AIAA-2016-0843

The Ohio State University

Flow Separation Control over a Boeing Vertol VR-7 using NS-DBD Plasma Actuators

Ata Esfahani, Achal Singhal, Chris Clifford and Mo Samimy

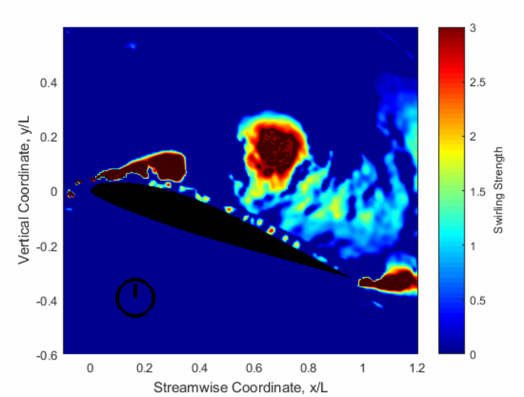
Gas Dynamics and Turbulence Laboratory

Aerospace Research Center

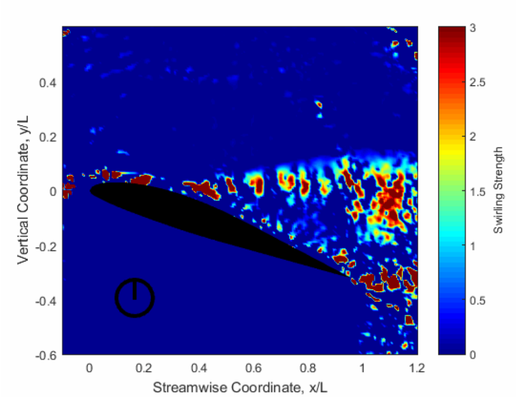
The Ohio State University

54th AIAA Aerospace Sciences Meeting

San Diego, CA, 4-8 Jan 2016



$St_e = 1.2$



$St_e = 10.0$

Acknowledgements

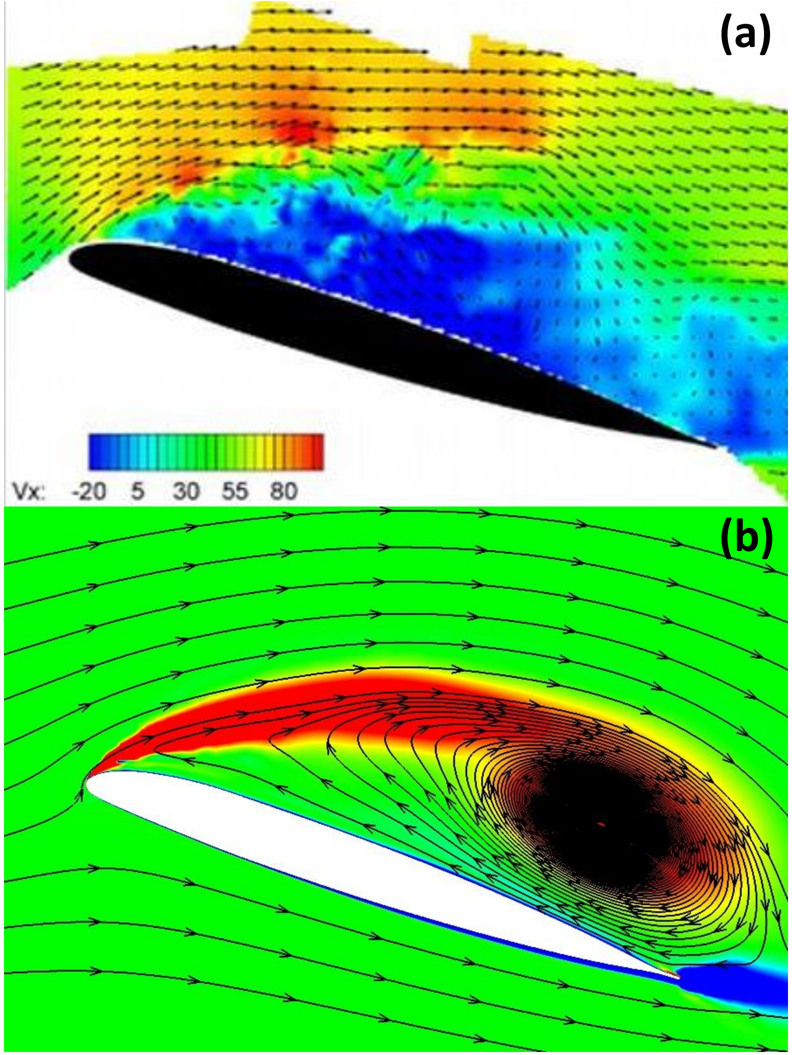
The authors gratefully appreciate the support provided by the **Army Research Laboratory** with Dr. Bryan Glaz and by the **Army Research Office** with Dr. Matthew Munson. Helpful discussion provided by the members of the Gas Dynamics and Turbulence Laboratory is much appreciated.

Outline

- ❑ Background
- ❑ Objectives
- ❑ Experimental Facilities and Techniques
- ❑ Results and Discussion
  - ❑ Time-averaged PIV: Velocity and Vorticity
  - ❑ Phase-locked PIV: Coherent Structures
  - ❑ Fluctuating Pressure Spectra
- ❑ Conclusions

Background

- Thin airfoils are employed commonly as rotorcraft blade sections
- **High value of** $C_{L_{max}}$ and **low drag** at compressible Mach numbers are required for rotorcraft blades
- These requirements mean that the ideal rotorcraft blade airfoil is **cambered** and has **low thickness** (~8 – 10 % chord)
- The typical signature of rotorcraft airfoils is a **small radius of curvature leading edge**
- Considerable amount of **centrifugal acceleration** is required to maintain an attached flow around such leading edges and the flow control is more difficult to achieve in this configuration (Wynanski and Amitay, 2003)[1]



(a) Instantaneous velocity field over a rotorcraft blade obtained by PIV and (b) numerical simulation of the flow field for the same blade (DLR Institute of Aerodynamics and Flow Technology)

Outline

- Background
- **Objectives**
- Experimental Facilities and Techniques
- Results and Discussion
  - Time-averaged PIV: Velocity and Vorticity
  - Phase-locked PIV: Coherent Structures
  - Fluctuating Pressure Spectra
- Conclusions

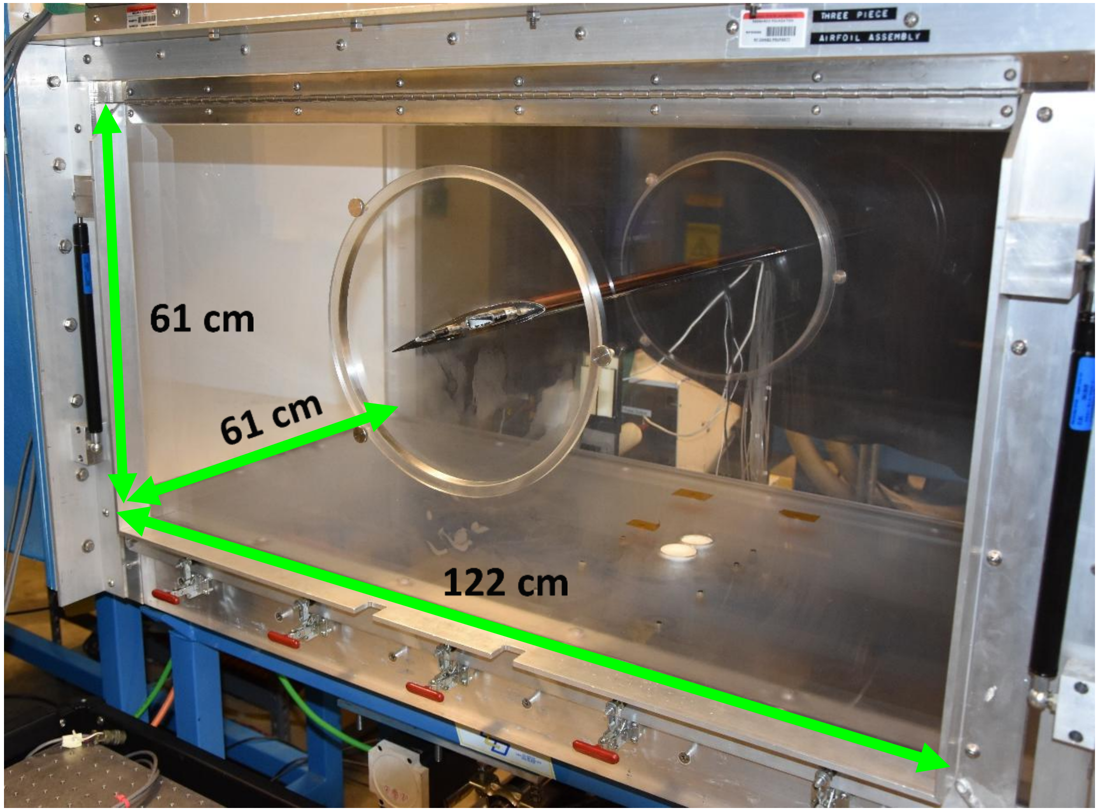
Objectives

- Investigate and characterize the performance of NS-DBD actuators in controlling static stall over VR-7 airfoil
- Explore the flow physics involved and understand control mechanisms
- Compare the control authority of NS-DBDs for thick (gentle TE stall) and thin (abrupt LE stall) airfoils

Outline

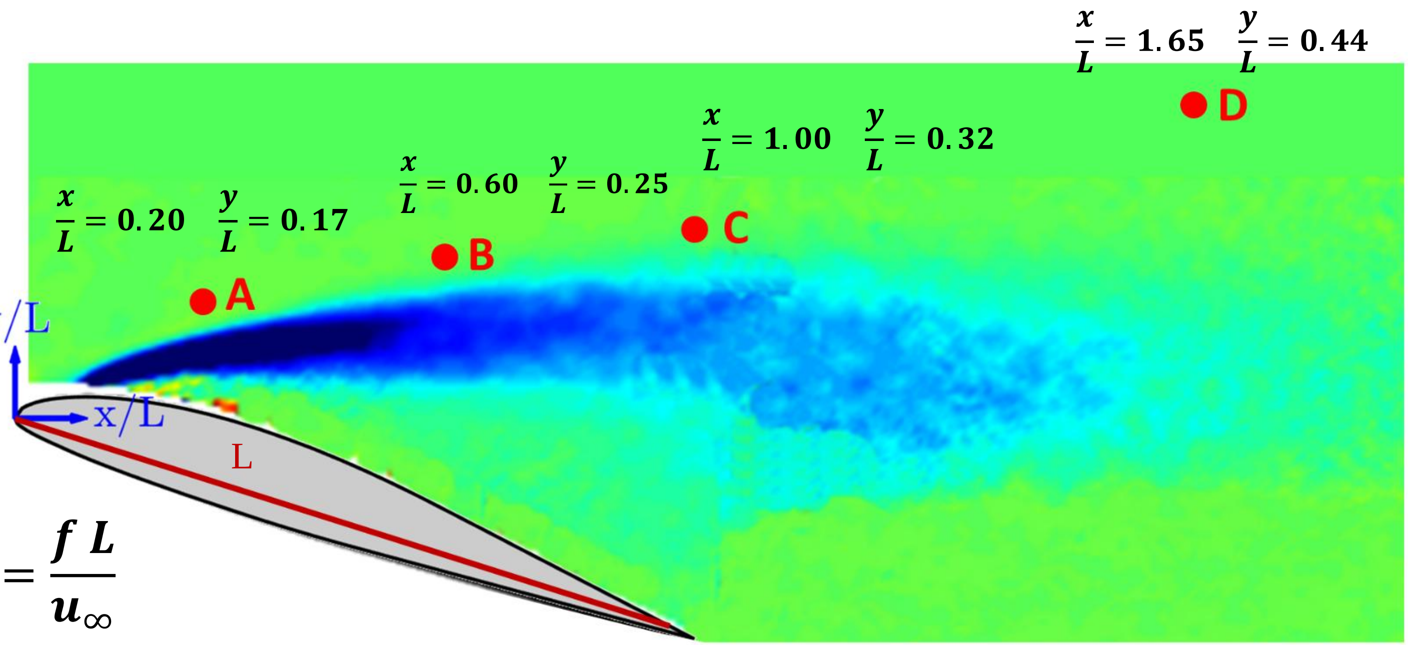
- Background
- Objectives
- **Experimental Facilities and Techniques**
- Results and Discussion
  - Time-averaged PIV: Velocity and Vorticity
  - Phase-locked PIV: Coherent Structures
  - Fluctuating Pressure Spectra
- Conclusions

