CONTROL OF BOUNDARY LAYER SEPARATION AND THE WAKE OF AN AIRFOIL USING NS-DBD PLASMA ACTUATORS

by

Timothy Ashcraft

A Thesis Submitted to the Faculty of the

DEPARTMENT OF AEROSPACE AND MECHANICAL ENGINEERING

In Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN AEROSPACE ENGINEERING

In the Graduate College

THE UNIVERSITY OF ARIZONA

2016

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at the University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that an accurate acknowledgement of the source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his or her judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: Timothy Ashcraft

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Jesse Little
Assistant Professor

Date

Acknowledgements

I would first like to thank my wife, Ashley, for her enduring love and support. During two deployments, seven moves, countless adventures as an Army wife, and my pursuit of a master's degree, she has literally held down the fort with our daughter, Adeline, and son, Lincoln. They keep me grounded wherever our journeys take us.

Dr. Jesse Little is the archetype advisor with an unprecedented work ethic. His guidance and patience allowed me to explore previously uncharted territory in the world of academia. It is hard to imagine transitioning from the operational Army to the laboratory without his leadership.

A special thanks to the members of my thesis committee, Dr. Cholik Chan and Dr. Edward Kerschen. Your expertise and teachings in the fundamentals of fluid mechanics were integral in my graduate education pursuits.

I am forever indebted to my colleagues for answering a daily dose of questions with sincerity and grace. A special thanks to Ken Decker, my academic "wingman," whose assistance cannot be overstated; Marcel Dengler, for his thorough initial work in this project and subsequent Skype meetings; Sebastian Endrikat for teaching me everything PIV and German culture; Ashish Singh for his infinite wisdom and genuine tutoring; Stephen Pineda for assistance with MATLAB and the more-than-occasional comic relief; David Dones for heavy lifting with airfoil construction and maintenance; and Zack Wellington for filling in the gaps wherever and whenever needed. Thanks to Dale Drew and Lane Hammond for doing yeoman's work in the machine shop.

My parents, Dave and Joan, have blessed me with encouragement in every walk of life. I am also privileged to have an older brother and best friend, Chris, who enjoys golf

and hiking therapy as much as I do. My grandfather, Clarence Leslie “Stub” Ashcraft Jr., who epitomized what it means to “Bear Down!” taught me love of country and the University of Arizona.

This work has been supported by the U.S. Army Research Office (ARO) Young Investigator Program (W911NF-14-1-0662 monitored by Dr. Matthew Munson), U.S. ARO High School Apprenticeship Program/University Research Apprenticeship Program, Arizona-NASA Space Grant Consortium, Department of Aerospace and Mechanical Engineering and the College of Engineering at the University of Arizona. My funding was provided by the Army’s Advanced Civil Schooling Program and the Civil and Mechanical Engineering Department at the United States Military Academy. Fabrication of the NACA 0012 model was made possible by a University of Arizona Faculty Seed Grant and carried out as part of an Aerospace Engineering Undergraduate Senior Design Project by Cesar Barroso, Lee Ficke, George Gudgeon, Andrew McGuckin and Nathan Turner.

I am grateful for the support of LTC Philip Root – gifted professor and valued mentor, CW4 (Ret.) Robert Valdez Jr. – attack standardization pilot and instructor extraordinaire, and Dr. Bruce Simon – Professor Emeritus, talented musician, and friend. Without the tactical skill of CW4 Jacob Marceaux, the “Michael Jordan” of Apache helicopters, I simply would not be here today. To the “Steel Hunters” of C Company, 1-501st Aviation Regiment, serving with you in combat remains the greatest professional honor of my life.

Lastly, it is to CW2 Chris Thibodeau who paid the ultimate sacrifice, his wife LeeSandra, and son Liam, that I dedicate this work. *Forever in Flight!*

Table of Contents

Acknowledgements.....	3
List of Figures	6
List of Tables	8
Nomenclature	8
Abstract	9
1. Introduction.....	10
2. Background	12
2.1 Flow Control History	12
2.2 Leading Edge Airfoil Separation Control	14
2.3 DBD Plasma Actuators	16
2.4 Separation Control with DBD Plasma Actuators.....	21
2.5 Wake Control	23
3. Experimental Facilities and Techniques	28
3.1 Wind Tunnel	28
3.2 Airfoil Model	29
3.3 ns-DBD Plasma Actuator.....	32
3.4 Diagnostics and Practical Implementation.....	35
4. Results	42
4.1 Test Conditions	42
4.2 Pressure Measurements.....	42
4.3 PIV Results	47
4.4 Constant Temperature Anemometry	55
5. Discussion and Conclusions	63
5.1 Future Work	66
References	67
Appendix A.....	71
Appendix B	72
Appendix C	75
Appendix D.....	81

List of Figures

Figure 1. Sketch by Leonardo da Vinci of quasi-stationary, counter-rotating vortices in the midst of the random wake (Gad-el-Hak 2000).	12
Figure 2. Smoke flow visualization over the top surface of a (truncated) $\frac{3}{4}$ NACA 0015 airfoil (a) baseline data, (b) excitation at $F^+ = 2.6$ by means of an oscillating ribbon near the leading edge $Re = 40,000$ (Greenblatt et al. 2000).	14
Figure 3. Example of visible plasma formed by an ac-DBD actuator on a cylinder (Gregory et al. 2007).	16
Figure 4. Common types and construction of plasma actuators (Cattafesta et al. 2011)..	18
Figure 5. Example plots of (a) voltage and current traces and (b) instantaneous power and energy traces for a 30-cm-long ns-DBD actuator driven at 10 Hz (Little et al. 2012).	19
Figure 6. Example mean velocity profiles for ns and ac-DBD plasma actuators operating in quiescent air with 2 kHz carrier frequency using (a) 100% and (b) 50% duty cycle at 90 Hz measured 20 mm downstream on a 30 cm DBD load (Little et al. 2010).....	20
Figure 7. Phase-averaged schlieren images of compression waves generated by a nanosecond pulse discharge for several time delays after the discharge pulse (Little et al. 2012). Images taken along the axis of the discharge.	21
Figure 8. Phase-averaged schlieren images taken from a direction perpendicular to the cylinder axis (Little et al. 2012).	21
Figure 9. Representations of basic classes of vortex-body encounter: (a) parallel vortex; streamwise (perpendicular) vortex (b) without and (c) with breakdown; and (d) normal vortex interactions (Rockwell 1998).....	25
Figure 10. Possible regimes of flow patterns over a NACA-0012 airfoil at post-stall angles of attack versus Reynolds number. All data are taken from experiment unless noted. Shaded regions denote tentative approximate boundaries (Wu et al. 1998).....	27
Figure 11. Wind tunnel viewed from the operator side (external side of tunnel loop) looking upstream.	29
Figure 12. Schematic of experimental setup in wind tunnel test section.	29
Figure 13. Chord-wise pressure tap distribution.	31
Figure 14. Pressure tap locations on suction side of airfoil.	31
Figure 15. Vertically-mounted NACA 0012 airfoil.	32
Figure 16. Asymmetric ns-DBD Plasma Actuator Schematic.	33
Figure 17. (a) ns-DBD plasma actuator on leading edge of NACA 0012 airfoil and (b) airfoil, actuator and pressure tube connections.	34
Figure 18. Sample traces of (a) Voltage and Current and (b) Instantaneous Power and Energy for a 76.5-cm-long (30 in.) ns-DBD actuator.	35

