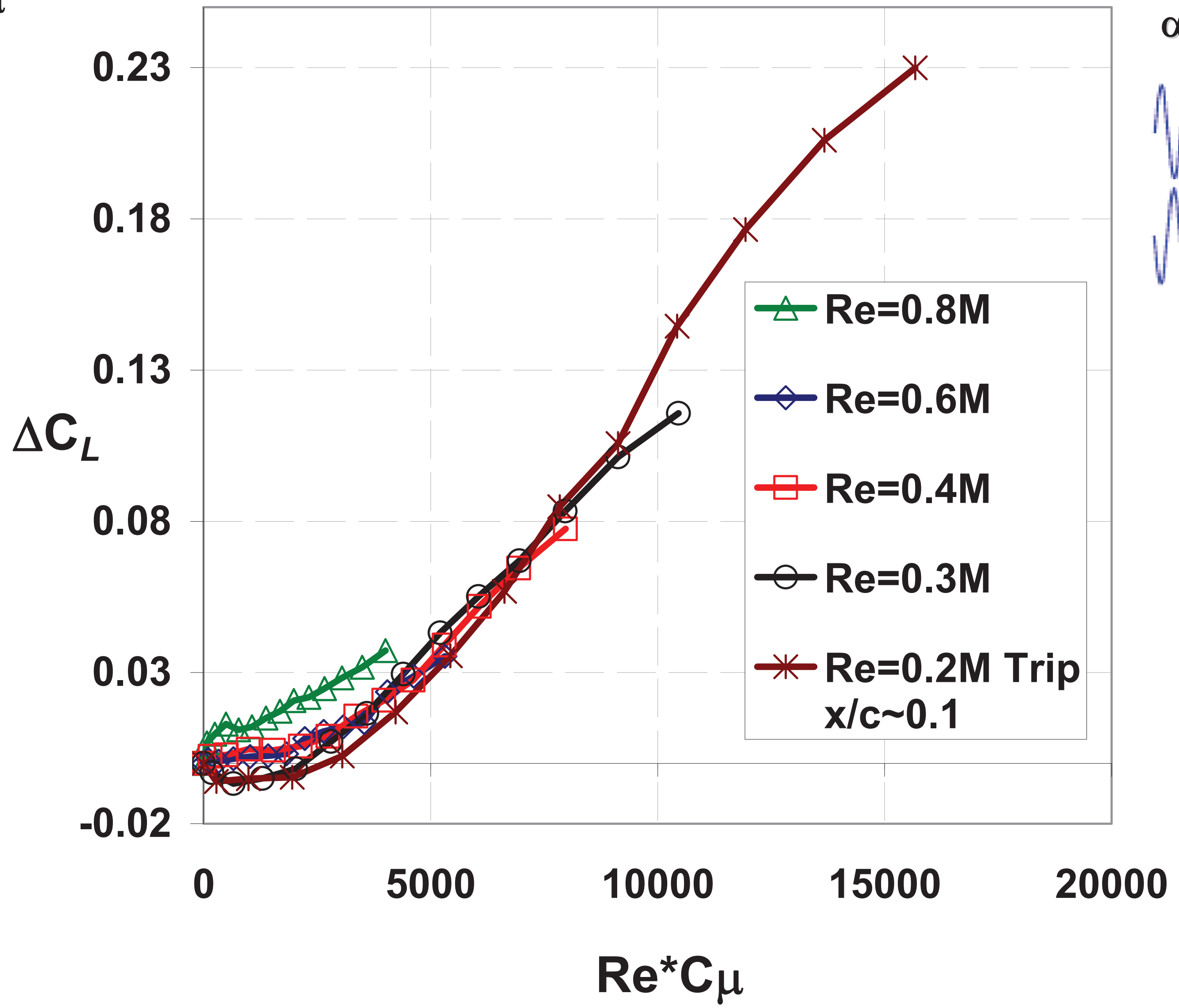
High Frequency Amp Scaling

- Re*Cμ

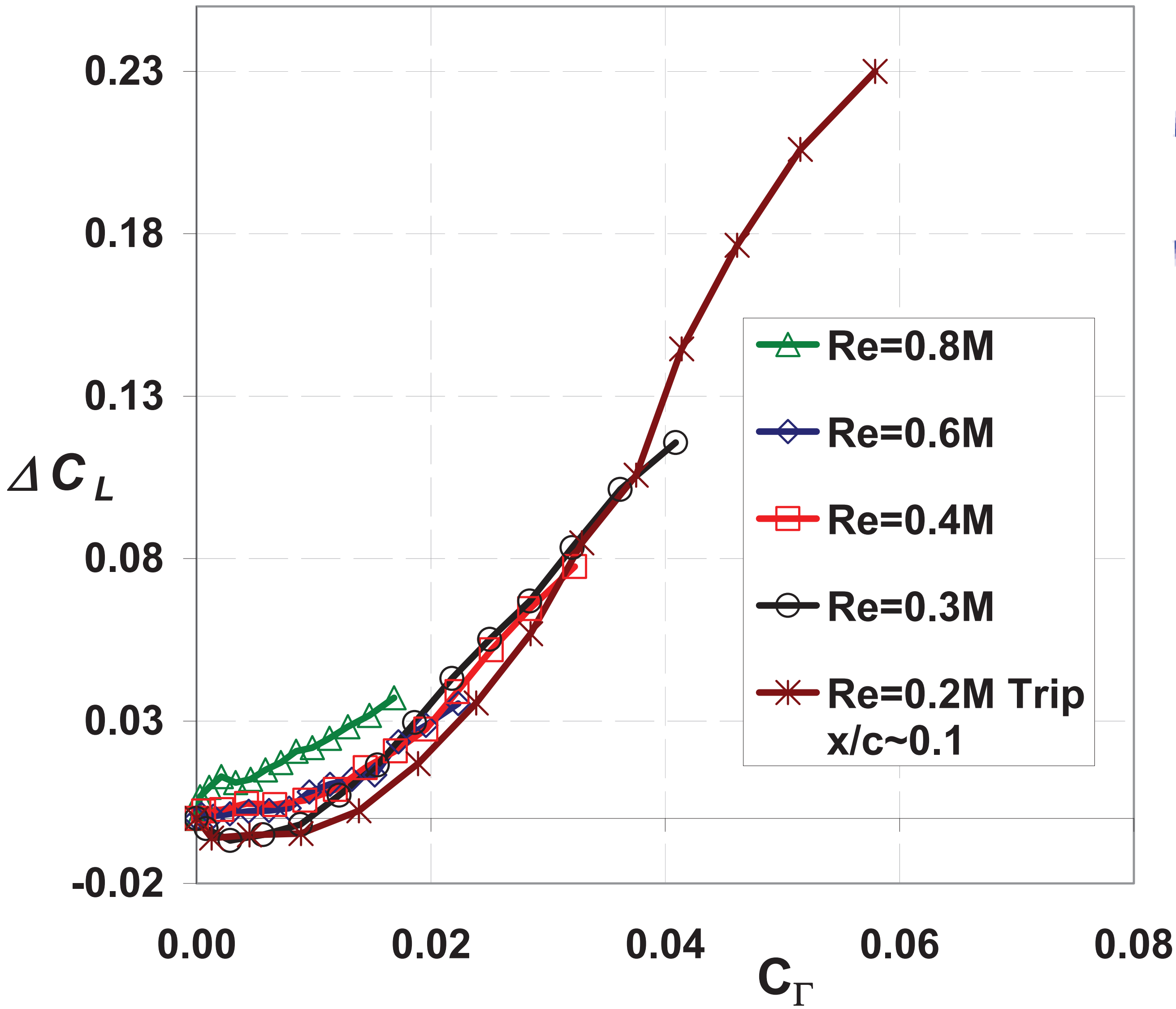
α=16°, PS, Pi



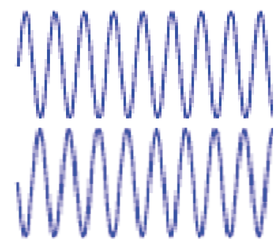


High Frequency Amp Scaling

- Vort. Flux Coeff.



α=16°, PS, Pi



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Amplitude Scaling Summary

		$F^+=1$	$F^+>10$
• **Velocity ratio (VR)**	$VR \equiv \frac{U_p}{U_e} \approx \frac{U_p}{U_\infty}$	X	X
• **Strouhal weighted VR (Nagib et al, 2006)**	$H \equiv \frac{VR}{\sqrt{S_t}}$	X	√
• **Momentum coefficient**	$C_\mu \equiv \frac{h}{c}(VR)^2$	X	X
• **Reynolds corrected C_μ** • ***m=0.2 (Turb.), m=0.5 (Lam.)*** • ***used m=1…***	$C_{\mu,\mathrm{Re}} \equiv \frac{h}{c}(VR)^2\,\mathrm{Re}^m$	~ √	√
• **Vorticity flux coeff.**	$C_\Gamma \equiv \frac{(VR)^2}{C_L S_t}$	X	√

Conclusions

- Three existing and two new excitation magnitude scaling options for active separation control at Reynolds numbers below one Million.
- The physical background for the scaling options was discussed and their relevance was evaluated using two different sets of experimental data.
- For F^{+}~1, 2D excitation:
  - The traditional *VR* and $C\mu$ - do not scale the data
  - Only the Re*$C\mu$ is valid
- This conclusion is also limited for positive lift increment.
- For F^{+}>10, 3D excitation, the Re corrected $C\mu$, the *St* corrected velocity ratio and the vorticity flux coefficient, *all* scale the amplitudes equally well.