Wind Tunnel and Airfoil



- Göttingen type wind tunnel with turbulence intensity of 0.25%
- Test conditions: $\boldsymbol{Re_c}$ **= 500,000** corresponding to $\boldsymbol{U_\infty}$ **= 36** $\boldsymbol{\frac{m}{s}}$, **α = 19°**
- Airfoil: composite Boeing Vertol VR-7 airfoil, chord length $\boldsymbol{L = 20.3\ cm}$, mounted in the center of test section between two acrylic disks

Experimental Configuration

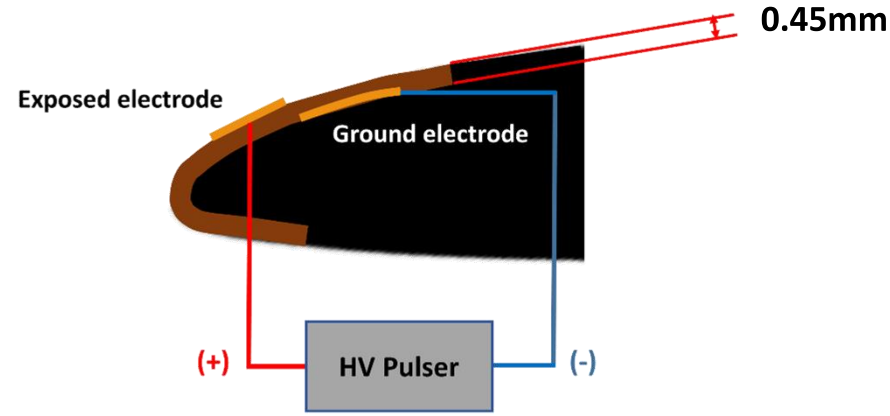


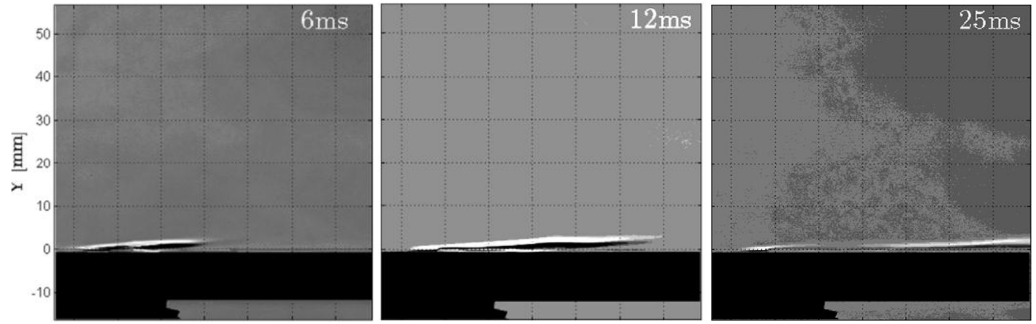
$$St = \frac{f\,L}{u_\infty}$$

- An **EMI-resistant microphone** (Brüel and Kjær model 4939) and a Nexus 2690 signal conditioner were used to acquire **time-resolved pressure fluctuations**
- Microphone was positioned along the **shear layer edge**
- Probe location (**D**) was used to get a tone for **phase-locked PIV**

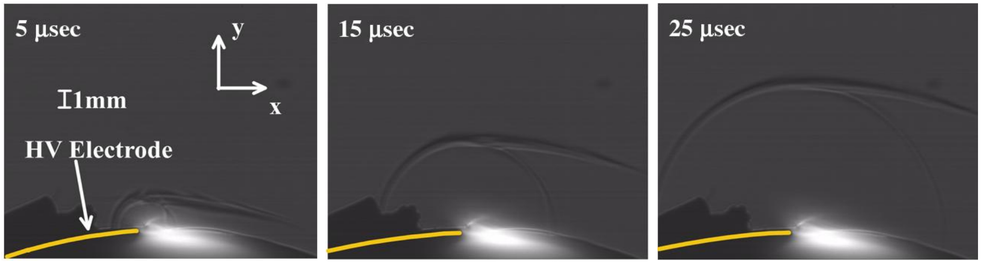
DBD Actuator and Nanosecond Pulser

- The pulser generates high-voltage (**~ 10 KV**), high-repetition rate pulses (**100 Hz- 10 KHz**) through magnetic wave compression that are approximately **90 ns wide** at FWHM
- The energy input by the pulser is **12 mJ** per pulse
- The barrier discharge created between copper electrodes, generates thermal perturbations that excite the flow instabilities
- Experimental evidence suggests that **thermal perturbations** are the main mechanism responsible for flow control