Figure 19. Scanivalve (a) ZOC33 miniature pressure scanner module and (b) RADBASE4000 base unit.....	36
Figure 20. LaVision (a) 5.5 million pixel imager sCMOS Camera with Nikon Nikkor 50mm f 1.2 lens (b) aerosol generator.	38
Figure 21. Dantec Dynamics (a) StreamLine Pro Research CTA System and (b) Gold-plated wire probe (55P01).....	40
Figure 22. C_p distributions for first 3mm actuator location at $Re = 740k$ at (a) 14° (b) 15° (c) 16° (d) 17° (e) 18° (f) 19°	44
Figure 23. Suction side C_p at $x/c = 0.09$ vs. dimensionless forcing frequency, F^+ , for NACA 0012 airfoil at $Re = 0.74 \times 10^6$ and (a) $\alpha = 16^\circ$ and (b) $\alpha = 18^\circ$	45
Figure 24. (a) Mid-span and 3D C_p distribution for $F^+ \approx 0.15$ ($f_f = 20$ Hz) (b) $F^+ \approx 0.46$ ($f_f = 60$ Hz) (c) $F^+ \approx 1.14$ ($f_f = 150$ Hz) (d) C_p distribution for select control cases at $\alpha = 18^\circ$ and $Re = 740k$	47
Figure 25. Plots of time-averaged dimensionless streamwise velocity U^* at $Re = 0.74 \times 10^6$, $\alpha = 18^\circ$ (a) Baseline case (no control) and NS-DBD forcing at (b) $F^+ \approx 0.15$ ($f_f = 20$ Hz) (c) $F^+ \approx 0.46$ ($f_f = 60$ Hz) and (d) $F^+ \approx 1.14$ ($f_f = 150$ Hz).	49
Figure 26. Dimensionless time-averaged vorticity Ω^* at $Re = 0.74 \times 10^6$, $\alpha = 18^\circ$ (a) Baseline case (no control) and ns-DBD forcing at (b) $F^+ \approx 0.15$ ($f_f = 20$ Hz) (c) $F^+ \approx 0.46$ ($f_f = 60$ Hz) and (d) $F^+ \approx 1.14$ ($f_f = 150$ Hz).	50
Figure 27. Phase-averaged PIV for ns-DBD forcing at $F^+ \approx 0.15$ ($f_f = 20$ Hz) (a) Dimensionless Streamwise Fluctuating Velocity u^* (b) Dimensionless Vertical Fluctuating Velocity v^* and (c) Dimensionless Spanwise Vorticity Ω^*	52
Figure 28. Phase-averaged PIV for ns-DBD forcing at $F^+ \approx 0.46$ ($f_f = 60$ Hz) (a) Dimensionless Streamwise Fluctuating Velocity u^* (b) Dimensionless Vertical Fluctuating Velocity v^* and (c) Dimensionless Spanwise Vorticity Ω^*	53
Figure 29. Phase-averaged PIV for ns-DBD forcing at $F^+ \approx 1.14$ ($f_f = 150$ Hz) (a) Dimensionless Streamwise Fluctuating Velocity u^* (b) Dimensionless Vertical Fluctuating Velocity v^* and (c) Dimensionless Spanwise Vorticity Ω^*	54
Figure 30. PSD vs. Strouhal number for noise floor and actuation at $F^+ = 1.14$ ($f_f = 150$ Hz).	56
Figure 31. (a) Mid-span PSD for all Forcing Frequencies (b) Auto Correlations at all Forcing Frequencies. Hot wire probe is located at $x/c = 7$ and $y/c = -0.08$	58
Figure 32. (a) Baseline PSD (b) PSD at $F^+ = 0.15$ ($f_f = 20$ Hz) (c) $F^+ = 0.46$ ($f_f = 60$ Hz) (d) $F^+ = 1.14$ ($f_f = 150$ Hz).....	61
Figure 33. Correlation data at (a) No actuation (b) $F^+ = 0.15$ ($f_f = 20$ Hz) (c) $F^+ = 0.46$ ($f_f = 60$ Hz) (d) $F^+ = 1.14$ ($f_f = 150$ Hz).	63

List of Tables

Table 1. Airfoil Summary.	30
Table 2. Technical Specifications for gold-plated Hot wire Sensors.....	71

Nomenclature

c	=	model chord, 30.48 cm
C_L	=	lift coefficient
C_P	=	pressure coefficient
f	=	frequency
f_f	=	forcing frequency
F^+	=	dimensionless forcing frequency, $f_f c / U_\infty$
Re	=	chord-based Reynolds number, $U_\infty c / \nu$
St	=	Strouhal number, $f c / U_\infty$
T^*	=	convective time, $t U_\infty / c$
$\tilde{u}$	=	phase-averaged fluctuating streamwise velocity, $(\tilde{U} - \bar{U})$
$\tilde{u}^*$	=	dimensionless phase-averaged fluctuating streamwise velocity, $\tilde{u} / U_\infty$
U	=	instantaneous streamwise velocity
$\bar{U}$	=	time-averaged streamwise velocity
$\bar{U}^*$	=	dimensionless time-averaged streamwise velocity, $\bar{U} / U_\infty$
$\tilde{U}$	=	phase-averaged streamwise velocity
$\tilde{U}^*$	=	dimensionless phase-averaged streamwise velocity
U_∞	=	freestream velocity
$\tilde{v}$	=	phase-averaged fluctuating vertical velocity, $(\tilde{V} - \bar{V})$
$\tilde{v}^*$	=	dimensionless phase-averaged fluctuating normal velocity, $\tilde{v} / U_\infty$
V	=	instantaneous vertical velocity
$\bar{V}$	=	time-averaged vertical velocity
$\bar{V}^*$	=	dimensionless time-averaged vertical velocity, $\bar{V} / U_\infty$
$\tilde{V}$	=	phase-averaged vertical velocity
$\tilde{V}^*$	=	dimensionless phase-averaged vertical velocity
x/c	=	dimensionless streamwise coordinate
y/c	=	dimensionless vertical coordinate
α	=	angle of attack in degrees
Ψ	=	phase angle
Ω	=	instantaneous vorticity
$\bar{\Omega}$	=	time-averaged vorticity
$\bar{\Omega}^*$	=	dimensionless time-averaged vorticity, $\bar{\Omega} c / U_\infty$
$\tilde{\Omega}$	=	phase-averaged vorticity
$\tilde{\Omega}^*$	=	dimensionless phase-averaged vorticity, $\tilde{\Omega} c / U_\infty$
PSD	=	dimensionless Power Spectral Density $(\tilde{u} / U_\infty)^2 / St$

Abstract

The efficacy of nanosecond pulse driven dielectric barrier discharge (ns-DBD) plasma actuators for boundary layer separation and wake control is investigated experimentally. A single ns-DBD plasma actuator is placed at the leading edge of a NACA 0012 airfoil model. Both baseline and controlled flow fields are studied using static pressure measurements, Particle Image Velocimetry (PIV) and Constant Temperature Anemometry (CTA). Experiments are primarily performed at $Re = 0.74 \times 10^6$ and $\alpha = 18^\circ$. C_P , PIV and CTA data show that a forcing frequency of $F^+ = 1.14$ is optimal for separation control. CTA surveys of the wake at $x/c = 7$ indicate three approximate regimes of behavior. Forcing in the range $0.92 < F^+ < 1.52$ results in the best conditions for separation control over the airfoil, but has no dominant signature in the wake at $x/c = 7$. Excitation in the range of $0.23 < F^+ < 0.92$ produces a single dominant frequency in the wake while $F^+ < 0.23$ shows behavior representing a possible impulse response or nonlinear effects. PIV data confirm these observations in all three regimes. Cross-correlations of CTA data are also employed to evaluate the two-dimensionality of the excited wake. The initial results presented here are part of an ongoing effort to use active flow control (AFC), in the form of ns-DBDs, as an enabling technology for the study of unsteady aerodynamics and vortex-body interactions.

1. Introduction

Unsteadiness is present in many flows of high interest to both rotary and fixed wing platforms. Rotorcraft and turbomachinery performance are particularly dependent on the response of aerodynamic surfaces to unsteady and vortex-dominated flows. Fixed wing unmanned aerial vehicles (UAVs) can also operate in unsteady environments especially at low altitudes, in urban settings and during formation flight. Future generations of both rotary and fixed wing aircraft will encounter progressively more challenging unsteady flight regimes as autonomous systems mature. Classical unsteady aerodynamics (e.g. Kussner, Loewy, Miles, Sears, Theodorsen, Wagner, etc.) provides analytical solutions for a variety of conditions (Leishmann 2000). These methods give substantial insight, but are not capable of predicting viscous effects like partially separated or stalled conditions. Phenomena like dynamic stall and vortex-body interactions (VBI), or more generally body-turbulence, create additional complexities. These flows not only generate unsteadiness, but can operate in the midst of unsteadiness from preceding blades, components and/or naturally occurring flight environments. Vortex wake models of varying complexity have been developed, but relating these to time-dependent viscous effects remains challenging and often intractable at high Reynolds number (Re). These difficulties are not isolated to theoretical and computational approaches. Reasonable scale experimental efforts that produce relevant interactions between flow unsteadiness, vortical wakes and aerodynamic surfaces, including viscous effects, are often limited to large-scale wind tunnel or flight tests that are not appropriate for fundamental and systematic investigation.

In this work, the capability of AFC as a tool for creating unsteady flow fields of practical interest is investigated. The unsteadiness generation technique is based on the use

of ns-DBD plasma actuators for boundary layer separation control. In previous efforts, ns-DBD plasma was used as a flow control actuator for delaying static airfoil stall (Roupassov et al. 2009, Rethmel et al. 2011, Little et al. 2012, Kelley 2014). It was also observed that the ns-DBD could initiate vortex formation in the airfoil wake over a substantial bandwidth up to Re and Mach (M) numbers of 1.15×10^6 and 0.26 respectively (Rethmel et al. 2011). This high amplitude capability is appealing from a flow control actuator perspective and continues to inspire both fundamental and applied AFC efforts. However, this may also be used as a tool for producing controlled unsteady vortical wakes. More specifically, it could provide a platform for fundamental and systematic investigations of flow physics and control associated with practical vortex-body interactions. This would allow modeling, sensing and control investigations for flows that possess significant unsteady components in bandwidth and Re ranges that have not been adequately addressed to date.