- Therefore, the Reynolds weighted $C\mu$ is the preferred choice, relevant to both excitation modes.
- Incidence also considered, using Ue from local Cp

Vorticity flux ratio - 4

- **Actuators also generate vorticity flux and alter circulation**

$$C_{VF} \equiv \frac{\left[U_p(t,y)\dfrac{dU_p(t,y)}{dy}\right]_{\max}}{\left[U_{BL}(y)\dfrac{dU_{BL}(y)}{dy}\right]_{\max}} \approx \frac{U_p^2}{h/2}\frac{\theta}{U_e^2} = \frac{2\theta}{h}\left(\frac{U_p}{U_e}\right)^2 \approx \frac{0.01c}{h}\left(\frac{U_p}{U_e}\right)^2$$

- **While the momentum coefficient** $C_\mu \equiv \frac{2h}{c}\left(\frac{U_p}{U_e}\right)^2$
- **For** $h/c = 0.005 \ \ (and \ \ \theta/c = 0.005)$
- **So the ratio** $C_{VF}/C_\mu \equiv \frac{0.01c}{h}\Big/\frac{2h}{c} = \frac{0.005c^2}{h^2} \approx \frac{5x10^{-3}}{2.5x10^{-5}} = 200$
- **Is very large; define *Vorticity Flux Coefficient***

AFC Open Forum:
Actuators Comparison Criteria

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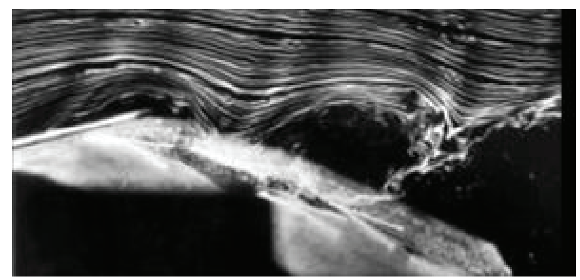

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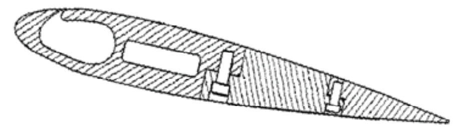
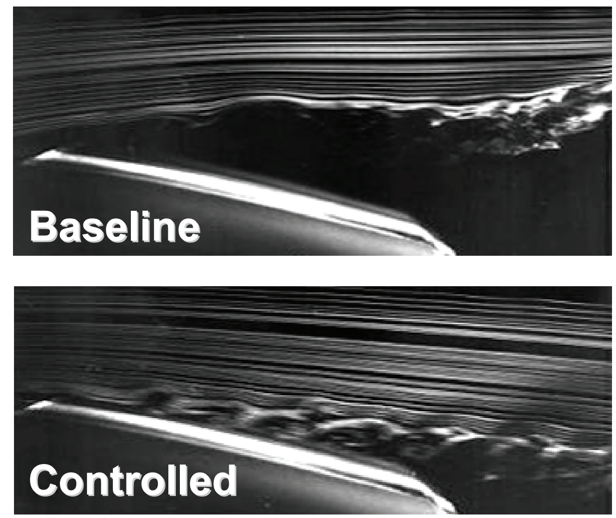
I. Dayan, S. Paster, E. Nevo, Meadow Aero Lab members

Motivation

- Active control of boundary layer separation
- Actuation: key enabling technology
- Many actuator types exist
- No accepted criteria for actuator comparison
- Rare to find:
  - Energy, efficiency, weight, cost data





(Neuburger, ’89, Re<100k)