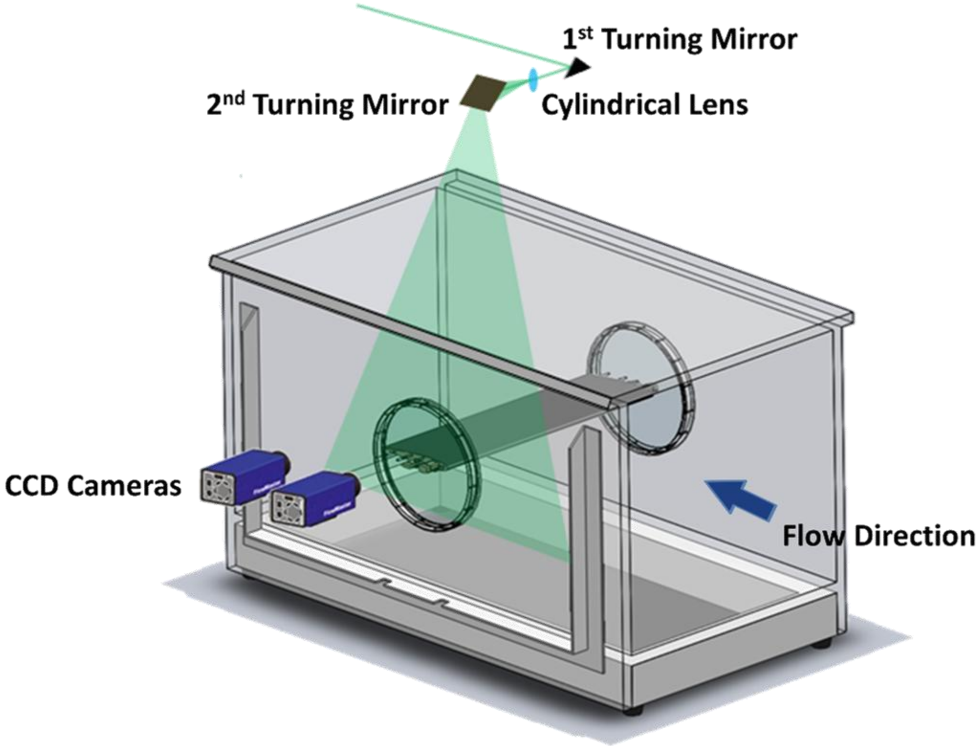
1

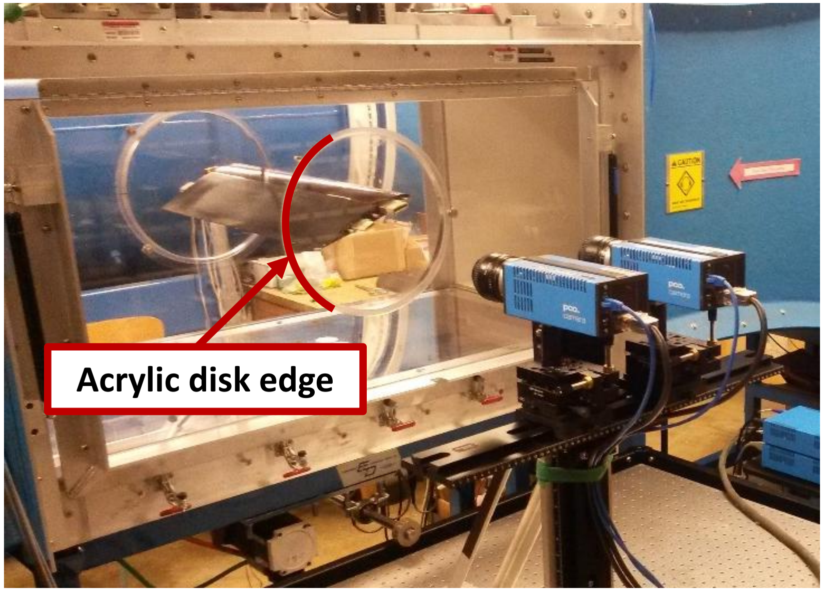


2

1. Correale et al. J Phys. D: Appl. Phys. (47) 2014
2. Little et al. AIAAJ 50 (2) Feb 2012

2D-2C Particle Image Velocimetry





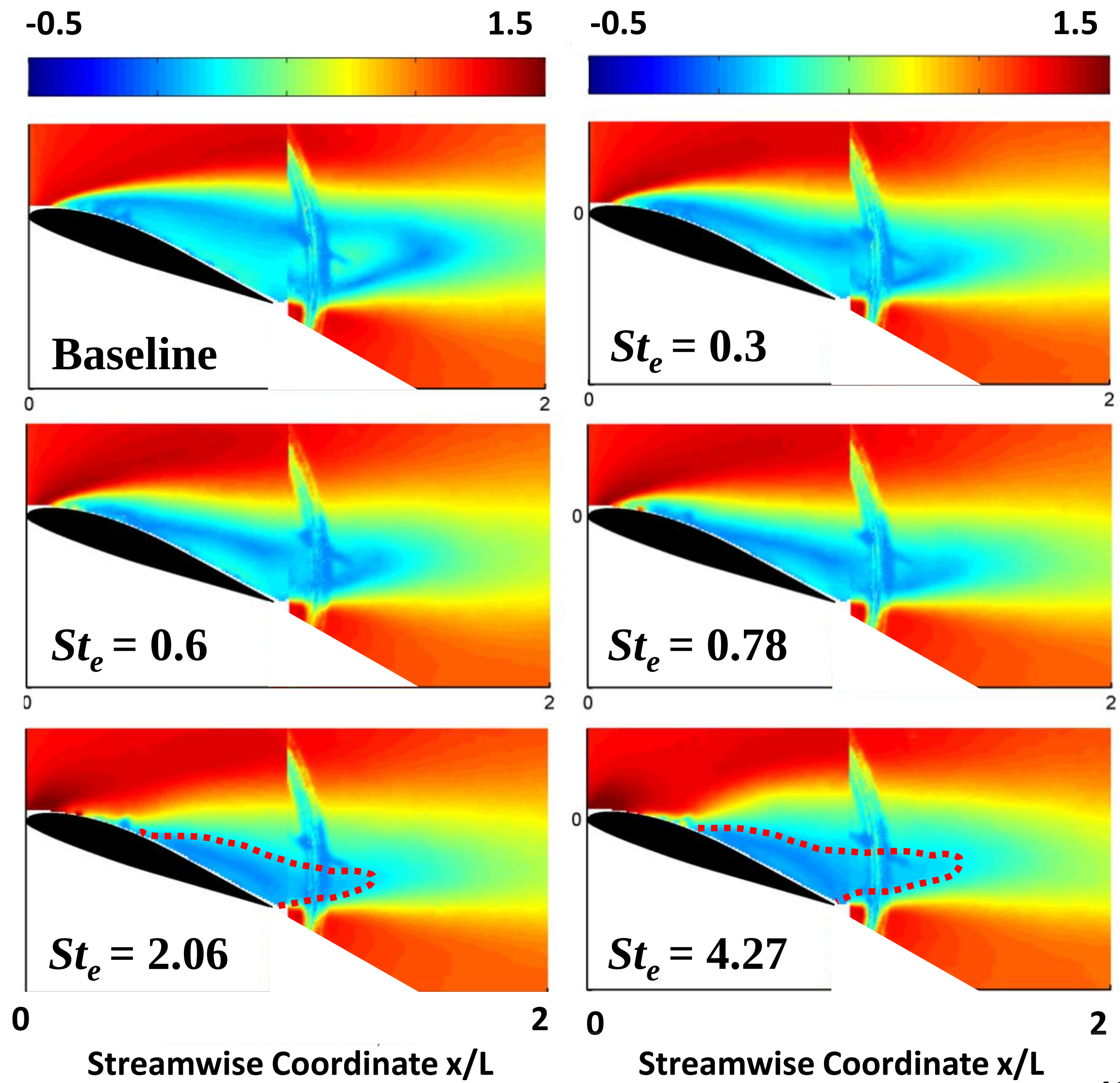
- Streamwise two-component PIV (ensemble-averaged and phase-averaged) using an Nd:YAG dual-head 532 nm laser and 4 MP 14-bit dual-frame camera capable of acquiring images at 10 Hz
- The signal from **microphone** was used to **detect shedding** for the baseline cases and trigger the laser and cameras. For the **excited cases**, the laser and cameras were **locked to the actuator signal**

Outline

- Goals/Objectives
- Experimental Facilities and Techniques
- Results and Discussion
  - **Time-averaged PIV: Velocity and Vorticity**
  - Phase-locked PIV: Coherent Structures
  - Fluctuating Pressure Spectra
- Conclusions

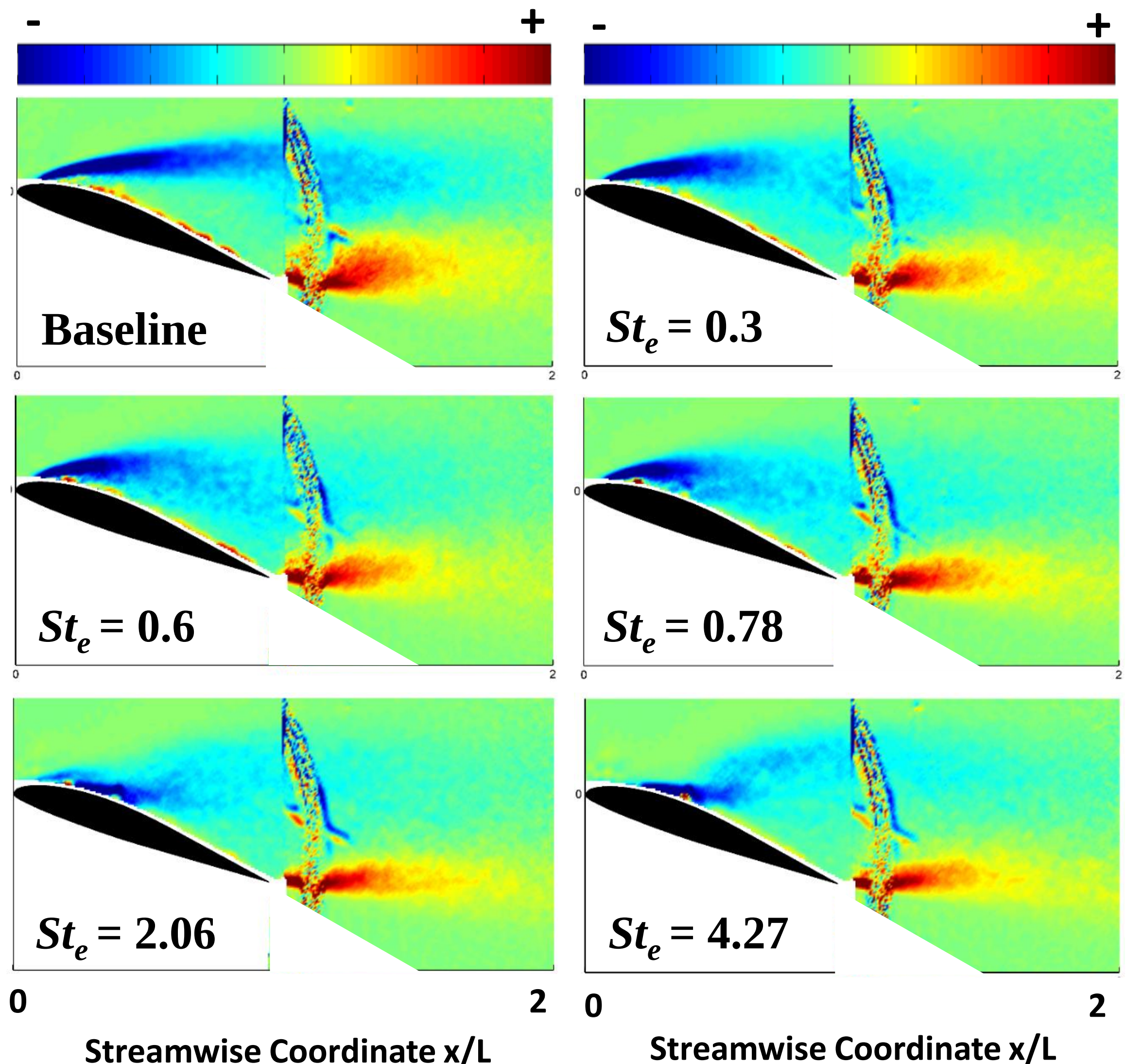
Time-averaged Total Velocity ($\sqrt{u^2 + v^2}$): Excitation Effects

- Excitation at **high St_e** (e.g. 2.06 and 4.27) confines the low-speed recirculating flow region close to the airfoil surface, **moves the separation point downstream**
- The flow around LE is significantly accelerated when excited at **high St_e**
- **Shear layer is distorted** at **high St_e**, which can be attributed to acceleration of flow around LE and concentration of reversed flow close to airfoil



Time-averaged Vorticity ($\nabla \times U$): Excitation Effects

- Excitation at **low St_e** (e.g. 0.3, 0.6 and 0.78) **tilts the separated shear layer** towards airfoil surface
- Excitation at **high St_e increases incoherence** of vortical structures, leads to the **generation of weak structures** that quickly breakdown
- Excitation at **high St_e** leads to shedding of smaller CCW vorticity concentrations into the wake, weakening of CW vorticity concentrations downstream of the leading edge

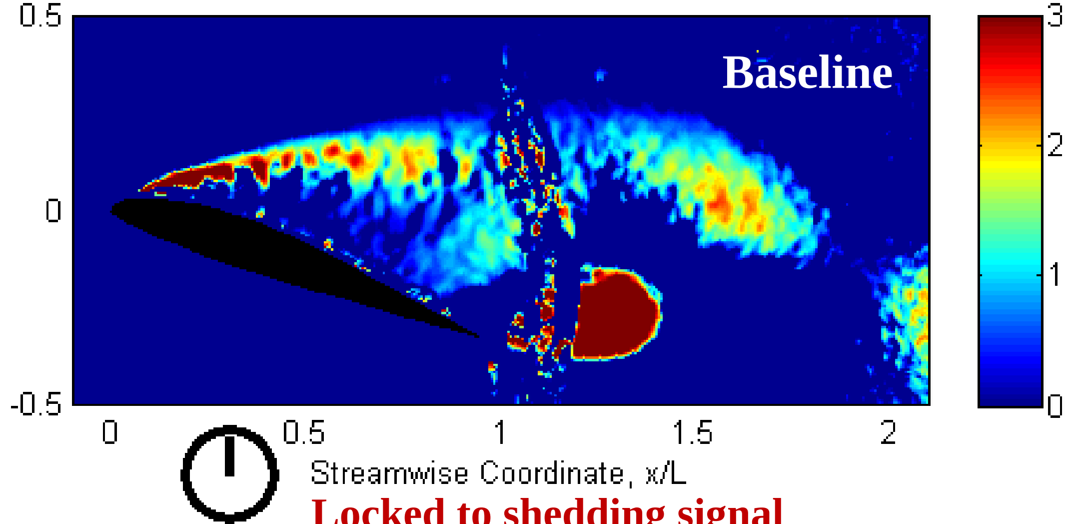


Outline

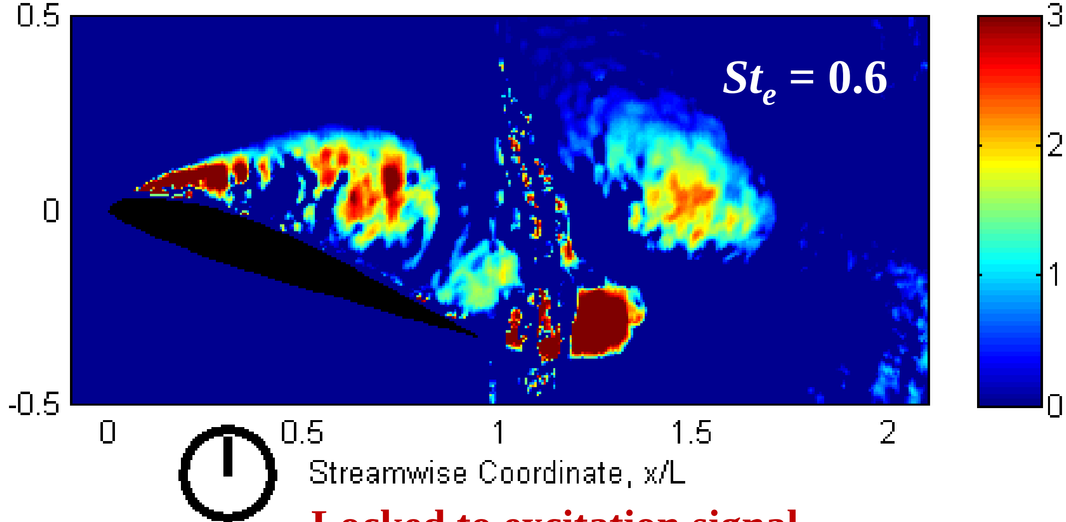
- ❑ Goals/Objectives
- ❑ Experimental Facilities and Techniques
- ❑ Results and Discussion
  - ❑ Time-averaged PIV: Velocity and Vorticity
  - ❑ **Phase-locked PIV: Coherent Structures**
  - ❑ Fluctuating Pressure Spectra
- ❑ Conclusions