The results presented here summarize ongoing efforts for using AFC as an enabling tool for the study of unsteady aerodynamics and VBI. The structure of the paper aligns with two major objectives. First, the capability of ns-DBD plasma actuators for controlling leading edge separation on a NACA 0012 is confirmed. This AFC technique has been used with great success for NASA EET (Little et al. 2012) and NACA 0015 (Rethmel et al. 2011) airfoils in the past and it is not surprising that it is also successful here. Second, the capability of ns-DBDs for exciting coherent vortical wakes is evaluated in detail. Future work is intended to examine the aerodynamic response of a target (flat plate or simplified lifting body) immersed in these unsteady flows with particular focus on the importance (or lack thereof) of viscous effects.

2. Background

2.1 Flow Control History

The use of passive and active devices to control flow dates back to some of the earliest known engineers. As early as 120 B.C.E., Hero published findings on pneumatic and hydrostatic pressure effects, including the aptly-named and infamous Hero's fountain (Alexandria 1851). Leonardo da Vinci (1452-1519) considered the use of water routing for power generation, and offered observations in the organization and behavior of certain flows (Gad-el-Hak 2000). The substantial contributions of Daniel Bernoulli (1700-1782) and Leonhard Euler (1707-1783) in modeling ideal, inviscid flows (theoretical hydrodynamics) allowed for theoretical predictions of certain pressures and velocities for the first time. Ludwig Prandtl (1875-1953) provided an equally vital advancement when he presented his boundary-layer theory in 1904 (on the heels of the Wright brothers' first flight in 1903). Prandtl successfully introduced a theoretical approach to analyzing applied viscous flows, and with that, a new era of flow control exploration was born.

Figure 1. Sketch by Leonardo da Vinci of quasi-stationary, counter-rotating vortices in the midst of the random wake (Gad-el-Hak 2000).

Subsequently, several subclasses of flow control emerged, including boundary layer control, passive control, and AFC (Joslin 2009). Boundary layer control often refers to delaying separation over an object immersed in a fluid. For example, Prandtl studied the effects of steady suction to remove a boundary layer over a cylinder using both theoretical and experimental techniques. Passive flow control adds no additional energy to a system, and is solely based on mixing regions of high and low momentum. These devices became popular for their relatively simple employment and maintenance. Some examples include spoilers, Gurney flaps, and riblets on wing surfaces. Active flow control adds energy to a system through the use of an actuator. This technique was introduced as an improvement to passive control, enabling the user to turn the actuation on and off when desired during various flow conditions. Prime examples include blowing jets and DBD plasma actuators. In modern flow control, many devices fit these basic categorical descriptions, while others are complex hybrids or derivatives of their predecessors.

Today, myriad applications and experiments exist to implement both passive and active flow control. There is virtually an endless demand and desire for such devices, ranging from external aerodynamic performance improvements to the optimization of internal combustion efficiency. Particular focus is placed on AFC devices that have low weight and energy consumption. Previous works have demonstrated the ability to control boundary layer separation using AFC. However, the use of AFC devices as disturbance generators for the study of unsteady aerodynamics and VBI is relatively arcane. The ability to excite natural flow instabilities with these devices provides great possibilities.

2.2 Leading Edge Airfoil Separation Control

Boundary layer separation occurs when a flow encounters a strong adverse pressure gradient over the surface in question. This adverse pressure gradient, along with viscous effects in the boundary layer, can produce reversed flow over the surface. In the case of airfoils, this may result in decreased lift and substantially increased drag, commonly referred to as stall. In thin airfoils, this is often observed at the leading edge at high angles of attack.

The experiment in Figure 2 provides one example of successful boundary layer separation control on the leading edge of an airfoil. A NACA 0015 airfoil is placed in stall and equipped with an oscillating ribbon (AFC device) at the leading edge. When the ribbon is oscillated at the optimal frequency, the separated flow becomes attached. Smoke flow visualization shows both reattached flow and the existence of large coherent structures above the airfoil surface.

Figure 2. Smoke flow visualization over the top surface of a (truncated) $\frac{3}{4}$ NACA 0015 airfoil (a) baseline data, (b) excitation at $F^+ = 2.6$ by means of an oscillating ribbon near the leading edge $Re = 40,000$ (Greenblatt et al. 2000).

AFC of leading edge separation has advanced in recent decades. A widely accepted development is the use of pulsed blowing, pulsed suction (both unsteady techniques) or a combination of both as a more effective approach than steady forcing for nominally two-

dimensional excitation (Seifert et al. 1996). Related research suggests that the range of dimensionless frequencies effective for separation control is on the order of unity (Huang et al. 2006, Greenblatt et al. 2008, Patel et al. 2008, Little 2010). This dimensionless frequency, often termed the reduced frequency, is defined as $F^+ = f_f x_{sp} / U_\infty$, where f_f is the forcing frequency, x_{sp} is the length over the surface where the flow is separated (i.e. separated region) and U_∞ is the freestream velocity (Darabi et al. 2004, Glezer et al. 2005). The characteristic length scale, x_{sp} , is generally assumed to be the length of the separated region over the body in question (Seifert et al. 1996). It is also known that the optimal reduced frequency also depends on the response of the flow to the actuation (Wynanski 2004).

The characteristic length scale x_{sp} for this work is chosen as the model chord c . The justification for this is twofold. First, the airfoil is evaluated at deep stall angles which moves the separation point close to the leading edge, nearly extending the separated region over the entire chord. Second, many other works use the chord as the characteristic length scale, which provides easier comparison to those experiments. The reader should also note that the freestream velocity is sometimes replaced with the local velocity at the boundary layer edge, U_e . It is somewhat troublesome to define F^+ based on U_e in this work since deep stall is examined and it is also much less common to find this in the literature. Therefore, the dimensionless forcing frequency for this work is defined as $F^+ = f_f c / U_\infty$.

A reduced frequency of unity indicates that at least one perturbation is excited while the flow propagates over the separated region. Selection of the actuator location is critical because the shear layer created between the freestream and separated region amplifies small perturbations introduced near the region of receptivity. In general, the actuator

location is chosen at or slightly upstream of the separation line to ensure the shear layer is excited by perturbations near its receptivity region. An indication of successful excitation is the formation of large spanwise vortices developed via the Kelvin-Helmholtz instability. These vortices facilitate the transfer of momentum between the freestream and separated regions, consequently reattaching the flow to the body surface in the mean flow (Darabi et al. 2004, Melton et al. 2005). These vortices may couple with other instabilities downstream (separation bubbles, wakes, etc.) and these dynamics are also considered in flow control efforts.

2.3 DBD Plasma Actuators

The use of plasma actuators for flow control is attractive for several reasons: relatively simple construction, minimal interference with aero-lines on the aerodynamic surface, rapid time response and low power usage. In some cases, they may also demonstrate high amplitude and bandwidth capabilities. The alternating current (ac-DBD) plasma actuator is by far the most common. It is fabricated with two electrodes arranged in asymmetric orientation that sandwiches a dielectric substance. When energized with sufficient voltage (≥ 5 kV) AC (1-10 kHz), the signal between the electrodes ionizes the air immediately above the dielectric covering the enclosed electrode. The dielectric layer allows for significant plasma generation while preventing arcing of the discharge. A representation of plasma generation from an ac-DBD actuator on a cylinder is visible in Figure 3.

Figure 3. Example of visible plasma formed by an ac-DBD actuator on a cylinder (Gregory et al. 2007).

One self-induced limitation of the DBD plasma actuator is the accumulation of charged particles over the dielectric surface that oppose the electric field. To sustain the discharge, higher voltages must continuously be applied (Little 2010). This can be avoided by applying an AC waveform that creates movement of charged particles back and forth over the exposed electrode and dielectric barrier. This, in turn, transfers momentum to the flow via ion-neutral collisions. Numerous experiments characterize this behavior in detail (Moreau 2007, Hoskinson et al. 2008, Enloe 2008a, Corke et al. 2009, Corke et al. 2010, Little 2010).