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Comparison criteria: OFM

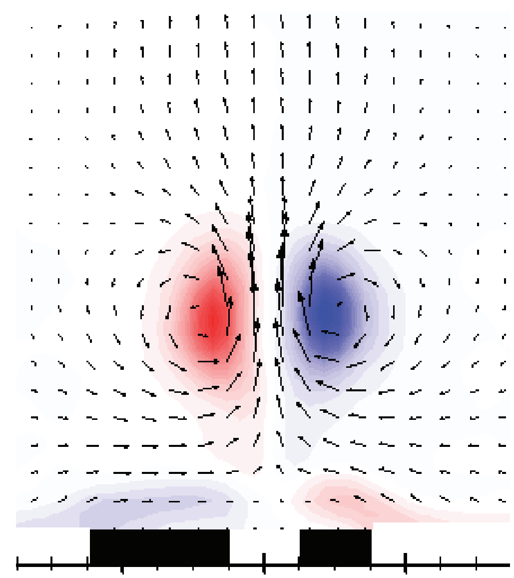
- **Overall Figure of Merit**

$$OFM \equiv \frac{F_a^2 U_p}{W_a P}$$

- **Actuator operates in still air**
- **F_a – force generated**
- **When not/can not be measured could be estimated by**

$$F_a \approx C \rho A_a U_p^2$$

- **With C from 0.25 to 0.5 (blowing only, velocity profile)**
- **U_p- peak generated velocity**
- **W_a – actuator weight**
- **P – actuator energy consumption**
  - **Electric, fluidic, combined**



(Yehoshua)

Comparison criteria: AFM-1

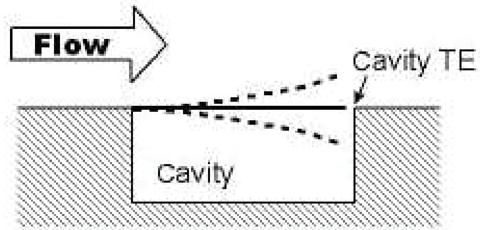
- Aerodynamic Figure of Merit (1)

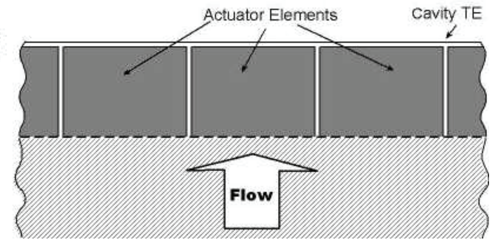
$$AFM1 \equiv \frac{U_\infty L_c \big/ (U_\infty D_c + P)}{\left(L \big/ D\right)_{baseline}}$$

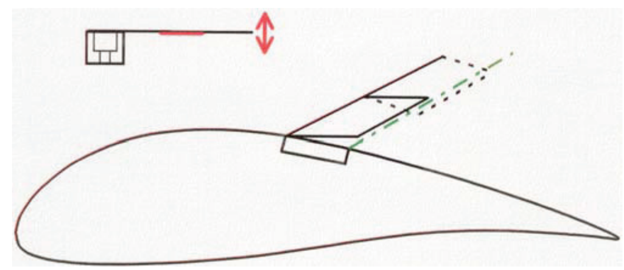
- Application, actuators and flow condition dependent
- U_∞ – Free-stream velocity
- L – lift (baseline or controlled)
- D – Drag (baseline or controlled)
- P – actuator energy consumption
- Situation: Have system and actuators
- Question: Direct energy into power-plant or actuators?
- Answer: Only when *AFM1* > 1 operate actuators

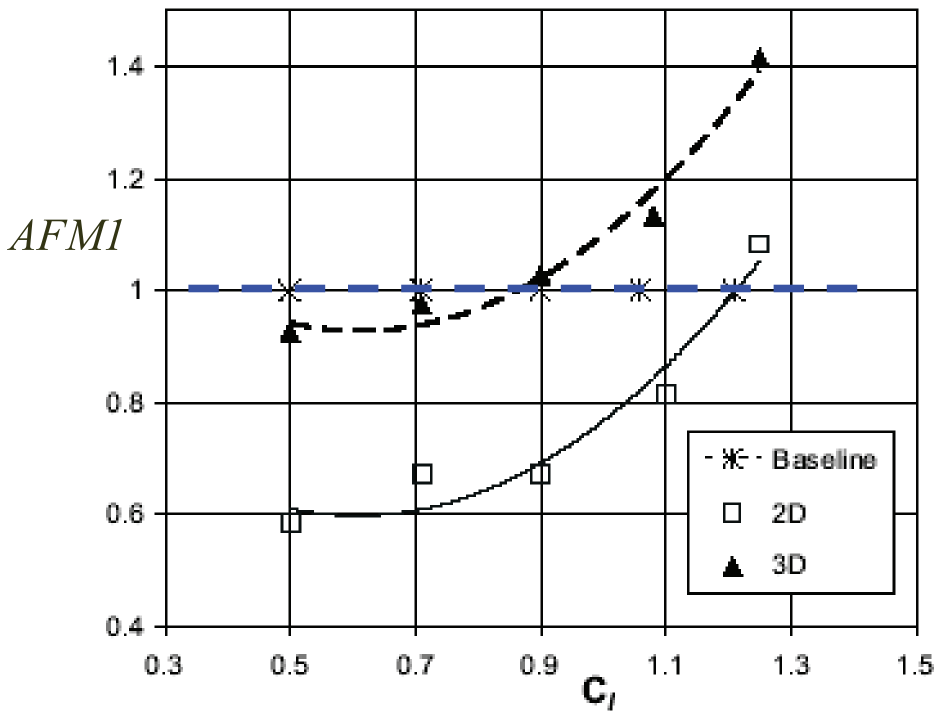
AFM-1 Example: 3D PZE

- Low Re Control of separation
- TAU Developed piezo-benders
- Considered energy efficiency
- Found that 3D excitation more effective than 2D









$$AFM1 \equiv \frac{U_\infty L_c \big/ (U_\infty D_c + P_a)}{\left(L/D\right)_{baseline}}$$

(Seifert et al, '99)

Comparison criteria: AFM-2

- **Aerodynamic Figure of Merit (2)**

$$AFM2 \equiv \frac{U_\infty (L_c - W_a) / (U_\infty D_c + P)}{(L/D)_{baseline}}$$

- **Application, actuators and flow condition dependent**
- U_∞ **– Free-stream velocity**
- L **– lift (baseline or controlled)**
- D **– Drag (baseline or controlled)**
- W_a **– weight of actuation system (incl. drivers, cables…)**
- P **– actuation SYSTEM energy consumption**
- **Situation: Scaled** $AFM1$**>1 and actuation system weight known (or predicted)**
- **Question: Should we include actuation in system?**
- **Answer: only when *AFM2* > 1 (probably 1.1 minimum)**