Phase-locked Swirling Strength: Baseline

- **TE vortices are weakened** as a result of excitation
- The vortices shed from LE and TE are synchronous under **low *St_e*** excitation
- **Merging events** that precede generation of large-scale coherent structures can be clearly seen when locked to excitation signal
- Excitation by NS-DBD actuators, **expedites the development of non-linear interactions** (merging events) that lead to transition and breakdown of structures



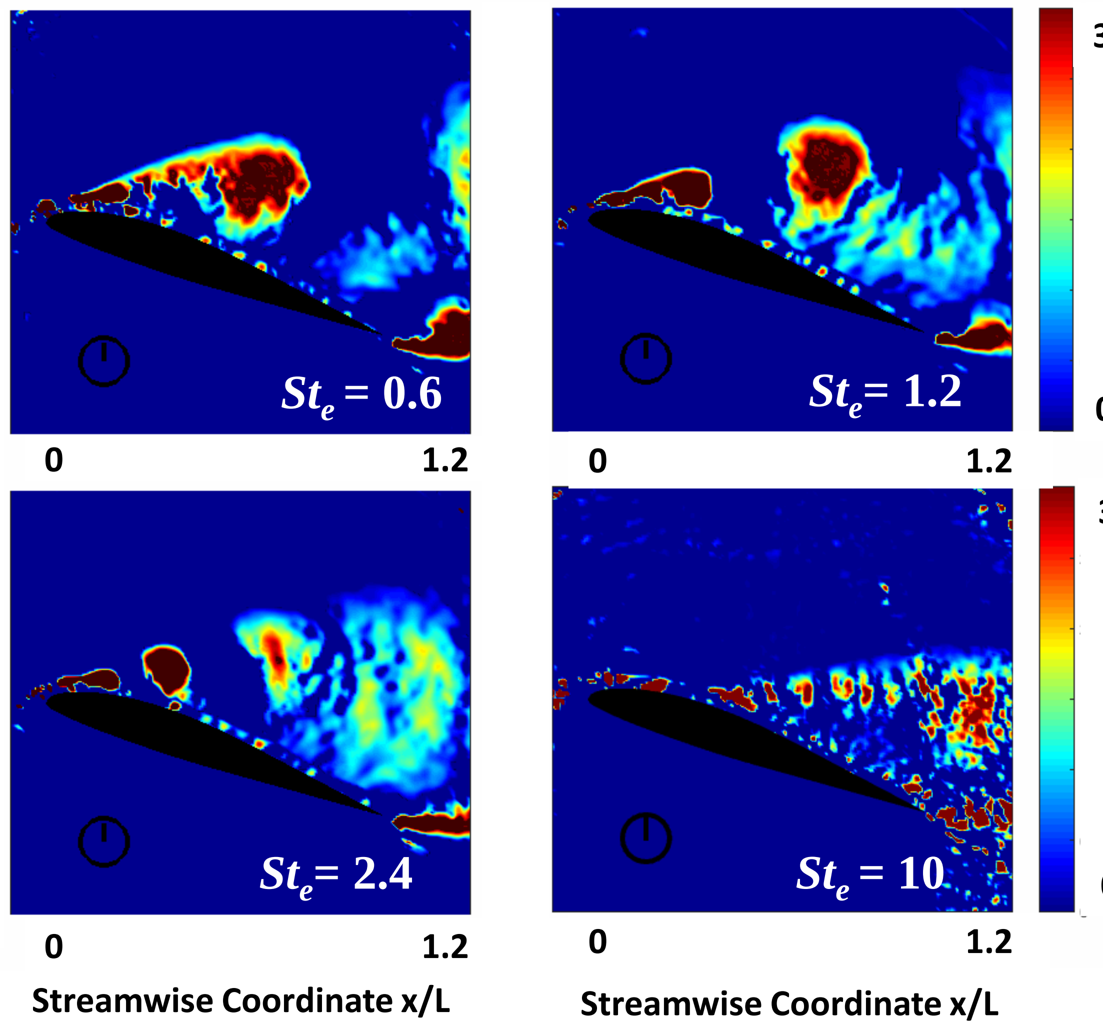
Locked to shedding signal



Locked to excitation signal

Phase-locked Swirling Strength: Excitation Effects

- Doubling the excitation frequency, halves the wavelength of generated structures
- The trajectory of vortex cores remains unchanged when the flow is excited at **low Strouhal numbers**
- The large-scale coherent structures generated when flow is excited closed to **PM freq** increase mixing and momentum diffusion closer to airfoil surface
- Coherence of the structures is lost at **high** St_e , consequently breakdown of vortices is expedited

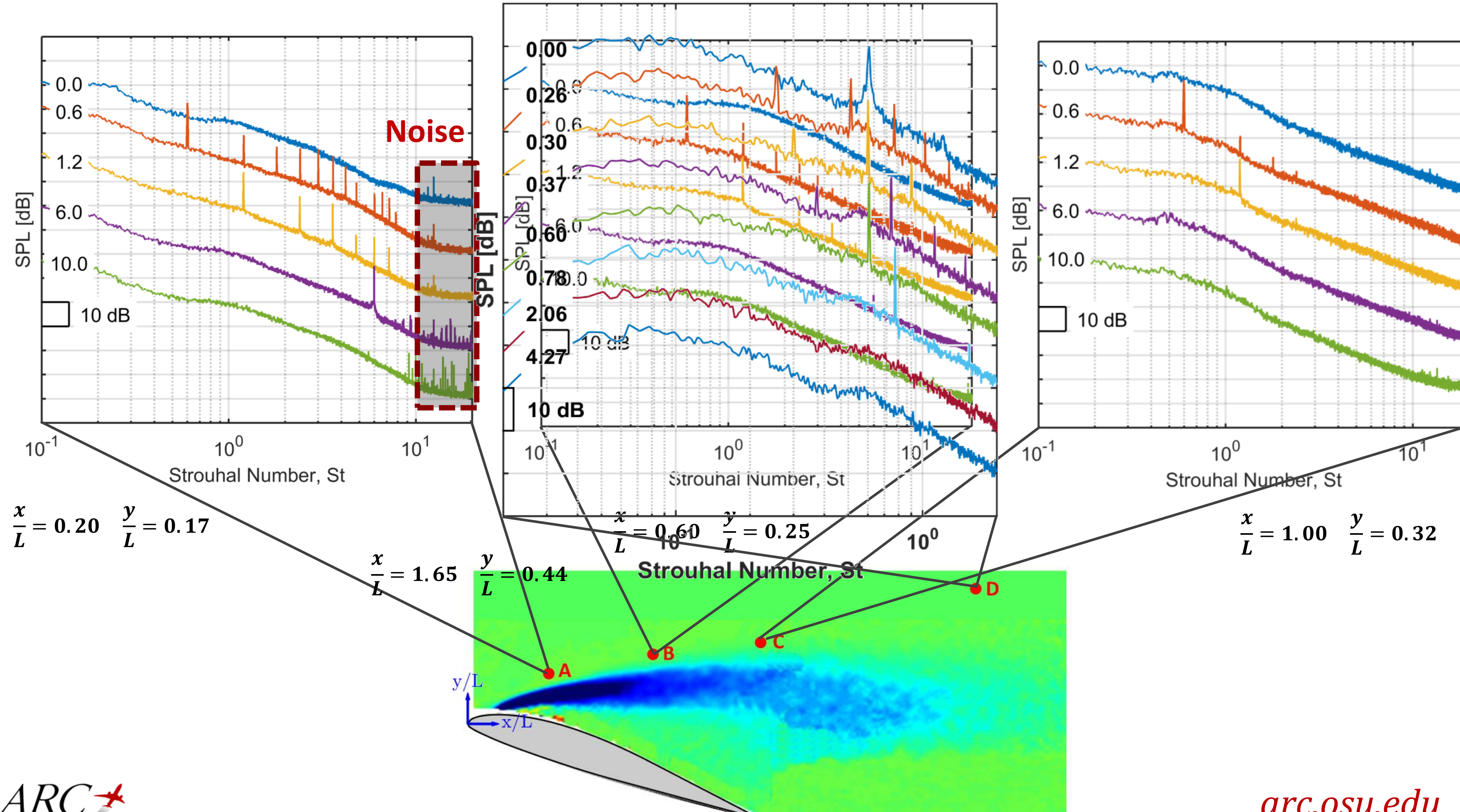


Outline

- Goals/Objectives
- Experimental Facilities and Techniques
- Results and Discussion
  - Time-averaged PIV: Velocity and Vorticity
  - Phase-locked PIV: Coherent Structures
  - **Fluctuating Pressure Spectra**
- Conclusions

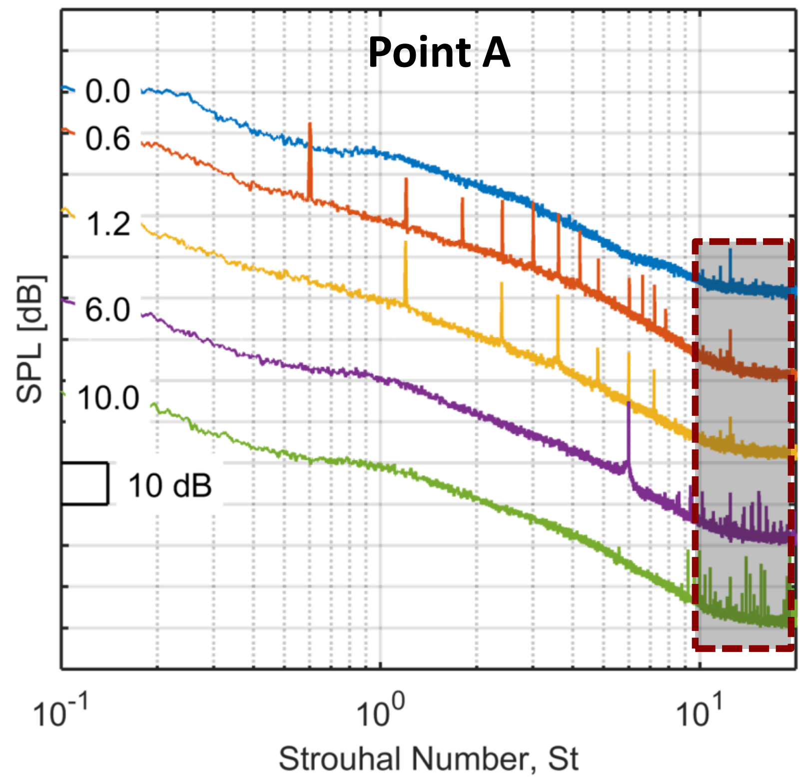
Pressure Spectra over the Airfoil: Low vs. High St_e