One alternative to the ac-DBD is the localized arc filament plasma actuator (LAFPA), which operates through a thermal mechanism generated from an arc discharge between two pin electrodes. The LAFPA is capable of functioning over higher bandwidths and creates a compression wave due to rapid localized heating of the flow. The flow in question responds to selected frequencies at which the actuator is excited and amplifies the induced perturbations. The LAFPA must be housed in ceramic-type material due to the strong near surface heating. LAFPA's are effective in many applications such as high speed jets, but they generally require multiple actuators to effectively control the flow (Samimy et al. 2007).

Other classical types of plasma actuators include corona and sliding discharge actuators Figure 4. The corona actuators have a direct voltage source connected to two exposed electrodes placed on a dielectric (Figure 4a). Ionization of the fluid above the dielectric occurs, producing current in the range of tens of milliamps (Cattafesta et al. 2011). The corona actuator uses momentum transfer between ionized and neutral particles to excite instabilities in the flow. The sliding actuator supplies a combination of ac and dc

voltage with the addition of a third electrode (Figure 4c). The dc component provides more uniform plasma distribution and higher body force when compared to a single ac-DBD (Figure 4b).

Figure 4. Common types and construction of plasma actuators (Cattafesta et al. 2011).

The ns-DBD plasma actuator (used exclusively in this work) functions through a thermal mechanism, but is capable of spatially distributing the discharge. The ns-DBD construction is identical to the ac-DBD but employs a high voltage waveform with very short rise time. The input waveform consists of a pulse with rise time on the order of nanoseconds, with peak voltages ranging between 5-50 kV. The extremely short rise time of the ns-DBD actuator generates a compression wave due to rapid localized heating of

near surface gas by the plasma. The dielectric barrier and short pulse prevents arcing of the plasma and enables the thermal effect to be spatially distributed.

Figure 5a displays representative discharge voltage and current traces for a 30-cm-long DBD actuator. Figure 5b plots instantaneous power and energy coupled to the load. In this example, steady state energy (11 mJ) is achieved approximately 150 ns after the onset of the pulse. Peak power of up to 600 kW is generated but the energy is less than 1mJ/pulse/cm for the length of the actuator in question. It should be noted that the potential for non-uniform distribution along the electrodes exists if the actuator length is comparable with the physical length of the high-voltage pulse (Opaits et al. 2009).

Figure 5. Example plots of (a) voltage and current traces and (b) instantaneous power and energy traces for a 30-cm-long ns-DBD actuator driven at 10 Hz (Little et al. 2012).

Knowledge of ns-DBDs has also expanded in recent years. As opposed to being housed in ceramics (like LAFPA), ns-DBDs can be housed in plastic dielectrics. It is also now apparent that ns-DBDs possess some high amplitude capability, but this effect is localized in space (Lehmann 2015). Consequently, ns-DBDs are best suited for use in relatively thin boundary layers with well-known separation locations. The leading edge of an airfoil post-stall is a prime example of this and ns-DBD control of such flows has been widely reported (Starikovskii et al. 2009, Little 2010, Rethmel et al. 2011, Kelley 2014).

The velocity profiles in Figure 6 illustrate the different mechanisms by which ac-DBD and ns-DBD plasma actuators operate. The two data sets are for the same physical actuator supplied with different waveforms in quiescent air. For the 100% duty cycle (Figure 6a), the ac-DBD forms a near-wall jet, while in the 50% duty cycle case (Figure 6b), it yields a fuller velocity profile due to a pulsing nature. In both cases, the ns-DBD does not produce sufficient velocities for practical flow control situations. Rather, ns-DBDs provide control through rapid localized heating of the near surface gas.

Figure 6. Example mean velocity profiles for ns and ac-DBD plasma actuators operating in quiescent air with 2 kHz carrier frequency using (a) 100% and (b) 50% duty cycle at 90 Hz measured 20 mm downstream on a 30 cm DBD load (Little et al. 2010).

The rapid heating of the flow at the actuator interface results in the generation of a compression wave which expands radially outward from the axis of discharge. An example compression wave generated over a 30 cm actuator on a cylinder is visible in Figure 7 and Figure 8 (Little et al. 2012). The figures display the density gradient on the vertical axis and the second derivative of the density on the horizontal axis. The images in Figure 7 are taken parallel to the cylinder axis and show quasi-planar and cylindrical compression wave that is relatively uniform along the viewing axis. The images in Figure 8 are taken perpendicular to the cylinder axis and show a nearly plane wave front along the vertical

axis with multiple circular waves. Because the schlieren images are averaged over multiple discharge pulses, it appears that the individual waves originate from relatively stable filaments that are repeatedly generated near the same locations. Estimations of the surface temperature can range between 70 and 400 K for a compression wave at Mach 1.13 for various pulse durations (Roupassov et al., 2009).

Figure 7. Phase-averaged schlieren images of compression waves generated by a nanosecond pulse discharge for several time delays after the discharge pulse (Little et al. 2012). Images taken along the axis of the discharge.

Figure 8. Phase-averaged schlieren images taken from a direction perpendicular to the cylinder axis (Little et al. 2012).

2.4 Separation Control with DBD Plasma Actuators

Initial experimentation using ac-DBD plasma actuators yielded great potential for separation control (Roth et al. 2000, Post et al. 2004). Demonstration of boundary layer and leading edge airfoil separation control was performed most successfully when the excitation was created with F^+ on the order of unity (Huang et al. 2006, Greenblatt et al.

2008, Patel et al. 2008). The mechanism used by the ac-DBD for separation control is commonly attributed to the near-wall jet described above (Figure 6a). The flow is most receptive to the ac-DBD perturbations when the actuator is placed at or slightly upstream of the separation location (Huang et al. 2006, Sosa et al. 2007, Jolibois et al. 2008).

The ac-DBD is a zero net mass flux (ZNMF) actuator, meaning it does not add mass to the flow, but rather functions through momentum addition. These actuators traditionally scale in amplitude with U_∞ (i.e. velocity ratio) or U_∞^2 (i.e. momentum coefficient, C_μ) (Greenblatt et al. 2000, Seifert et al. 2009, Kelley 2014). In order to produce enough momentum at higher flow speeds, however, the ac-DBD must be supplied with a significant amount of voltage, thus requiring an associated increase to the dielectric barrier thickness (Corke et al. 2010). The ns-DBD is also a ZNMF actuator and is of interest due to the thermal mechanism by which it perturbs the flow. The scaling for the ns-DBD is currently unknown and under development, but it achieves comparable separation control to the ac-DBD while using lower energy.

The use of ns-DBD plasma actuators for separation control has been well documented in recent years on various airfoils (Roupassov et al. 2009, Rethmel et al. 2011, Little et al. 2012, Kelley 2014, Esfahani 2016). During these experiments, separation control at higher flow speeds was achieved (up to Mach 0.85 and $Re > 10^6$) and there was little optimization of the device for such situations. Additionally, coherent vortical structures became apparent in the flow over a range of forcing frequencies. It is the focus of this work to observe the production and organization of these structures in an effort to better characterize the ns-DBD plasma actuator's ability to control separation and the airfoil wake.

2.5 Wake Control

The term “wake control” in this work refers to the ability to excite coherent structures in the wake. The choice of the ns-DBD plasma actuator for investigating the ability to control the wake of an airfoil is motivated by the aforementioned experiments. Specifically, the ns-DBD’s ability to excite natural instabilities in the flow and create coherent structures over a range of frequencies is attractive. It will be shown later that each nanosecond pulse generates a disturbance and later a vortex over a range of forcing frequencies. Because the ns-DBD plasma actuators transfer very little momentum into the flow, the vortices are formed through energy deposition or thermal disturbances. These vortices convect downstream and display behavior related to the frequency at which they are excited.

Active flow control of vortex-body interactions is much less advanced than that of turbulent shear flows such as jets, wakes, mixing layers, etc. Previous efforts in VBI did not have the benefits of today’s measurement capabilities for increasingly complex flows. The general interaction of a vortex with a body can produce unsteady loading, heat transfer, noise, vibration, and other detrimental or beneficial effects. A unique aspect of this work is the use of AFC (ns-DBD) for modeling, sensing, and controlling VBI to examine these effects. Particular motivation comes from the ability of AFC to excite natural flow instabilities, with the potential to better understand and study unsteady aerodynamics.

Historically common methods for producing such disturbances can be categorized into static (mixing layers, bluff-bodies) and dynamic (impulsive or oscillating airfoils). In vortex-body interaction (VBI) studies, these are employed upstream with a target body placed in the downstream unsteady wake. The natural instability in a mixing layer produces

vortices of the same sign. A practical example is the corner impingement observed in cavity flows. The Karman vortex street present in a wake is composed of alternating vortices with different sign.