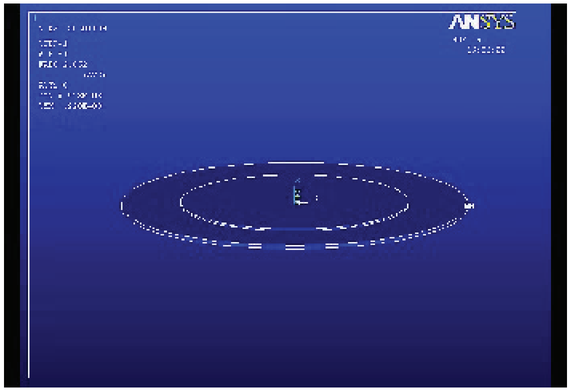
Actuation Methods

(Not a tutorial nor a comprehensive review)

- External
  - Speakers on tunnel walls
  - Speakers in cavities
  - Mechanical rotary
  - Mechanical – pneumatic
  - Ribbons + shakers
- Internal…

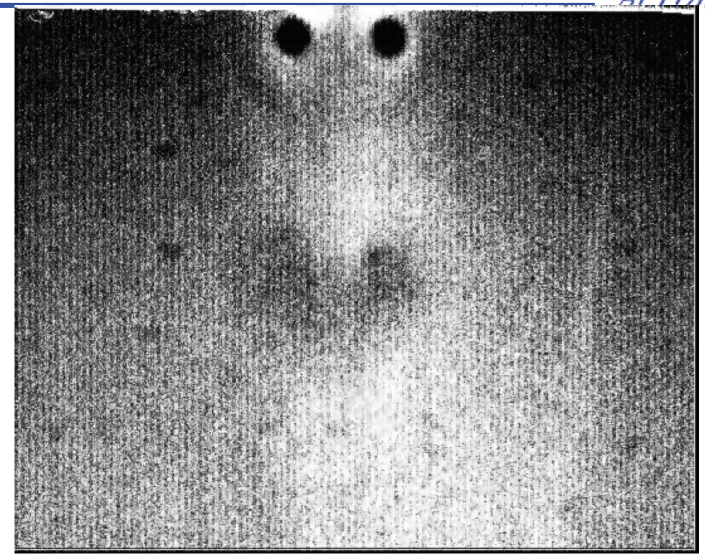
ZNMF Piezo Actuator Operation

1St mode - Membrane



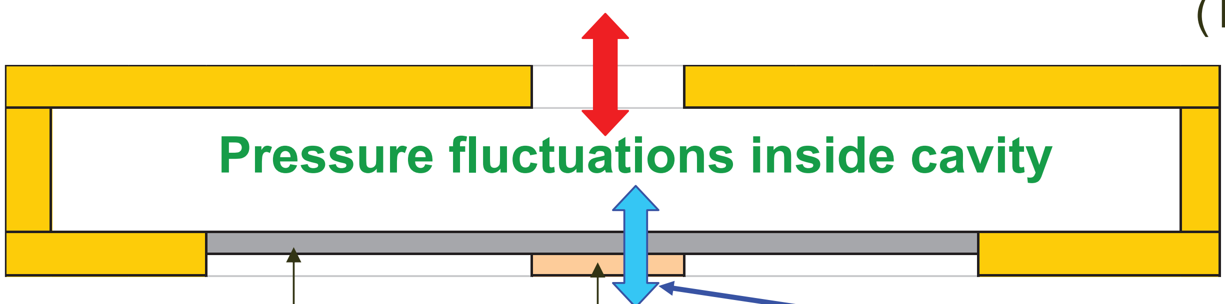
(Assaf Nahum)

Zero
Net
Mass
Flux



(Tal Yehoshua)

Cyclic air jet



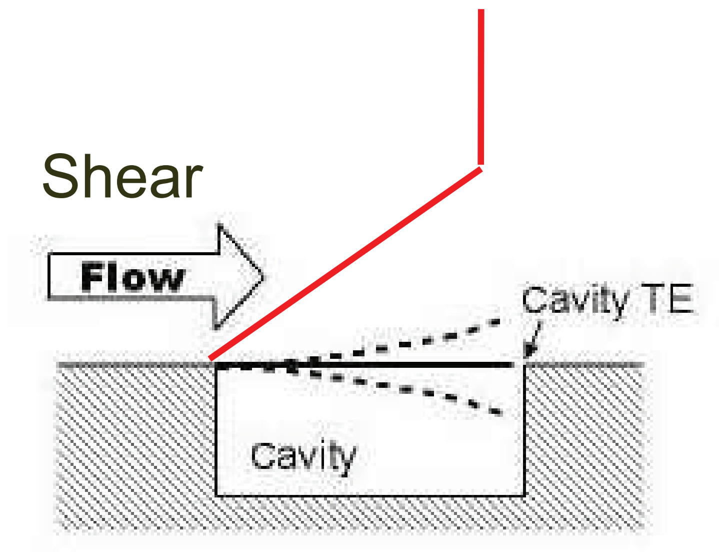
Metal disc

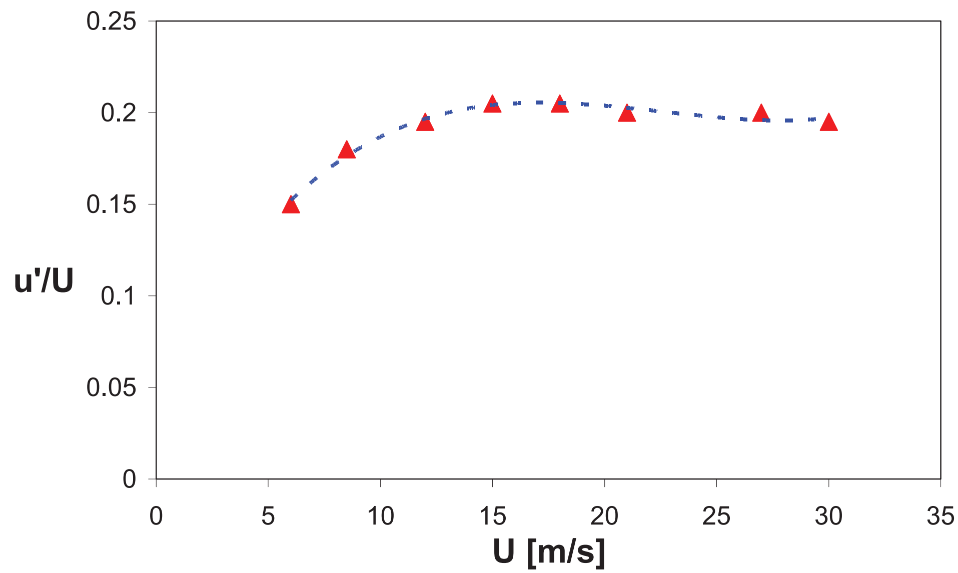
Piezoelectric crystal

AC Voltage

Surface Mechanical Actuators

- Requirement: Sufficient control authority (…any type)
- Type (affecting method and feasibility of characterization)
- Mechanical: Amplitude, Mode shape…
- Micro balloons, micro flaps…





(Seifert et al., 1998, *AIAA J.*, V. 36, N. 8.)