- Harmonics of excitation frequency appear in the spectrum
- Spectral peaks represent two phenomena: **compression waves, vortical structures**



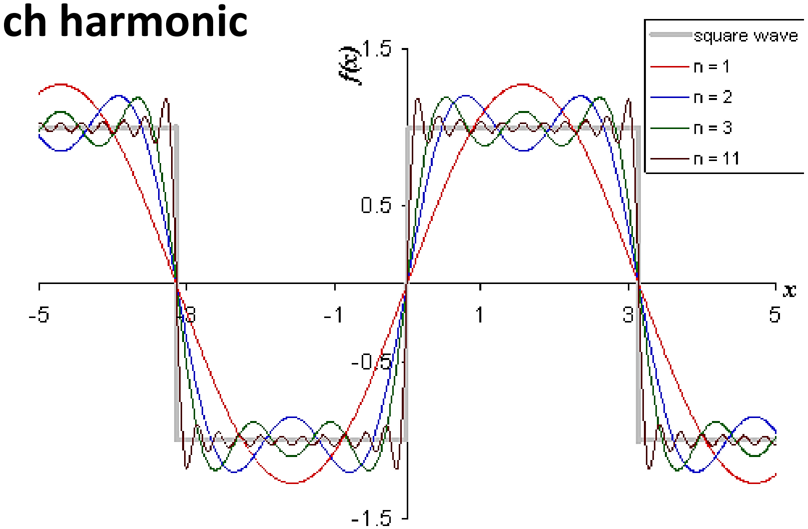
Pressure Spectra: Harmonics Explained

- Rectangular waveform fed to actuators contains both the excitation frequency and its higher order harmonics → harmonics are generated
- The **actual frequency at which the flow is excited** might not be the excitation frequency
- Excitation waveform is approximated by Fourier cosine series
- **Fourier constants indicate the amplitude of the perturbation generated by each harmonic**



$$x_T(t) = \sum_{n=0}^{\infty} a_n \cos n\omega t$$

where $a_n = \frac{2A}{n\pi} \sin\left(n\pi \frac{t_p}{T}\right)$



Outline

- ❑ Goals/Objectives
- ❑ Experimental Facilities and Techniques
- ❑ Results and Discussion
  - ❑ Time-averaged PIV: Velocity and Vorticity
  - ❑ Phase-locked PIV: Coherent Structures
  - ❑ Fluctuating Pressure Spectra
- ❑ **Conclusions**

Conclusions:

- Excitation at **low St_e** at the leading edge **generated organized coherent structures** in the shear layer over the separated region with a shedding Strouhal number corresponding to that of the excitation, synchronizing the vortex shedding from leading and trailing edges
- Coherent structures generated at **low St_e** promote momentum mixing and simultaneously remove energy from the freestream flow
- At **high St_e** , the wavelength of generated coherent structures is reduced and their **coherence and strength is decreased**
- Excitation at **low St_e** promoted vortex merging while excitation at **high St_e** resulted in smaller, weaker structures that quickly developed and disintegrate over the airfoil
- **Flow acceleration around LE** and **shear layer distortion** were observed when the flow was excited at **high St_e** . **This has not been the case for thick airfoils** [4-6]

Conclusions:

- The transition from most amplified frequency to preferred mode happens through multiple merging events that have been observed over the airfoil
- Excitation around the preferred mode frequency significantly **increased both the lift and drag**, but excitation at **high** St_e moved the separation point downstream and **reduced both the lift and drag**
- The rectangular waveform employed for excitation contains both the **excitation frequency and its harmonics**. It is not clear at which harmonic of the excitation frequency the flow is actually excited.

References:

[1] Greenblatt, D., and Wygnanski, I., “Effect of Leading-Edge Curvature on Airfoil Separation Control,” *Journal of Aircraft*, vol. 40, 2003, pp. 473–481.

[2] Kibens, V., “Discrete Noise Spectrum Generated by Acoustically Excited Jet,” *AIAA Journal*, vol. 18, 1980, pp. 434–441.

[3] Yarusevych, S., Sullivan, P. E., and Kawall, J. G., “On vortex shedding from an airfoil in low-Reynolds-number flows,” *Journal of Fluid Mechanics*, vol. 632, Aug. 2009, pp. 245–271.

[4] Rethmel, C., Little, J., Takashima, K., Sinha, A., Adamovich, I., and Samimy, M., “Flow Separation Control over an Airfoil with Nanosecond Pulse Driven DBD Plasma Actuators,” *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, American Institute of Aeronautics and Astronautics, .

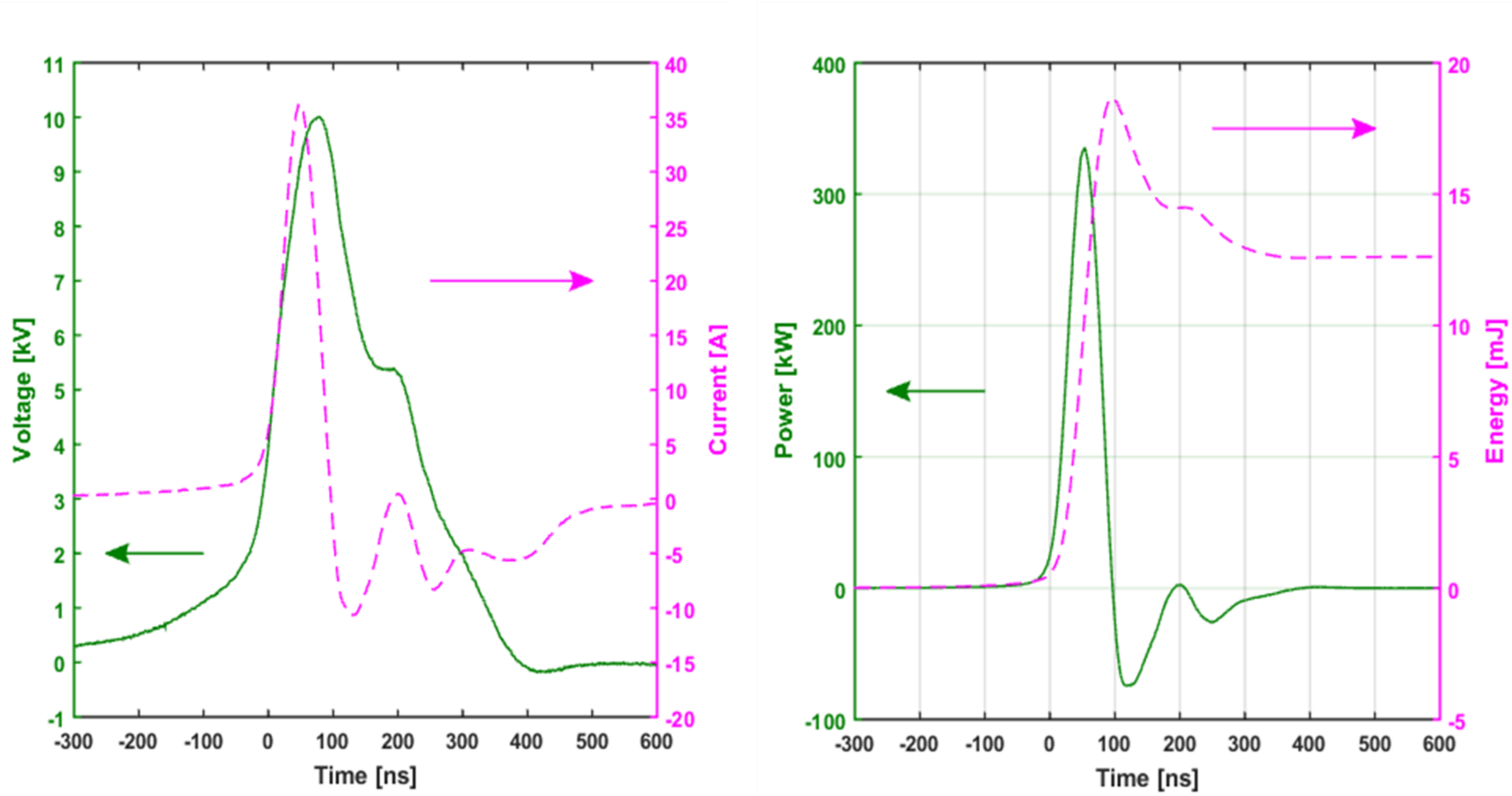
[5] Little, J., Takashima, K., Nishihara, M., Adamovich, I., and Samimy, M., “Separation Control with Nanosecond-Pulse-Driven Dielectric Barrier Discharge Plasma Actuators,” *AIAA Journal*, vol. 50, 2012, pp. 350–365.

[6] Little, J., Takashima, K., Nishihara, M., Adamovich, I., and Samimy, M., “High Lift Airfoil Leading Edge Separation Control with Nanosecond Pulse DBD Plasma Actuators,” *5th Flow Control Conference*, American Institute of Aeronautics and Astronautics, .

THANK YOU FOR YOUR ATTENTION

Questions?