Rockwell organized VBI into the four classifications shown in Figure 9 (Rockwell 1998). The focus of this work is the production of parallel vortices (Figure 9a). Various wake flows have been employed for parallel vortex-body interactions. For example, Meier employed a shock tube with a square cylinder upstream of a target airfoil for high subsonic flows at $Re = 200-300k$ (Meier 1985). Gursul placed an elliptical leading edge in the wake of a shedding plate in water (Gursul 1990). The interaction was governed by the vortex and body length scales, circulation, wavelength and proximity of the street with respect to the body. The vortex wavelength and size was varied using different plate thicknesses. No boundary layer separation was observed in these tests due to the low vortex Reynolds number, Re_v , and unloaded target ($Re_v = \Gamma/\nu$, where Γ is the circulation of the vortex, and ν is the kinematic viscosity). Small and large scale interactions were defined by the ratio of wavelength to body half-thickness.

Figure 9. Representations of basic classes of vortex-body encounter: (a) parallel vortex; streamwise (perpendicular) vortex (b) without and (c) with breakdown; and (d) normal vortex interactions (Rockwell 1998).

Oscillating airfoils that shed vortices from the trailing edge are similar to a Karman vortex street, but with different rotational sense and lower background turbulence levels. For example, Koochesfahani used an oscillating NACA 0012 to observe the structure of the airfoil wake with respect to the amplitude, frequency, and shape of the oscillation waveform (Koochesfahani 1989). Favier and Maresca longitudinally oscillated the disturbance airfoil through dynamic stall conditions such that vortices were shed from both the leading and trailing edge (Favier 1985). Booth used an oscillation schedule where vortices originated primarily near the trailing edge (Booth 1986). The potential advantage in these oscillating cases is that background turbulence levels are generally lower in comparison to bluff-body shedding. More recently, Peng generated vortices by applying a rapid pitch-up motion to an airfoil through a pneumatic system and studied the subsequent

interaction with a downstream, unloaded target airfoil (Peng 2015). Dual airfoil arrangements can also be employed as a wave or Schmidt propeller. Rival and Tropea examined a low Re case (30k) targeting MAV applications where the disturbance airfoil was oscillated in pure plunge (Rival 2010). Loads were calculated based on control volume analysis and pressure-integration from PIV measurements similar to previous studies (Wilder 1998). The interaction was primarily governed by target airfoil loading rather than vertical spacing relative to the vortical wake. Observations were in general agreement with previous studies despite the differences in disturbance generation (Wilder 1998). The case of two airfoils both performing oscillations has been examined at $Re = 85k$ (Lee 2011). Two airfoils were positioned in series and oscillated in pitch at the same conditions, but with phase difference of 0 and 180°. The axial spacing between the models was also studied. In contrast to the previous examples, large coherent vortices were not generated meaning the interactions were primarily driven by the turbulent wake. In general, as can be seen from the brief literature survey here, disturbance generators are limited to mechanical systems (dynamic), or in the case of static methods, the flow field in question.

The background investigation into wake control of an airfoil returns a wide array of experimental and computational studies. These studies cover a broad range, from wake-airfoil interaction noise reduction (Simonich 1993) to trailing edge plasma Gurney flaps (Zhang et al. 2009). Other experiments explore trailing edge separation (Little et al. 2010) and the effect of “smart” actuation (Post et al. 2004), but lack detailed characterization of the far wake and the ability of AFC to control those flow characteristics. This work aims to demonstrate the use of AFC (ns-DBDs) for producing controlled disturbances in the

wake over a range of frequencies using a static NACA 0012 airfoil as a disturbance generator.

Post-stall behavior has previously been explored both numerically and experimentally. The survey in Figure 10 provides possible flow regimes for a NACA 0012 airfoil in post-stall based on selected numerical models and experimental results (Wu et al. 1998). The low-frequency regime observed at post-stall angles and moderate Re is of particular interest. Wind tunnel measurements for an airfoil in deep stall ($\alpha = 18^\circ$) were compared to a two-dimensional Navier-Stokes code, and exposed a similar low-frequency regime (Zaman et al 1989).

Figure 10. Possible regimes of flow patterns over a NACA-0012 airfoil at post-stall angles of attack versus Reynolds number. All data are taken from experiment unless noted. Shaded regions denote tentative approximate boundaries (Wu et al. 1998).

The overall objective of this work is to develop AFC as an enabling technology for the study of unsteady aerodynamics and VBI. As a first step in this effort, ns-DBD plasma

actuators are used for producing controlled disturbances in the wake of a NACA 0012 airfoil over a range of conditions. These flow fields are of practical relevance since AFC excites natural instabilities that are already present in the flow and can be triggered by any number of real-world or laboratory events. Indeed, such natural oscillations have been observed in the literature (Zaman et al. 1989, Wu et al. 1998) and it is our desire to use these for the purposes of enabling new research directions in the study of vortex body interactions and their eventual control.

3. Experimental Facilities and Techniques

3.1 Wind Tunnel

Experiments are performed in a subsonic wind tunnel in the Department of Aerospace and Mechanical Engineering at University of Arizona (Figure 11). The wind tunnel is a closed loop facility with a 0.9 m x 1.2 m x 3.65 m (3 ft x 4 ft x 12 ft) test section. The speed of the flow in the tunnel can be varied up to $U_\infty = 80$ m/s (262.467 ft/s). Uniformity of the mean flow is at or better than $\pm 0.5\%$ across the operating range. Temperature in the tunnel is held within 0.44 °C (1 °F) of a set point controlled by the operator using a heat exchanger with chilled water supply. Over its operating range, the turbulence intensity is less than 0.15% for $f_{lowpass} = 10$ kHz and less than 0.05% for $f_{bandpass} = 1\text{ Hz} - 10\text{ kHz}$ (Dengler 2015). The tunnel is equipped with a five-component (normal/axial/pitch/yaw/roll) external pedestal balance and model positioning system for horizontally-mounted test models. Above the test section, a two-axis traverse is used to mount probes for data acquisition. For this work, the traverse is used in two different configurations: one for mounting a vertical sting for hot wire probes and the other for mounting two cameras on a sliding cantilever beam (Figure 12).

Figure 11. Wind tunnel viewed from the operator side (external side of tunnel loop) looking upstream.

Figure 12. Schematic of experimental setup in wind tunnel test section.

3.2 Airfoil Model

A NACA 0012 airfoil is used for this project, which falls under the four-digit series developed by the National Advisory Committee for Aeronautics (NACA). The numbering system is based on the airfoil geometry. The first digit represents the maximum camber in

percentage of the chord; the second digit describes the distance from the leading edge to the location of maximum camber in tenths of the chord; the last two digits define the maximum airfoil thickness in percent of the chord (Abbott et al. 1945). The NACA 0012 therefore has no camber and has a maximum thickness equal to 12% chord.

The airfoil model for this project was constructed at the University of Arizona using composite manufacturing. The model has a chord length of $c = 0.3048$ m (12 in) and a span of $b = 0.8636$ m (34 in). To improve two dimensionality of the flow over the model, two aluminum spacers are added at each end of the model with the same airfoil profile, allowing the model to effectively span the entire height of the wind tunnel test section. The surface of the model contains 64 static pressure taps. The suction side of the airfoil at mid-span contains 23 taps and the pressure side at mid-span contains 13 taps. The taps are more closely spaced near the leading edge to improve resolution, as is indicated in Figure 13 (Dengler 2015). The model also includes 28 taps at one-quarter and three-quarters span. These taps are used to evaluate three-dimensional effects in the flow and are shown in Figure 14 with a summary of airfoil data in Table 1.

Chord length - c	30.48 cm (12 in)
Span length - b	86.36 cm (34 in)
Instrumented pressure taps, suction side	23
instrumented pressure taps, pressure side	13
3D pressure taps	28

Table 1. Airfoil Summary.

Figure 13. Chord-wise pressure tap distribution.

Figure 14. Pressure tap locations on suction side of airfoil.

The airfoil is mounted vertically in the test section using a steel spar which runs through the model at one-quarter chord (Figure 15). The bottom of the airfoil contains a bearing which allows the airfoil to rotate to the desired angles of attack. The bearing rests in a slot in a removable plug on the floor of the test section. The top plug contains a hole in which the spar fits securely, which allows the angle of attack of the airfoil to be changed by rotating the top plug. The top plug contains tick marks that denote angle of attack in

increments of 0.5° . When the angle of attack is adjusted, thumb screws are tightened around the plug to secure the airfoil during testing.

Figure 15. Vertically-mounted NACA 0012 airfoil.