Combustion actuator

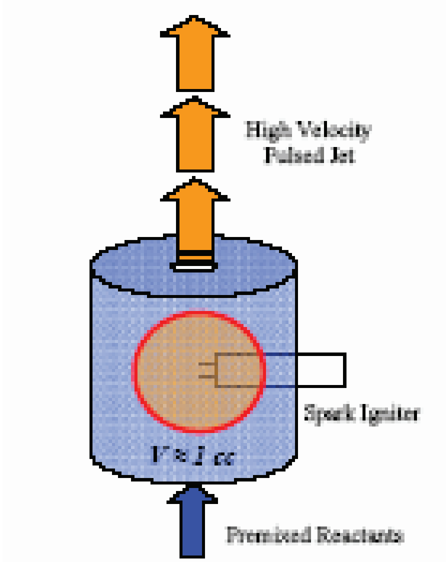
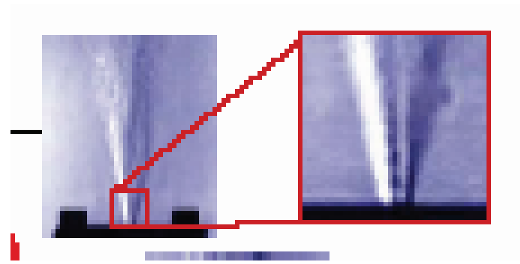
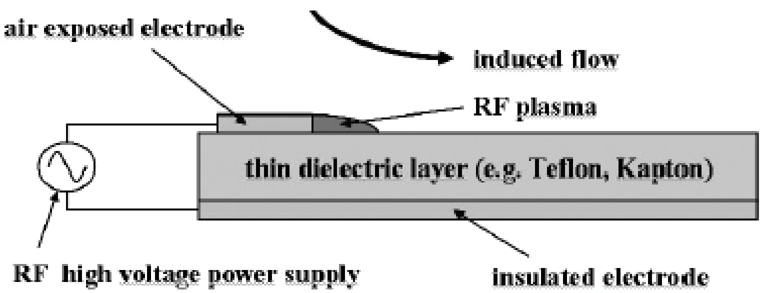


Figure 1. Schematic illustration of combustion-driven jet actuator



Microfabricated, Combustion-Driven Jet Actuators for Flow Control Applications
T. Crittenden and A. Glezer
Woodruff School of Mechanical Engineering
801 Ferst Drive N.W.
E. Birdsell and M. Allen
School of Electrical and Computer Engineering
777 Atlantic Drive N.W.
Georgia Institute of Technology, Atlanta, GA, USA 30332

Surface Plasma actuator



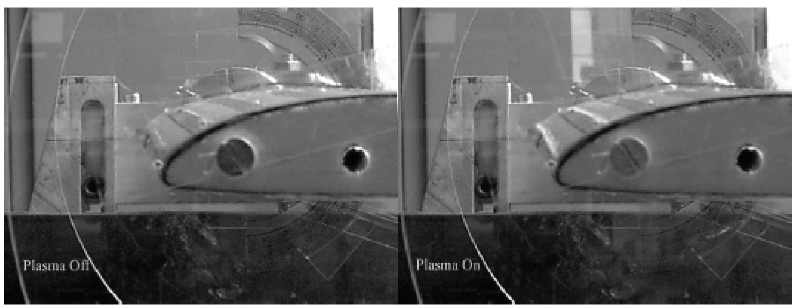
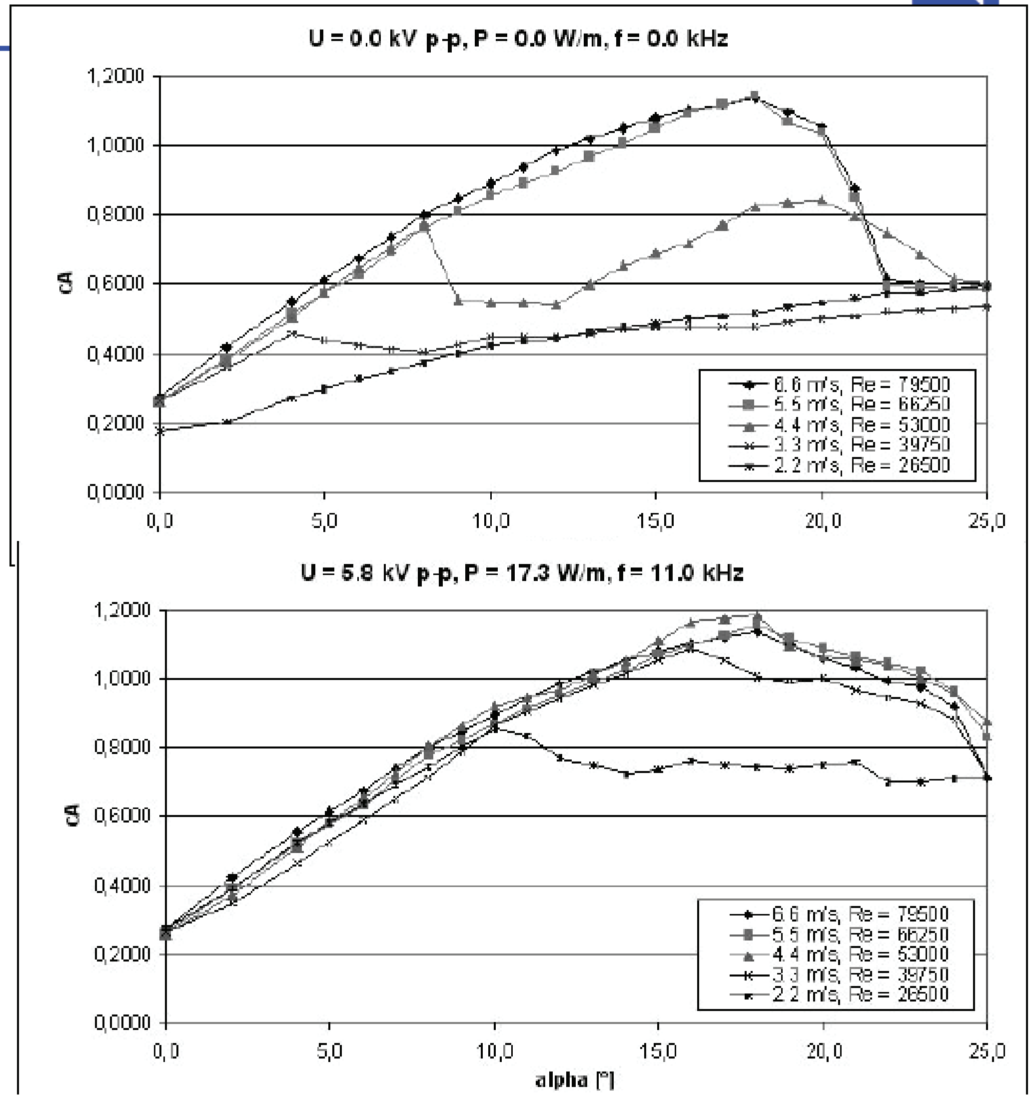