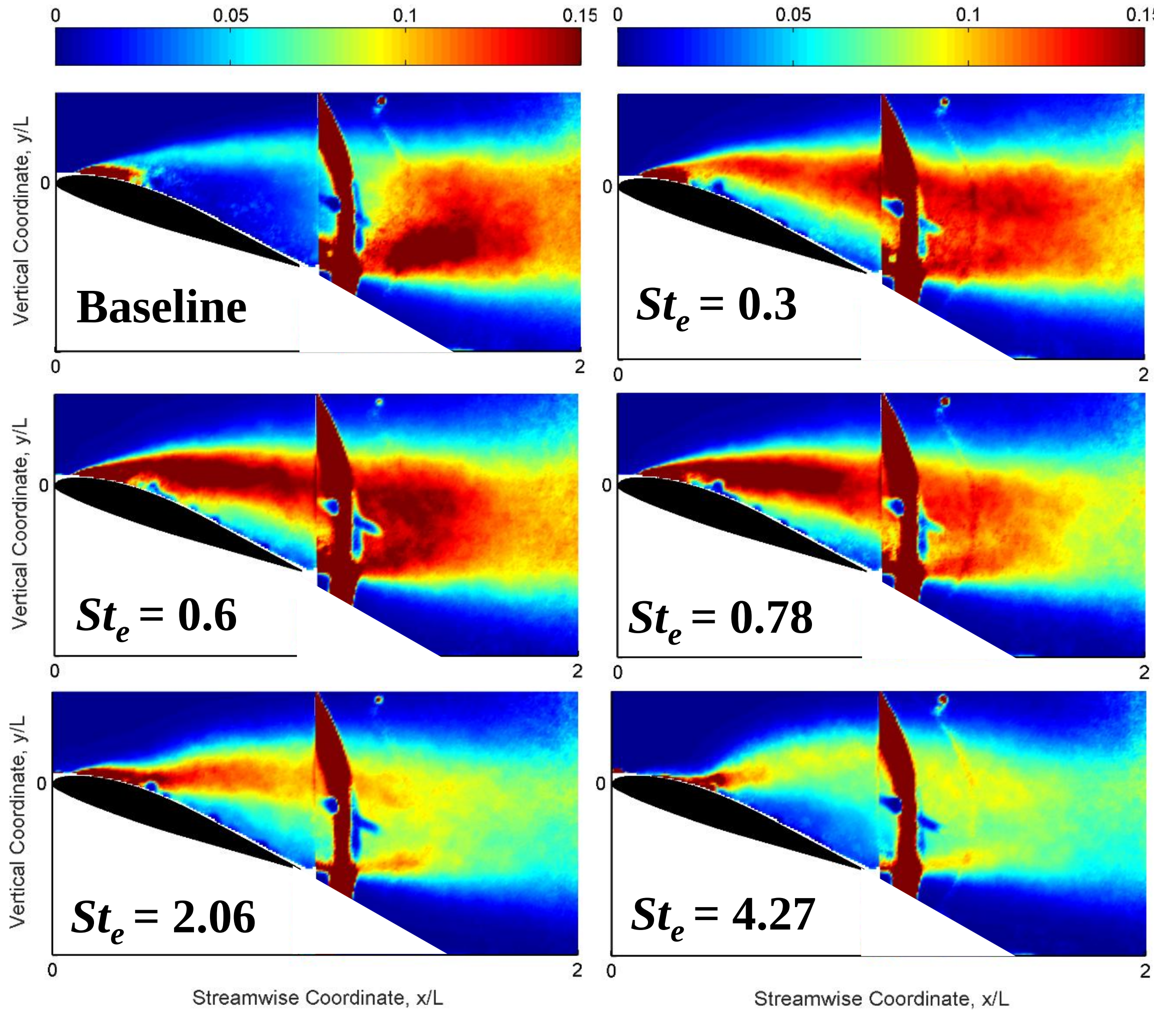
Discharge Characteristics



Discharge characteristics for pulse repetition rate of f_e = 100 Hz

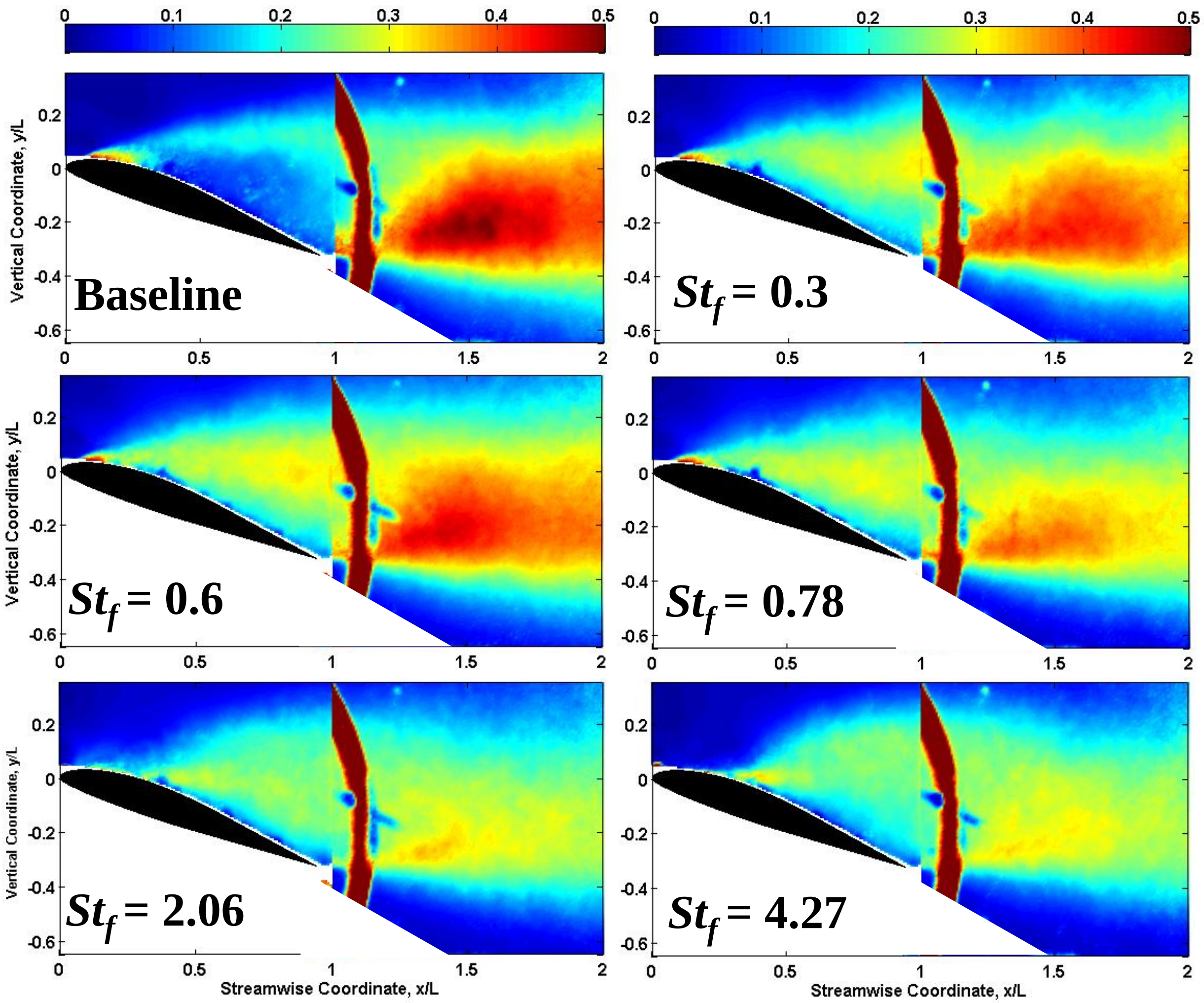
Time-averaged plots of TKE: Excitation Effects

- **Low St_e excitation** expedites the development of separated shear layer and promotes mixing
- Excitation at higher Strouhal numbers removes less and less energy from freestream which results in a significant reduction of drag
- Absence of large-scale, energetic structures is evident when the flow is excited at **high St_e**
- Due to low energy content of vertical structures at **high St_e** their signature is not registered by the probe located in the wake



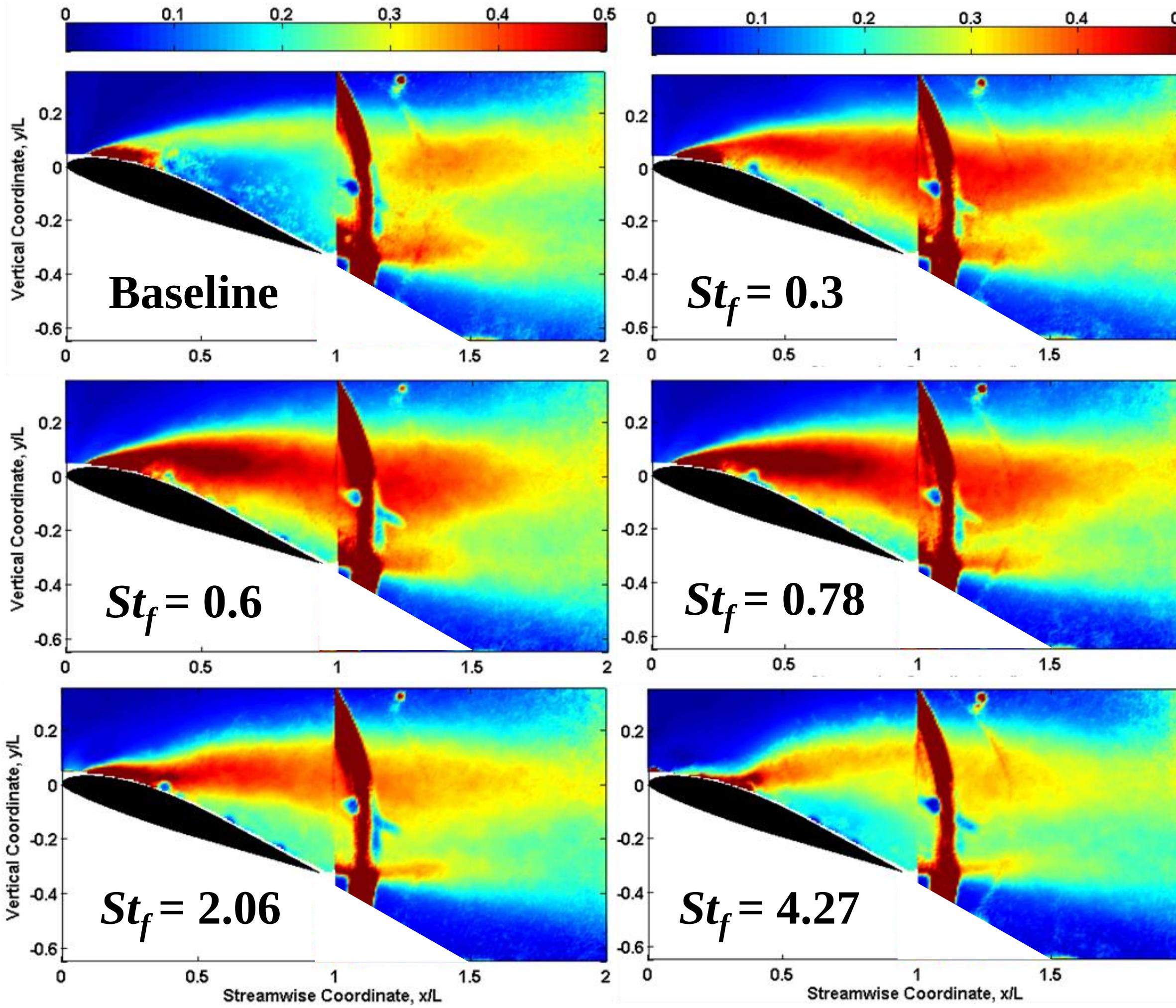
Time-averaged v_{rms}: Excitation Effects

- Actuation with NS-DBD actuator weakens the vortices shed from airfoil TE
- The separated shear layer is most receptive to excitation at **low *St_e*** as is evident by the amplitude of v_{rms}
- Actuation at frequencies close to preferred mode frequency (***St_e* = 0.6**) removes energy from freestream flow, increases drag