3.3 ns-DBD Plasma Actuator

3.3.1 Plasma Actuator Hardware

Actuators are composed of two copper tape electrodes separated by Kapton tape dielectric arranged in an asymmetric fashion (Figure 16 and Figure 17). The two electrodes are placed immediately adjacent to one another to encourage uniform plasma generation. The discharge is directed upstream such that the exposed electrode does not disturb the incoming boundary layer before encountering the plasma discharge. The covered ground electrode is 12.7 mm (1/2 in.) wide and the exposed high-voltage electrode is 6.35 mm (1/4 in.) wide. Each electrode has a thickness of 0.09 mm (3.5 mil). The dielectric barrier is composed of 2 layers of 0.76 mm (3 mil) Kapton tape with a dielectric strength on the order

of 10 kV. Each layer of Kapton tape has a 0.04 mm (1.5 mil) layer of silicone adhesive such that the actual Kapton thickness for each tape layer is only 0.04 mm (1.5 mil). The total thicknesses of the dielectric and the device as a whole are 0.15 mm (3 mil) and 0.30 mm (6 mil), respectively. The actuator is applied to a 0.05 mm (2 mil) base layer and then to the substrate in all cases. The actuator construction was optimized based on previous work in airfoil separation control using ns-DBD plasma actuators (Little et al. 2012).

Figure 16. Asymmetric ns-DBD Plasma Actuator Schematic.

High voltage nanosecond pulses are produced using a pulse generator designed and built by the Ohio State University (OSU) Nonequilibrium Thermodynamics Laboratory (NETL). The pulser is magnetic compression type, capable of both positive and negative polarity outputs with bandwidth of 10 kHz. Only positive polarity pulses are studied here. Pulse voltage is controlled by a 5 kW Sorenson dc power supply capable of 0-700 V output. Pulse parameters are strongly dependent on the DBD load. Input signals are generated by a Tektronix AF6310 function generator. A Tektronix P6015A high voltage probe and custom current probe are used in conjunction with a Tektronix TDS 2024C oscilloscope. Pulse voltage is measured at the output of the generator while current is measured between the encapsulated electrode and ground. A pair of 40 cm transmission cables connect the pulser to the DBD load (Figure 17b).

Figure 17. (a) ns-DBD plasma actuator on leading edge of NACA 0012 airfoil and (b) airfoil, actuator and pressure tube connections.

3.3.2 *Electrical Measurements*

Representative voltage and current traces on a 76.5-cm-long (30 in.) ns-DBD plasma actuator are shown in Figure 18a. The ns-DBD pulse width is ~ 200 ns and reaches a peak voltage of ~ 7.5 kV with max current of ~ 0.7 A/cm. Figure 18b plots instantaneous power and energy coupled to the load at these conditions. Steady-state energy with a peak gross energy (Dawson et al. 2013) over actuator length of ~ 0.3 mJ/cm is realized approximately 150 ns after the beginning of the pulse. The energy is calculated by integrating the absolute value of the product of voltage and current. Due to the length of the actuator, the peak power over the actuator length generated by the ns-DBD is only ~ 0.07 kW/cm. The pulse rise and fall time achieved is nearly 100 ns. The rise time and fall time is somewhat longer than previous experiments with this pulse generator (Little 2010).

This is due to the relatively large size of the actuator. Also note that the pulse energy is slightly lower than previous work (Little 2010). It will later be shown that even this small energy is sufficient for exciting the flow.

Figure 18. Sample traces of (a) Voltage and Current and (b) Instantaneous Power and Energy for a 76.5-cm-long (30 in.) ns-DBD actuator.

3.4 Diagnostics and Practical Implementation

3.4.1 Pressure Measurements

A Scanivalve E-RAD4000 is used to perform pressure measurements. This system consists of a ZOC33/64Px electronic pressure scanning module used in conjunction with a RADBASE4000 base unit with a RAD 3200 A/D converter (Figure 19). To measure pressure, 64 vinyl tubes are connected to the pressure taps along the airfoil surface and are attached to the module. The pressure module is connected to the A/D converter, which is part of the RADBASE4000 base unit. The base unit is then connected to the computer using an Ethernet cable, which transfers acquired data to the computer.

The ZOC33 pressure module is equipped with internal valve logic, capable of setting the module to four different modes: operate, calibrate, purge, and isolate. An external source of 65 psi ($\sim 448,159$ Pa) control pressure is connected to the 'Px CTL' and 'CAL CTL' pressure tubes on the pressure module to change modes, as described in the

ZOC33 pressure module manual. Because the pressure module comes pre-calibrated by Scanivalve, only the ‘CAL CTL’ pressure tube requires the external source of 65 psi. This configuration sets the module into “operate” mode.

Figure 19. Scanivalve (a) ZOC33 miniature pressure scanner module and (b) RADBASE4000 base unit.

The module contains piezoresistive pressure sensors. The pressure in each sensor leads to a separation of charge in the crystal which is proportional to the applied force. The separated charge is measured by the module and sent to the A/D converter. Pressure lines on the module measure the static pressure at each of the taps on the airfoil as well as the static pressure of the tunnel freestream. The base unit measures the pressure at each tap and subtracts the freestream static pressure. Thus, the data acquired in LabView is a differential pressure. The full scale pressure of the module is $p_{max} = 17,237$ Pa (2.5 psi). The resolution of the system is given as $\pm 0.1\%$ of the full scale reading, or $p_{resolution} = 17.2$ Pa (0.0025 psi). The freestream dynamic pressure at $U_{\infty} = 40$ m/s is $q = 980$ Pa (0.142 psi), meaning that resolution of the system is 1.76% of dynamic pressure (Dengler 2015).

To ensure constant flow conditions during data acquisition, the actuator is turned on prior to pressure data collection and remains on until after data acquisition is complete

for each set. Thus, the duration of actuation is greater than the duration over which pressure measurements are acquired. In these experiments, the LabView code is set such that 50 pressure data samples are collected in 32 s ($f_{sample} = 1.56$ Hz). The duration of actuation is 40 s.

Prior to taking measurements, a LabView code is used to zero the sensors. This is done with the tunnel off and the plasma off. Once the system is calibrated to zero, the tunnel is turned on and set to $U_{\infty} = 40$ m/s and $T = 22.22$ °C (72 °F). The data sets reported by LabView contain the differential pressure at each tap, the dynamic pressure, and the Reynolds number of the free stream for 50 samples. The values of differential and dynamic pressure are averaged over the 50 samples. The resulting values are then used to compute the C_p distribution over the airfoil surface using MATLAB. The statistical uncertainty of C_p is at most 4.23% with a confidence interval of 95%.

3.4.2 Particle Image Velocimetry

Two-component PIV is used to obtain quantitative measurements of the velocity fields from the leading edge of the airfoil to ~ 4.5 chord-lengths downstream in the wake. Images are acquired and processed using a LaVision PIV system (DaVis 8.3.0). Submicron DEHS seed particles are injected upstream of the test-section contraction using a LaVision aerosol generator (Figure 20). A double-pulsed 200 mJ Quantel Evergreen laser is used in conjunction with spherical and cylindrical lenses to form a light sheet approximately 1 mm thick for the PIV measurements. The time separation between laser pulses used for particle scattering is set according to the flow velocity, camera magnification, and correlation window size. Two images corresponding to the pulses from each laser head are acquired by two LaVision 5.5 million pixel Imager sCMOS cameras (Figure 20). The cameras are

equipped with a Nikon Nikkor 50 mm f 1.2 lens and are adjacently-mounted and calibrated to maximize the field of view while optimizing the particle size. For each image pair, sub-regions are cross-correlated using decreasing window size (64^2 – 32^2 pixel²) multi-pass processing with 50% overlap. The resulting velocity fields are post-processed to remove spurious vectors using an allowable vector range and median filter. Removed vectors are replaced using an interpolation scheme based on the average of neighboring vectors. A 3 x 3 Gaussian smoothing filter is also applied to the calculated velocity fields. The spatial resolution of the PIV is approximately 3.62 mm (0.012% of chord). In-depth detail for specific operations (i.e. vorticity, swirling strength, etc.) is available in the DaVis 8.3.0 software manual developed by LaVision.

Figure 20. LaVision (a) 5.5 million pixel imager sCMOS Camera with Nikon Nikkor 50mm f 1.2 lens (b) aerosol generator.

The PIV data are acquired without control (baseline) and with actuation at frequencies of $F^+ \approx 0.15$ ($f_f = 20$ Hz), $F^+ \approx 0.46$ ($f_f = 60$ Hz), and $F^+ \approx 1.14$ ($f_f = 150$ Hz). Time-averaged statistics for the airfoil, actuator, and wake are calculated from 500 instantaneous velocity fields with a maximum 5.62% statistical uncertainty using a 95% confidence interval. Phase-locked PIV data are acquired using the programmable timing unit of the LaVision system. The acquisition is synced with the frequency of the actuation

signal. Velocity fields at four phases (separated by $\pi/2$) of the actuator frequency are investigated by stepping through the forcing period using time delays. The resulting phase-locked data sets are averaged over 50 images at each phase which is sufficient for resolving the primary features of the phase-averaged flow fields (i.e. coherent structures).