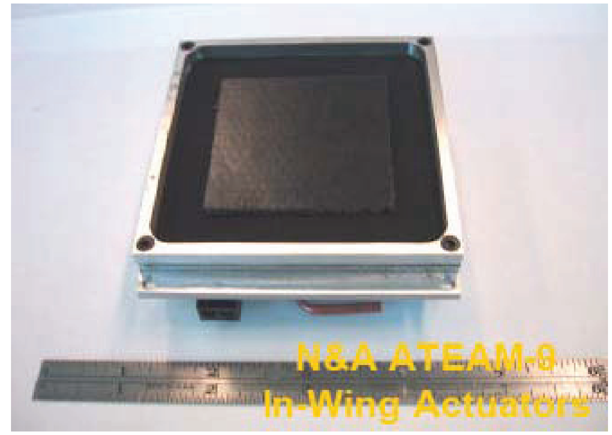
Figure 4 Two activated plasma actuators with 180° phase shift on the leading edge



Actu power – 17W/m
Uinf=2-6m/s
Plasma Up=2-4m/s
Lift recovery for Re<=50k
No drag data
1/2RoSU^3=4.4Watt

Active Flow Control by Surface Smooth Plasma Actuators
B. GÖKSEL, I. RECHENBERG, TUB

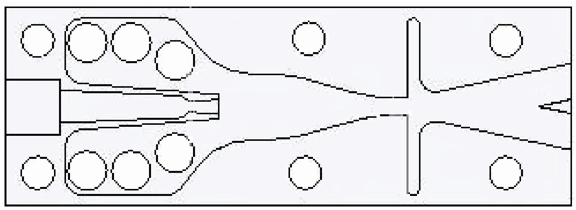
Electro Magnetic actuator (XV-15)



Actu power – 1000W/m
Up=80m/s
Wa>3kg

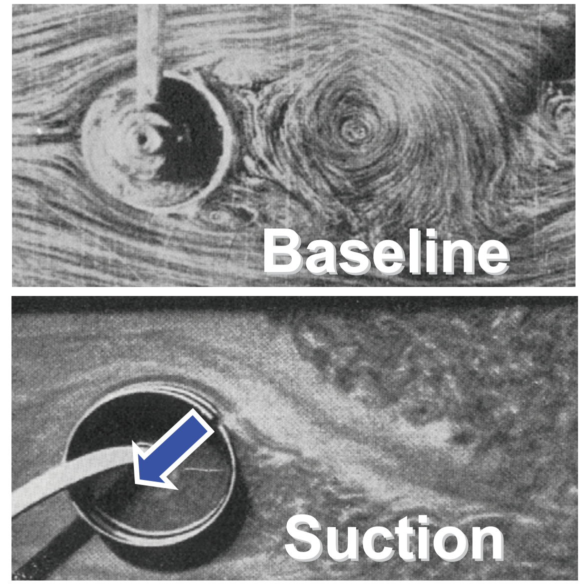
http://fdrc.iit.edu/research/docs/MAFC_XV_15_Briefing_Final.pdf

TAU
Suction and Oscillatory Blowing (SaOB) Actuator

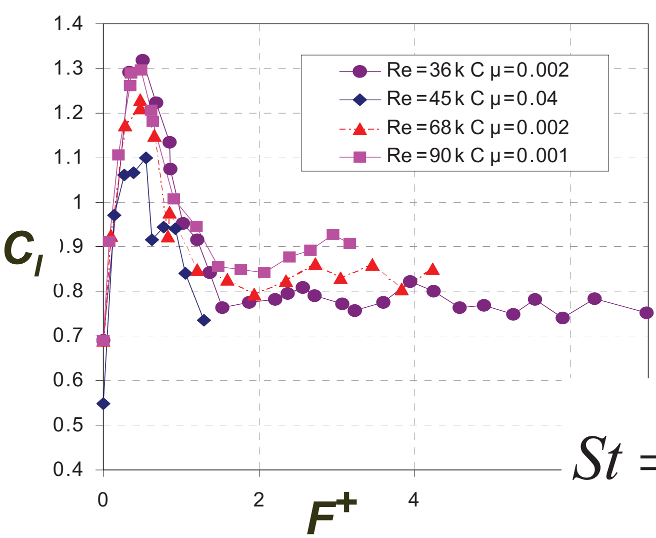


Background

- Boundary layer separation control by steady suction (note date…)
- Steady, wall tangential blowing
- Oscillatory blowing (directed ZMF)
- The importance of flow instability for efficient AFC



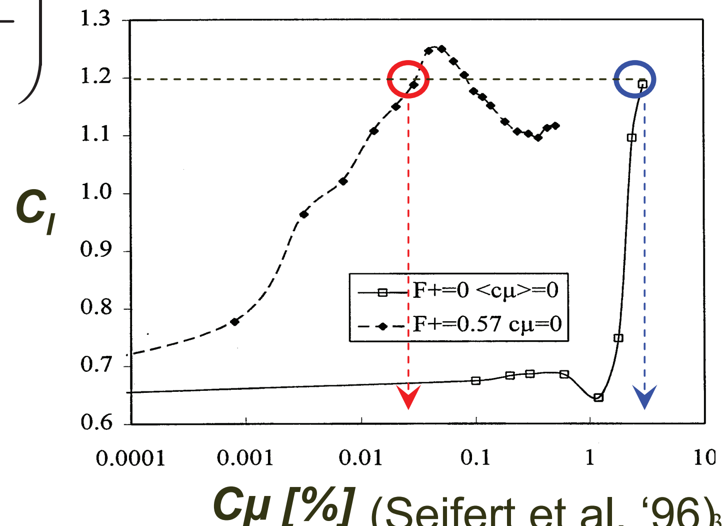
(Prandtl, 1904)



(Yom-Tov & Seifert, '05)

$$C_\mu = \frac{2h}{L}\left(\frac{U_{p,j}}{U_\infty}\right)^2$$

$$St = \frac{f \cdot L}{U_\infty} = F^+ \approx 1$$



(Seifert et al, '96)