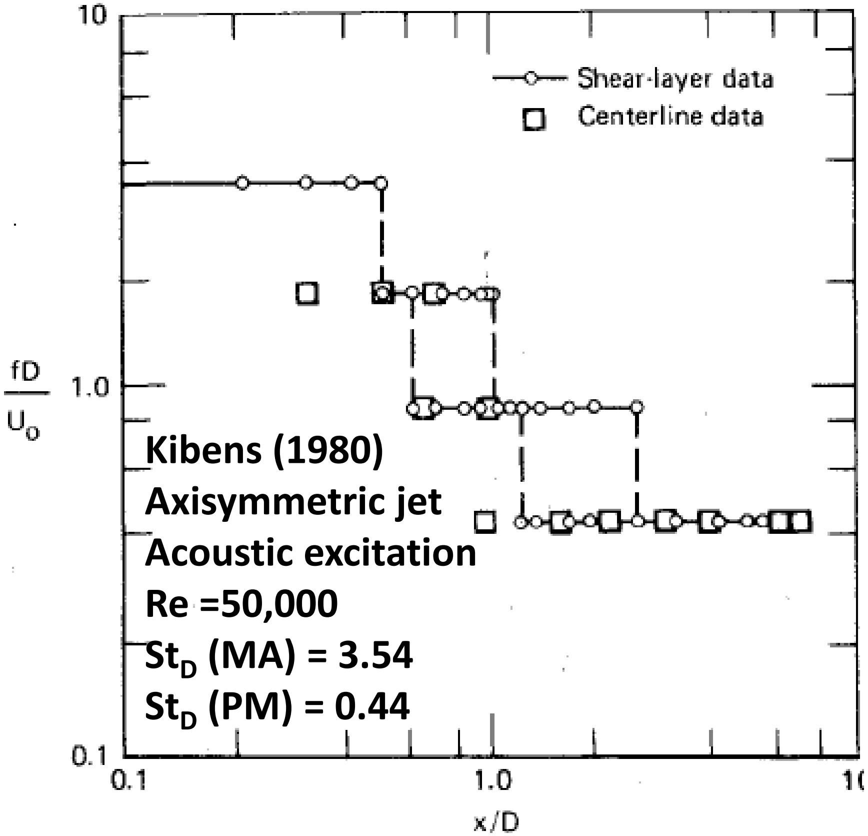


Time-averaged u_{rms}: Excitation Effects

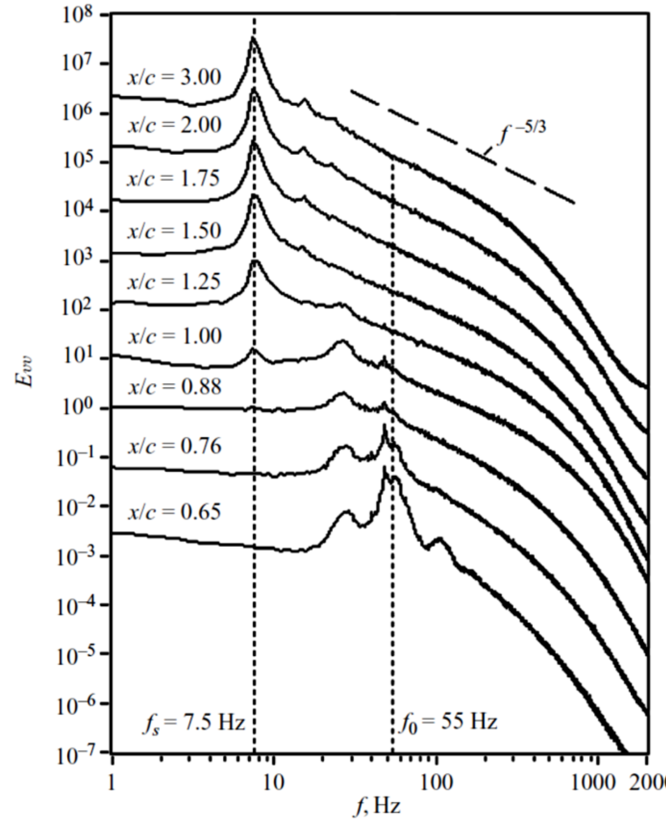
- Actuation with NS-DBD actuator weakens the vortices shed from airfoil TE
- The separated shear layer is most receptive to excitation at **low St_e** as is evident by the amplitude of v_{rms}
- Actuation at frequencies close to preferred mode frequency (**St_e = 0.6**) removes energy from freestream flow, increases drag



Most Amplified to Preferred Mode Frequency: Imposed Length Scale



Kibens (1980)
Axisymmetric jet
Acoustic excitation
Re =50,000
St_D (MA) = 3.54
St_D (PM) = 0.44

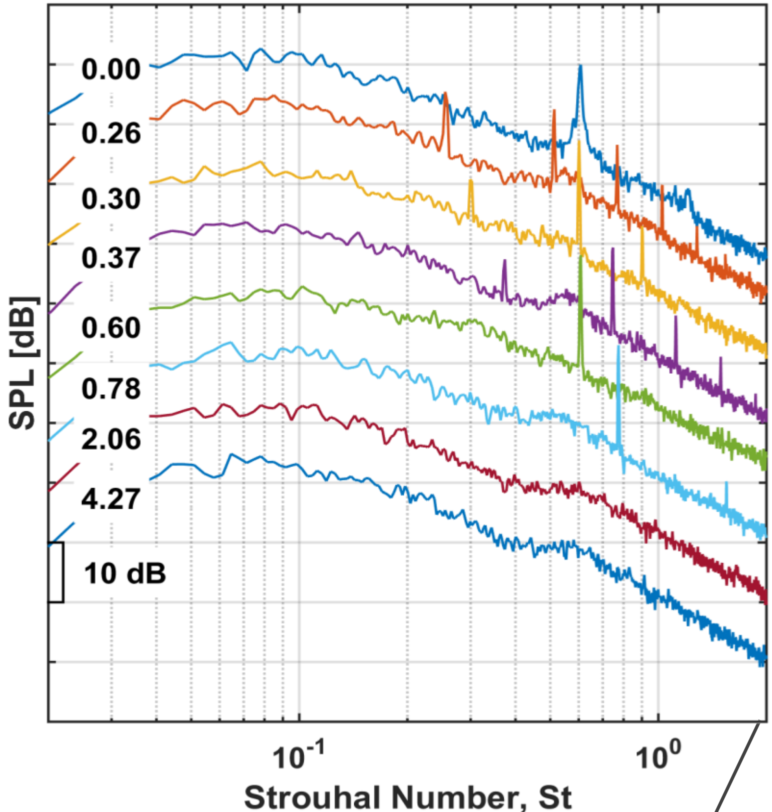


Yarusevych et al (2009)
Separated flow over airfoil
Re = 55,000
St = 0.74

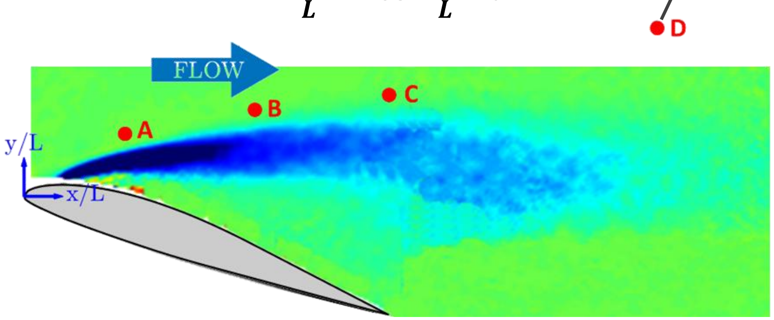
- Kibens and Yarusevych et al. [2,3] have reported that the transition from most amplified frequency to preferred mode in flows with an imposed length scale (jet shear layer, separated shear layer over airfoil) happens through several vortex merging events
- Merging is manifested as the growth of sub-harmonic content in the spectra

Wake Spectra: Low vs. High St_e

- Excitation at **low St_e** relocates energy to a band of frequencies close to the natural shedding frequency
- When the flow is actuated at **low St_e**, not only a peak at **St_e** is observed but also several harmonics are generated as well
- Excitation at **high St_e** results in generation of a broadband peak that is centered about **St = 0.5**
- At **high St_e**: increasing the St_e → peak becomes more defined
- The wake spectra at **low St_e** has the distinct signature shape of a turbulent shear layer (**not clear form global measurement**)

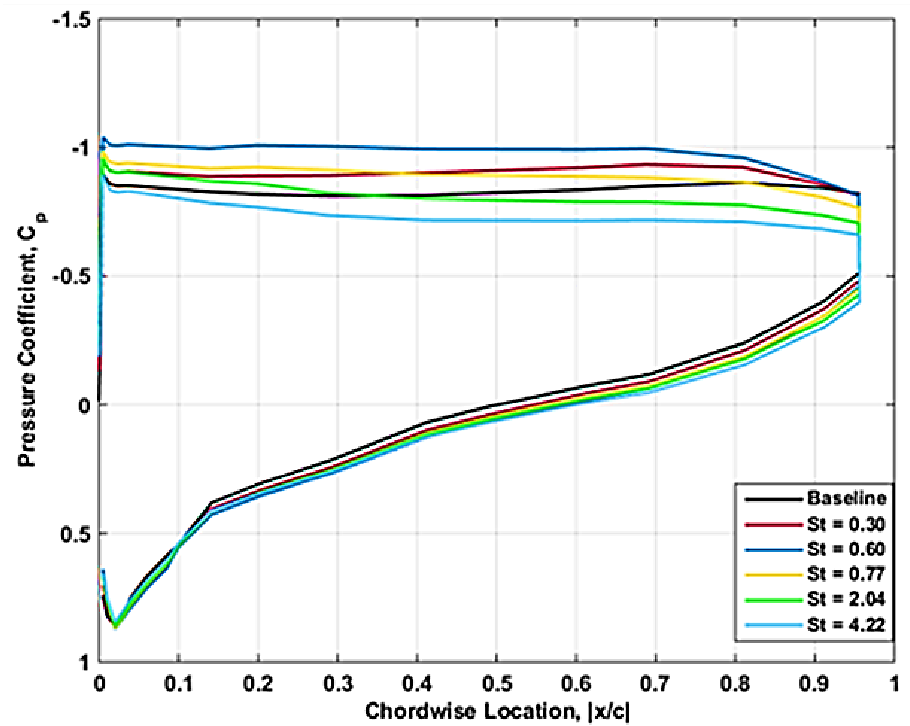


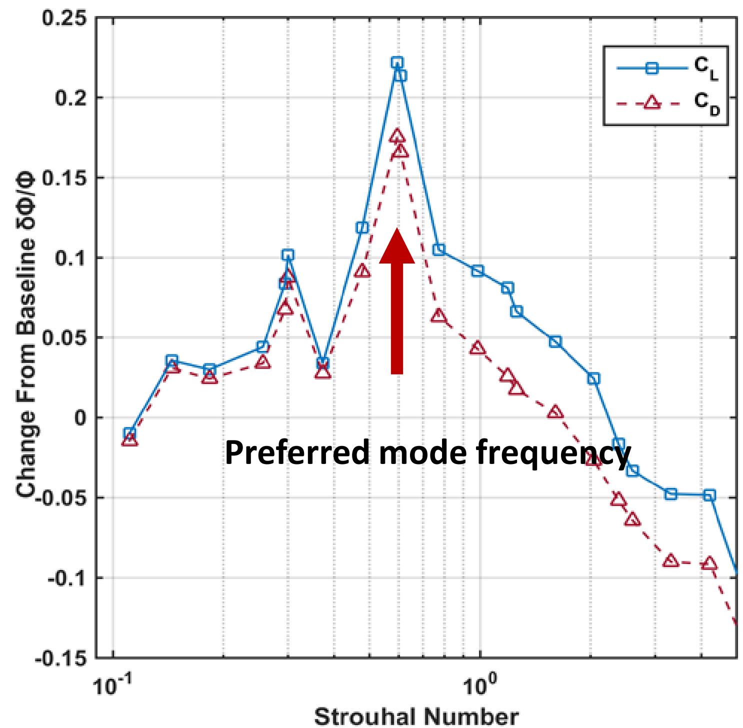
$\frac{x}{L} = 1.65 \quad \frac{y}{L} = 0.44$