3.4.3 Constant Temperature Anemometry

Constant Temperature Anemometry measures velocity using a wire kept at a constant temperature. Since the resistance of the wire depends on temperature, the wire can be used as a resistance in a Wheatstone Bridge. As air flows over the wire, the wire cools and its resistance decreases. This property provides a method of measuring velocity since the rate of cooling depends on velocity. The exact relationship is determined using a DANTEC automatic calibrator. Furthermore, a square wave response test is performed to determine the frequency response of the wire.

The hot wire probe (DANTEC 55P01) is held by a probe support (DANTEC 55H21) which is placed into a mounting hole on a vertical arm in the wind tunnel. Technical specifications for the 55P01 probe are provided in Appendix A. The vertical arm is mounted to a traverse on the top of the tunnel and enters the test section through a hole in the ceiling. The arm is then secured to the bottom of the tunnel to reduce vibrations. The probe is mounted 2.13 m ($x/c = 7$) behind the airfoil leading edge and is used to determine the velocity of one-dimensional flow (streamwise velocity) through CTA. Vortices are shed in the airfoil wake during testing, which causes fluctuations in the measured voltage of the hot wire. The spectrum of frequencies over which these fluctuations occur is analyzed to evaluate the presence of vortical structures in the airfoil wake.

Hot wire data are acquired using a DANTEC Streamline Pro Anemometer System. To calibrate the probe, a DANTEC automatic calibrator is employed. The automatic calibrator is connected to a compressed air supply and to a computer. The hot wire probe is connected to the DANTEC A/D board using a 20 m BNC cable. The calibration is performed by subjecting the probe to 20 velocities ranging from $U_\infty = 5\text{-}50$ m/s. The Streamline Pro software generates a calibration curve that allows voltage values of the probe to be converted to velocity.

Figure 21. Dantec Dynamics (a) StreamLine Pro Research CTA System and (b) Gold-plated wire probe (55P01).

The calibrated hot wire is mounted to the vertical arm in the test section and the tunnel is turned on and set to a speed of $U_\infty = 40\text{m/s}$. All measurements are acquired at this freestream velocity which corresponds to $Re \approx 740,000$ considering the airfoil chord of 0.3048 m (12 in). The temperature of the wind tunnel is maintained at $T = 22.2^\circ\text{C}$ (72°F). The sampling rate of the hot wire measurements is 10 kHz for 200,000 total samples, resulting in a total measurement duration of 20 s. Similar to pressure data, the total time that the plasma actuator is on must be greater than the time duration of hot wire measurements. The actuator is tested in the range from $F^+ = 0.08\text{-}1.22$ ($f_f = 10\text{-}160$ Hz) in steps of $\Delta F^+ = 0.08$ ($\Delta f_f = 10$ Hz).

The data processing is done using MATLAB with a frequency resolution of 1.22 Hz. Values of velocity are calculated using a fourth-order polynomial interpolation of the voltage values using the calibration curve. The power spectral density (PSD) is calculated using a Fast Fourier Transformation (FFT). In the FFT, the signal is split into 60 increments containing 8192 data samples. Each segment overlaps by 50%. The FFT of each segment is then averaged to reduce the variance of the results. The resulting PSD distribution is used to evaluate the presence of vortical structures in the wake occurring at the forcing frequency for each case.

The DANTEC system is also used to run three probes simultaneously. The mounting holes on the vertical arm are spaced such that probes can be placed at one-third, one-half, and two-thirds of the span of the airfoil. Each probe is calibrated using the same process as previously described. Furthermore, this configuration is used to test the same forcing frequencies as previously described and is processed using the same procedure. With each probe sampling simultaneously, it is possible to correlate the data set collected at mid-span with the data sets collected at one-third and two-thirds span respectively. As with the FFT, each data set is divided into 60 blocks containing 8192 samples with 50% overlap. Segments from the mid-span data set are cross-correlated from the one-third and two-thirds span data sets separately. The resulting correlation coefficient is normalized such that the value of the autocorrelation of the mid-span data set is unity at zero time lag. The correlation is then averaged over the 60 blocks. The results are used to evaluate the three-dimensionality of the structures as they propagate through the wake.

4. Results

4.1 Test Conditions

Control of boundary layer separation and the wake of a NACA 0012 airfoil is presented for $Re = 0.74 \times 10^6$ (40 m/s) with a post-stall angle of attack of 18° at atmospheric temperature and pressure. The baseline performance of the airfoil was verified in previous work (Dengler 2015). For all measurements, data are acquired by establishing a separated flow baseline condition and then energizing the ns-DBD plasma actuator. This work is comparable to published results on a NASA EET (Little et al. 2012) and NACA 0015 airfoil (Rethmel et al. 2011) and is a continuation of the work done on the same NACA 0012 at the University of Arizona (Dengler 2015).

4.2 Pressure Measurements

To select the optimum placement of the ns-DBD plasma actuator on the leading edge of the airfoil, C_p measurements were taken for the following actuator locations; 1 mm, 2 mm, 3 mm, 4.5 mm, and 6 mm. The actuator locations are referenced as an arc length from the leading edge ($x/c = 0$) to the plasma actuator interface as depicted in Figure 16 and Figure 17. The actuator interface is on the suction surface in all cases. Note that installation of the actuator prevents the use of all pressure taps at the leading edge. On the pressure side, seven mid-span and two 3D pressure taps are lost while on the suction side, five mid-span and two 3D pressure taps are lost. Thus, the pressure tap nearest the leading edge with reliable data on the suction side of the airfoil corresponds to $x/c = 0.09$.

For each location, frequency sweeps are conducted between $F^+ = 0.08 - 7.62$ ($f_f = 10 \text{ Hz} - 1 \text{ kHz}$) at angles of 14° ($C_{L,max}$), 17° , 18° , and 19° . The maximum lift coefficient $C_{L,max}$ occurs at $\alpha = 14^\circ$, in agreeance with previous characterization of the airfoil shown

in Appendix B (Dengler 2015). The 3 mm actuator location yielded the lowest C_p (indicating mean flow reattachment) at an angle of $\alpha = 16^\circ$ (Figure 22c). This suggests actuation is occurring near the receptivity region. The 3mm actuator location agrees with previous work carried out on the same airfoil (Dengler 2015). Due to changes in separation location with angle of attack, different actuator locations yield lower C_p at different angles.

The ns-DBD plasma actuator exhibits progressively different behavior as the angle of attack increases from stall to deep stall. The images in Figure 22 represent pressure distributions at different angles of attack over a range of frequencies for the first 3mm-located actuator. At an angle of $\alpha = 14^\circ$, the flow is still attached; therefore the addition of actuation is ineffectual (Figure 22a). At $\alpha = 15^\circ$ and 16° , the flow is being tripped independent of the forcing frequency, as indicated by nearly uniform pressure distributions in Figure 22b and Figure 22c. As the airfoil moves into deeper stall at $\alpha = 17^\circ$, 18° and 19° , flow reattachment exhibits a strong frequency dependence, as indicated in Figure 22d, Figure 22e, and Figure 22f respectively.

The 3mm actuator location at $\alpha = 18^\circ$ yields the lowest C_p for the airfoil in deep stall of all combinations tested (Figure 22e) and offers the most favorable conditions for this study. The 3mm location tests were then duplicated with a new actuator to demonstrate repeatability of construction and performance.

Figure 22. C_p distributions for first 3mm actuator location at $Re = 740k$ at (a) 14° (b) 15° (c) 16° (d) 17° (e) 18° (f) 19°.

These results were successfully duplicated with a second 3mm-located actuator.

Thus, all data presented henceforth are measured with the second 3mm actuator.

In order to determine the best frequency for reattachment, minimum C_p values at the leading edge were plotted against the forcing frequency. The plots in Figure 23a and Figure 23b show the minimum C_p value nearest the leading edge ($x/c = 0.09$) versus the dimensionless forcing frequency F^+ for $\alpha = 16^\circ$ and $\alpha = 18^\circ$ respectively. In Figure 23a, the minimum C_p value is independent of the forcing frequency, again indicating that the actuator merely trips the flow. Conversely, in Figure 23b shows a strong dependence on the forcing frequency, suggesting that the vortical structures created by the actuation are responsible for reattaching the flow in deep stall.