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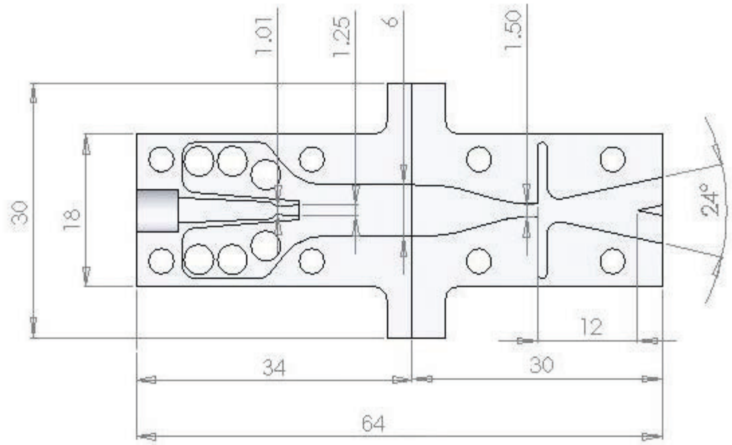
The SaOB actuator concept

Aerolab

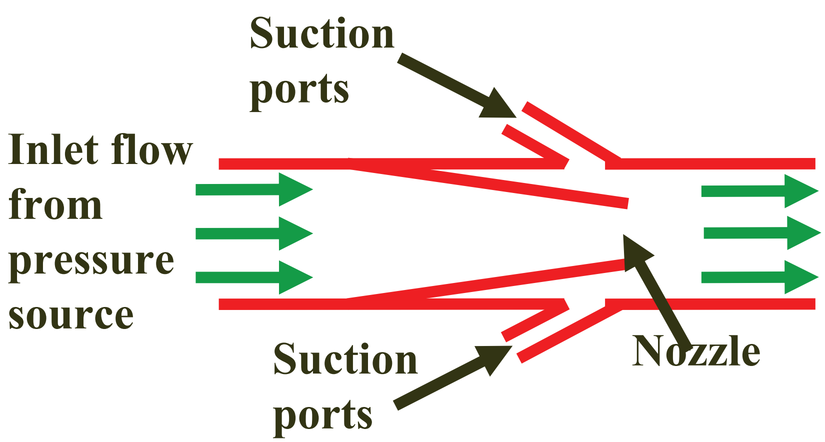
- G. Arwatz (MSc), I. Fono, London MEMS IUTAM, Sep ’06
- Available ZNMF devices limited to M=0.3
- Suction and oscillatory blowing – high potential for efficient AFC
- Combination of *steady suction* and *oscillatory blowing* in *one device*
- High velocity, near sonic, output
- Wide range of output frequencies
- Enables 3D excitation
- Frequency proportional to flow rat
- No moving parts
- Low power consumption



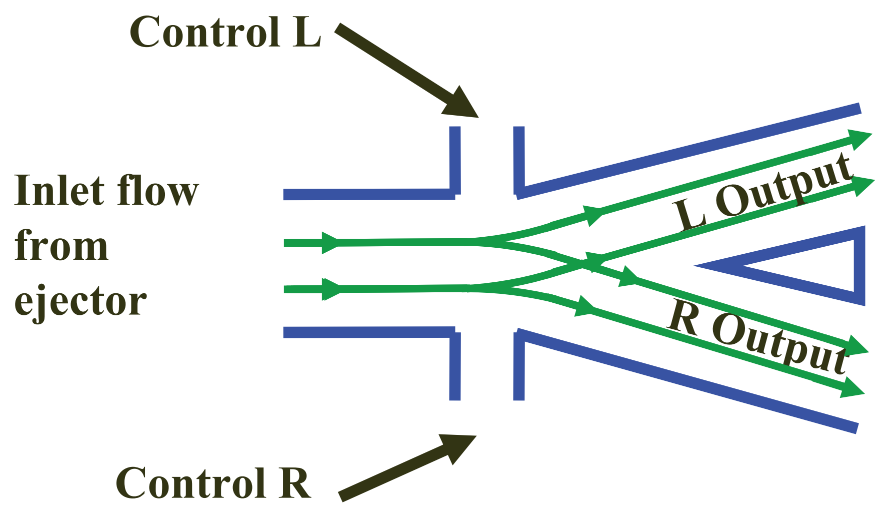
The SaOB actuator concept

- Combination of ejector and switching valve

Ejector (steady suction)

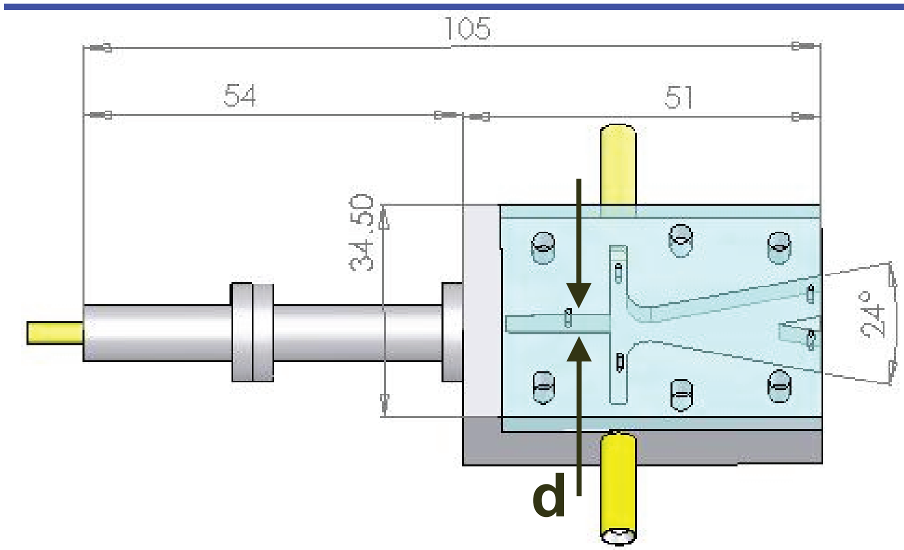


Bi-stable fluidic amplifier (oscillatory blowing)