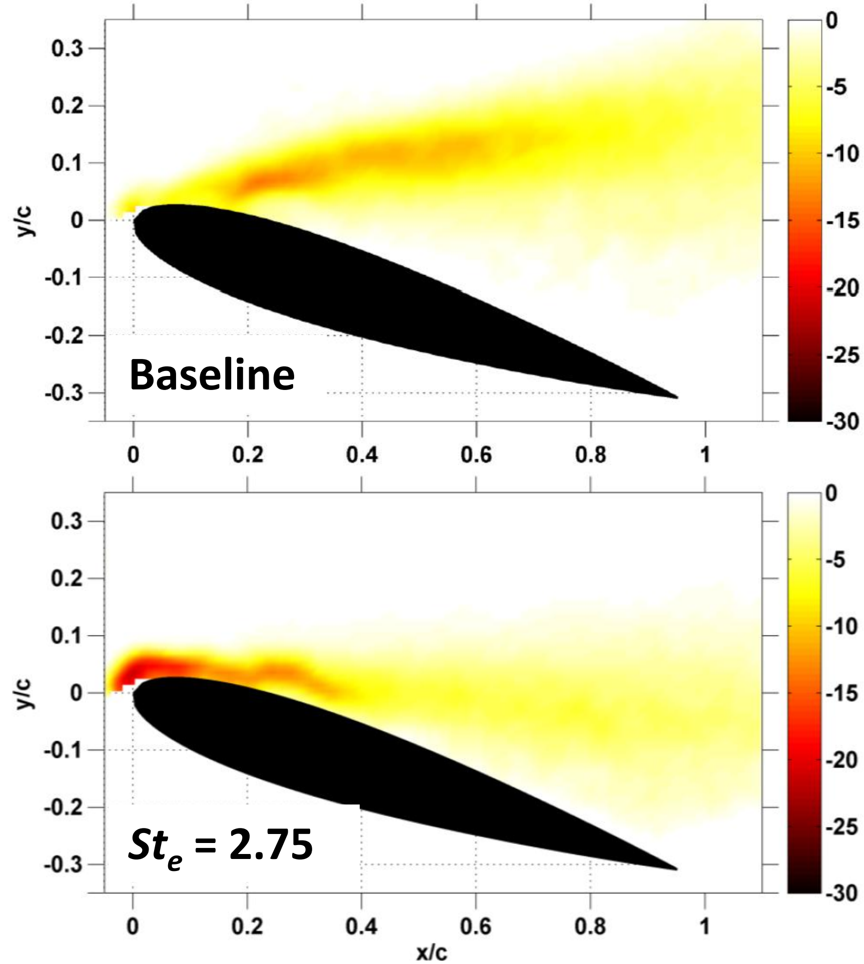
Surface Pressure Distribution: Excitation Effects

- The control mechanism at **low *St*$_e$** directly connects the changes in lift and drag together
- Actuation at **high *St*$_e$** results in significant acceleration of the flow around LE and a pressure recovery around TE
- Loss of pressure taps around LE → the increase in suction could not be registered
- The maximum increase in the C_l is 22.2% and the maximum increase in C_D is 17.5%



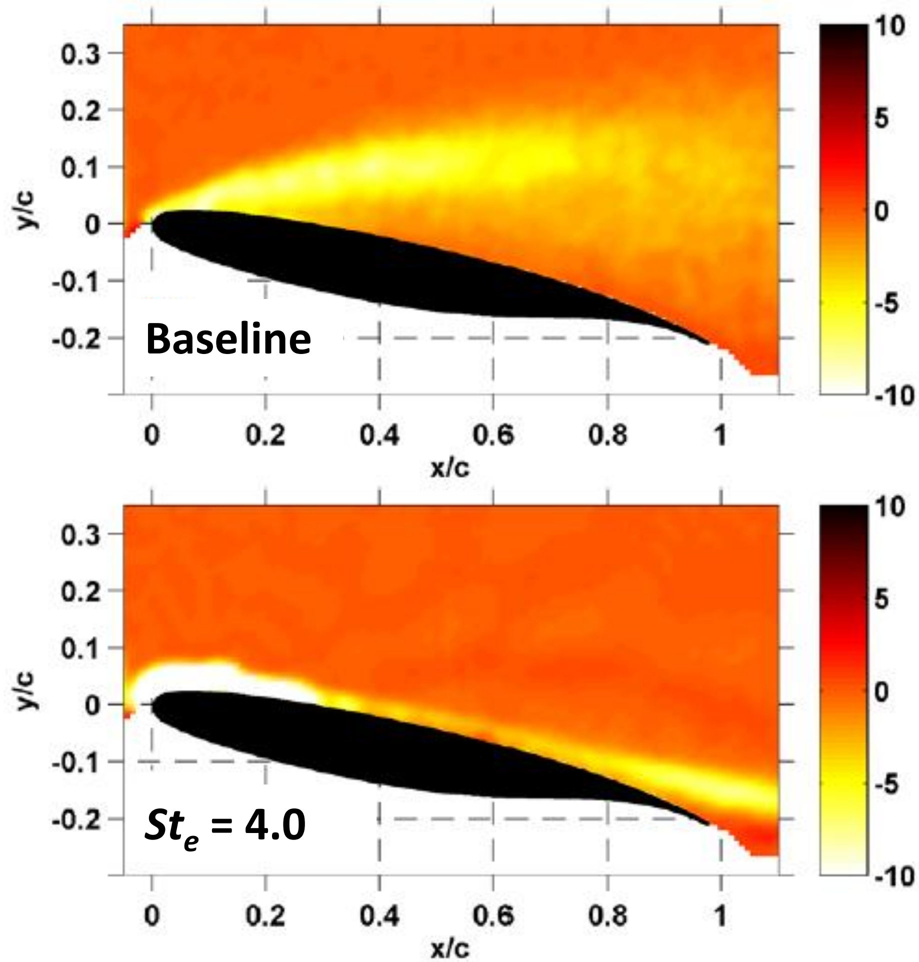


Time-averaged Vorticity for NACA 0015



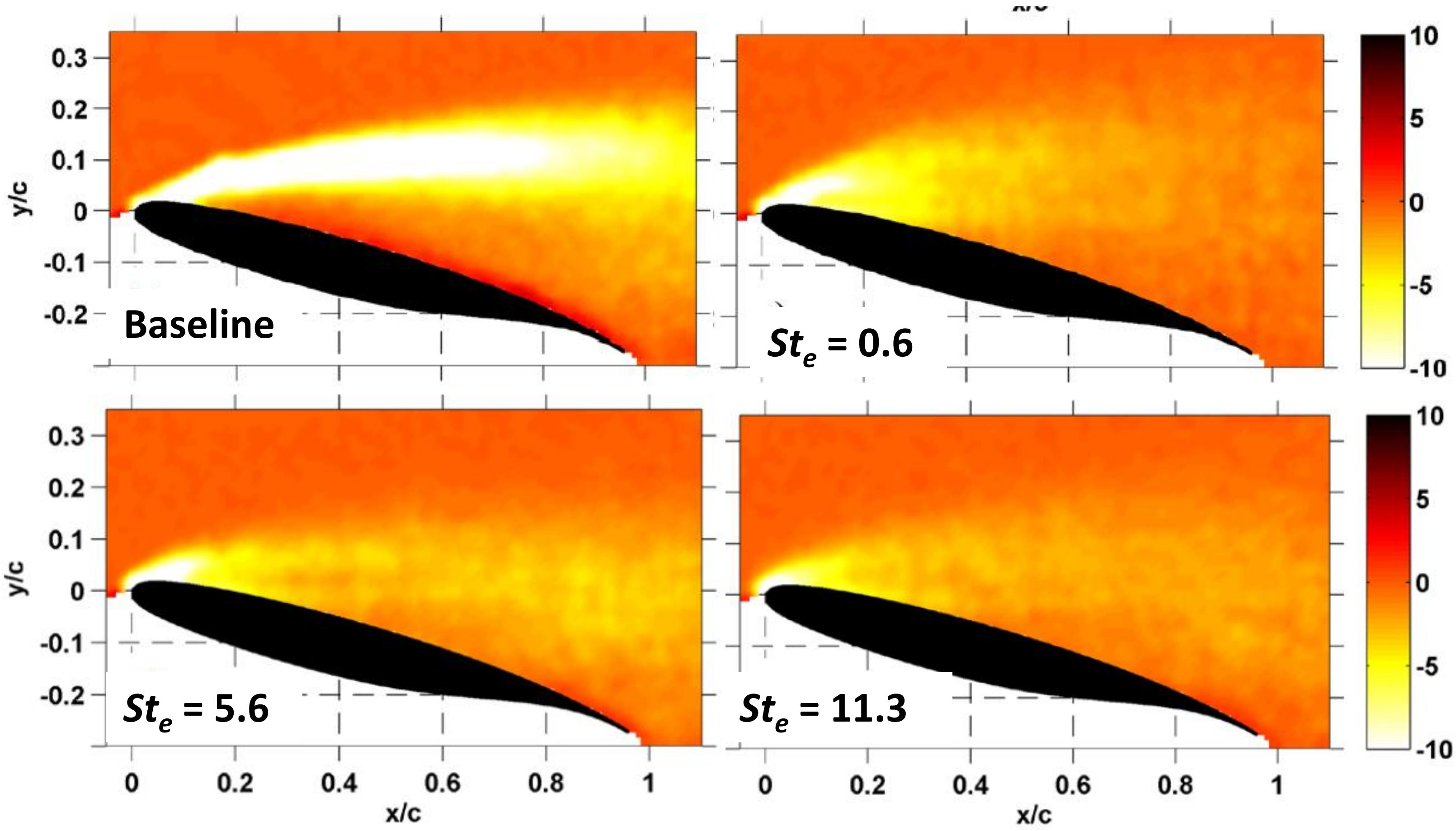
Time averaged vorticity maps at α = 18° and *Re* = 1.15x10^6 (Rethmel, 2011)

Time-averaged Vorticity for NASA EET



Time averaged vorticity maps at α = 12° and *Re* = 0.75x10^6 (Little, AIAA J, 2012)

Time-averaged Vorticity for NASA EET



Time averaged vorticity maps at α = 16° and *Re* = 0.75x10^6 (Little, AIAA J, 2012)