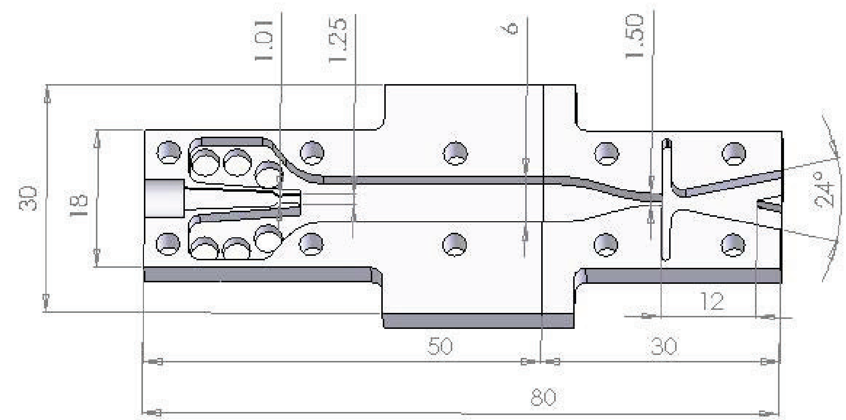


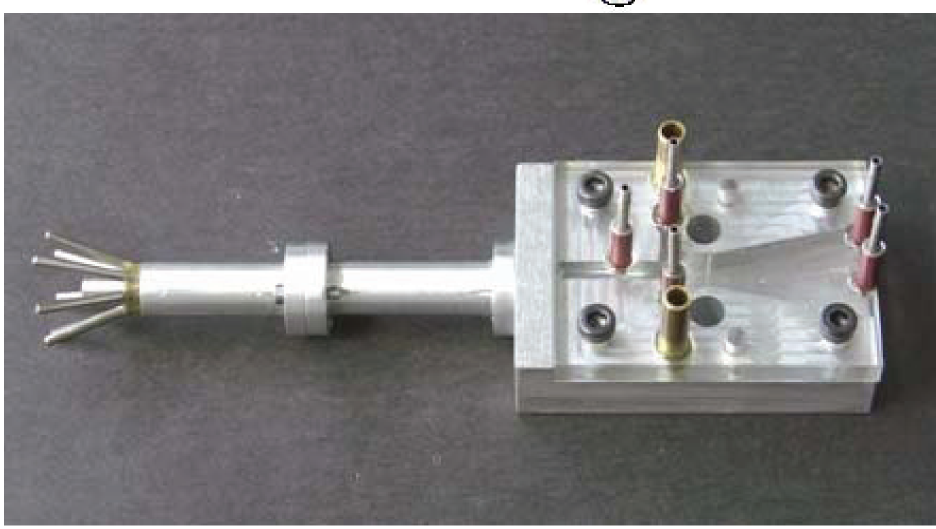
Valve generations, 2nd & 3rd

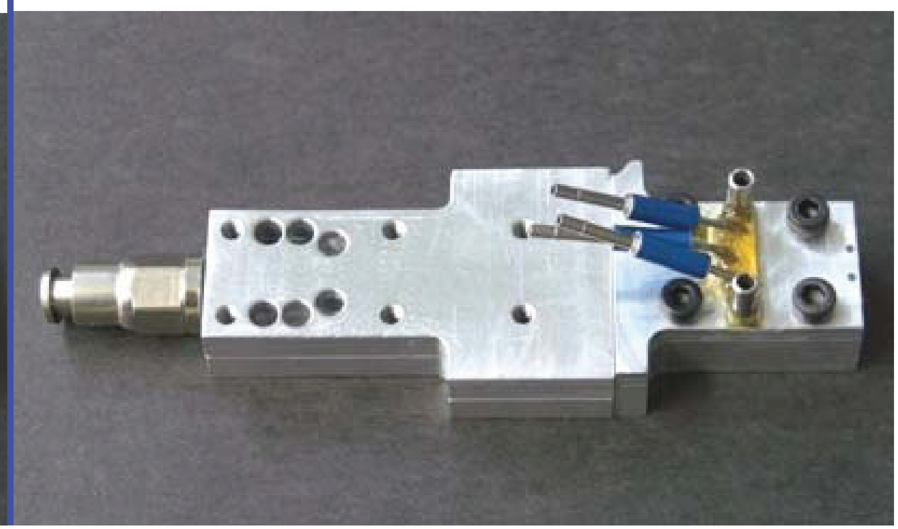
Medium scale d=3mm



Small scale d=1.5mm





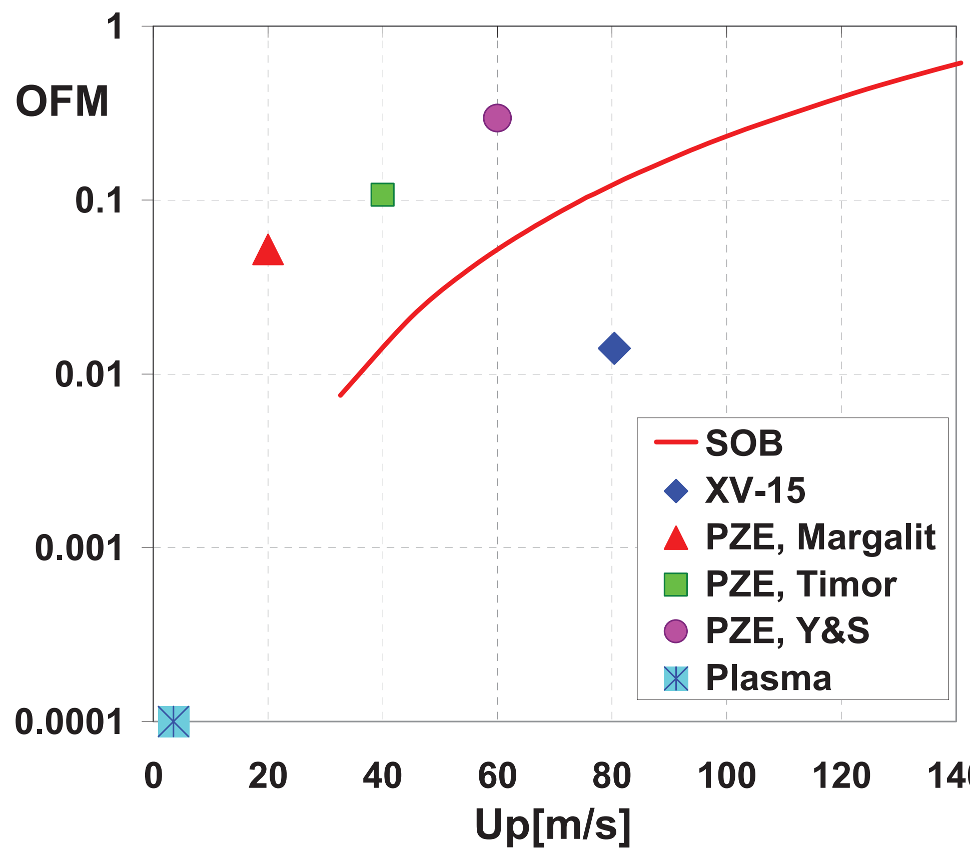


Actuators' Efficiency

- Overall Figure of Merit

$$OFM = \frac{F_a^2 U_p}{W_a P_a}$$

- Still air operation
- SaOB weight - 15 gm
- Thrust-suction+blowing
- Note: OFM Log scale



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Summary (Actuators)

- Actuator comparison criteria suggested
- Overall and Aerodynamic figures of merit
- New actuator for steady suction and oscillatory blowing was developed, modeled and characterized
- OFM for ZNMF, Plasma and SaOB actuators compared
- Rare to find data for AFM (Need: Weight, power, Up, L, D)
- Please measure and publish