The frequency sweep in Figure 23b shows that a forcing frequency of $F^+ \approx 1.14$ corresponds to the lowest C_p at $\alpha = 18^\circ$, indicating the best condition for separation control. The complete frequency sweep ranged from $F^+ = 0.08 - 7.62$ ($f_f = 10 \text{ Hz} - 1 \text{ kHz}$) and showed decreasing C_p values up to $F^+ = 1.14$ and increasing C_p values for every control case thereafter. Only results from frequencies at or below $F^+ \approx 1.52$ ($f_f = 200 \text{ Hz}$) are presented in Figure 22, Figure 23, and Figure 24.

Figure 23. Suction side C_p at $x/c = 0.09$ vs. dimensionless forcing frequency, F^+ , for NACA 0012 airfoil at $Re = 0.74 \times 10^6$ and (a) $\alpha = 16^\circ$ and (b) $\alpha = 18^\circ$.

Figure 24a-c show representative C_p plots with mid-span and 3D pressure tap distributions at $\alpha = 18^\circ$ and $Re = 740k$. Note the missing data near the leading edge due to the installation of the actuator. Variations between the mid-span and 3D values are negligible, and as a result, the flow is presumed mostly 2D over the central $\frac{1}{2}$ span of the airfoil even for AFC cases. Select frequencies shown in Figure 24a-c represent cases chosen for closer investigation with PIV. The baseline flow is characterized by a near-zero pressure gradient along the suction side of the airfoil indicating deep stall as expected. All forcing frequencies show an improvement over the baseline and it is clear that the best case for separation control is $F^+ \approx 1.14$ ($f_f = 150$ Hz). Note that forcing at $F^+ \approx 1.52$ ($f_f = 200$ Hz) is also quite successful, but reaches a slightly higher C_p value (Figure 24d).

The frequency dependence exhibited by the C_p distribution suggests that the actuator is exciting instabilities in the flow whose nature is dependent on the forcing frequency. The nature of these structures will be further investigated using optical evidence from PIV. Furthermore, the close agreement between the outboard pressure taps with the centerline taps indicates that this excitation is present over the entire span of the airfoil. This suggests that these structures may have a nominally two-dimensional nature. The two-dimensionality of these structures will be examined by correlating hot wire data using probes taking simultaneous samples at different spanwise locations in the wake ($x/c = 7$).

Figure 24. (a) Mid-span and 3D C_p distribution for $F^+ \approx 0.15$ ($f_f = 20$ Hz) (b) $F^+ \approx 0.46$ ($f_f = 60$ Hz) (c) $F^+ \approx 1.14$ ($f_f = 150$ Hz) (d) C_p distribution for select control cases at $\alpha = 18^\circ$ and $Re = 740k$.

4.3 PIV Results

Two component PIV is used as the primary experimental technique to map the flow field from the leading edge of the airfoil to approximately 4.5 chord-lengths downstream in the wake. One camera is used to capture flow over the airfoil surface, with a mask chosen to omit the regions contaminated by the tunnel wall plug. The wake (from $x/c = 1$ to ≈ 4.5) is captured in a subsequent test run using two cameras side-by-side. The data are processed and mapped to provide a quantitative visualization of the flow. This configuration shows a

reasonably large field of view for studying the ns-DBD's ability to control separation over the airfoil as well as to produce coherent structures in the wake.

PIV is acquired for the baseline flow and various forcing cases. All measurements are taken at $Re = 0.74 \times 10^6$ (40 m/s) with the airfoil in deep stall at $\alpha = 18^\circ$. To illustrate the effect that forcing frequency has on the nature of the developed structures, four exemplary cases will be presented: the baseline flow with no actuation, a forcing frequency of $F^+ \approx 0.15$ ($f_f = 20$ Hz), a forcing frequency of $F^+ \approx 0.46$ ($f_f = 60$ Hz), and a forcing frequency of $F^+ \approx 1.14$ ($f_f = 150$ Hz). These cases are chosen partly considering C_p data, but also considering CTA data which will be described in the subsequent section.

Figure 25 shows a comparison of the dimensionless time-averaged streamwise velocity $\bar{U}^*$ for the baseline and each forcing case under consideration. Contours of streamwise velocity and a profile at $x/c = 2$ are shown for each case. It is clear that the airfoil is fully-stalled with separated flow in the baseline case. Time-averaged forcing cases for $F^+ \approx 0.15$ ($f_f = 20$ Hz), $F^+ \approx 0.46$ ($f_f = 60$ Hz), and $F^+ \approx 1.14$ ($f_f = 150$ Hz) are presented in Figure 25b, Figure 25c, and Figure 25d, respectively, with the color scale held constant throughout to facilitate comparisons. There is noticeable decrease in flow separation with increasing frequency which is consistent with the C_p data in Figure 23b and Figure 24. The associated velocity profiles at $x/c = 2$ show more quantitatively that the momentum deficit in the wake is being reduced as a result of actuation. These profiles show a progressive decrease in wake size from the baseline case to the best case for separation control ($F^+ \approx 1.14$ ($f_f = 150$ Hz)). The reader should note that cases for $F^+ \approx 0.30$ ($f_f = 40$ Hz) and $F^+ \approx 0.76$ ($f_f = 100$ Hz) were also observed with PIV and exhibited similar behavior for their respective regimes. These results are available for viewing in Appendix C.

Figure 25. Plots of time-averaged dimensionless streamwise velocity $\bar{U}^*$ at $Re = 0.74 \times 10^6$, $\alpha = 18^\circ$ (a) Baseline case (no control) and NS-DBD forcing at (b) $F^+ \approx 0.15$ ($f_f = 20$ Hz) (c) $F^+ \approx 0.46$ ($f_f = 60$ Hz) and (d) $F^+ \approx 1.14$ ($f_f = 150$ Hz).

Figure 26 shows the dimensionless time-averaged vorticity $\bar{\Omega}^*$ at $Re = 0.74 \times 10^6$ for the baseline and control cases. Note that the vertical lines near $x/c = 3$ are due to stitching of the two camera images and are unphysical. The baseline flow clearly shows deep stall consistent with the near-zero pressure gradient along the suction surface (see Figure 24). A strong region of vorticity signifies the boundary between the freestream and separated

region over the model. The separated region is visible in Figure 26a immediately above the surface of the airfoil, and is replaced by strong regions of vorticity for the control cases in Figure 26b-d. This does not exclusively imply reattachment but it is indicated by pressure data (Figure 24). All forcing cases increase vorticity over the airfoil and cause significant momentum transfer into the separated region for all forcing cases. As expected, forcing at $F^+ \approx 1.14$ ($f_f = 150$ Hz) draws the high shear region closest to the airfoil surface allowing this momentum transfer to control separation.

Figure 26. Dimensionless time-averaged vorticity $\bar{\Omega}^*$ at $Re = 0.74 \times 10^6$, $\alpha = 18^\circ$ (a) Baseline case (no control) and ns-DBD forcing at (b) $F^+ \approx 0.15$ ($f_f = 20$ Hz) (c) $F^+ \approx 0.46$ ($f_f = 60$ Hz) and (d) $F^+ \approx 1.14$ ($f_f = 150$ Hz).

Streamwise and vertical velocity fluctuations provide insight into the actuator's ability to produce strong fluctuations in the wake. Figure 27a, Figure 28a, and Figure 29a show dimensionless phased-averaged streamwise velocity fluctuations $\tilde{u}^* = \tilde{u}/U_\infty$, and Figure 27b, Figure 28b, and Figure 29b show dimensionless phased-averaged vertical velocity fluctuations $\tilde{v}^* = \tilde{v}/U_\infty$, over the airfoil where $\tilde{u}$ and $\tilde{v}$ denote a dimensional phase-averaged quantity. The streamwise fluctuations offer the best comparison to hot wire data (presented in the next section), because the hot wire measurements in this work collect the streamwise velocity component. Dimensionless vorticity is also provided in Figure 27c, Figure 28c, and Figure 29c for reference. Figure 27, Figure 28, and Figure 29 are grouped by forcing frequency and represent two of four phases of the actuation period separated by a phase shift of $\pi/2$. The remaining phases exhibit similar behavior and are viewable in Appendix C. For all phase-averaged data presented here, the baseline flow is subtracted to expose the formation and organization of structures for each forcing frequency.

For the control case of $F^+ \approx 0.15$ ($f_f = 20$ Hz) strong fluctuations (Figure 27a and b) are visible above the airfoil surface followed by a rapid reduction in strength and organization after $x/c = 1$. Similarly, the vorticity (Figure 27c) shows a large structure over the airfoil near $x/c = 0.5$ for the first phase, but its behavior beyond $x/c = 1.5$ is quite noisy and devoid of organized flow features. This case is believed to represent either an impulse-like response or nonlinear behavior in that a clear sinusoidal oscillation at the forcing frequency is not produced downstream. Rather, it appears the flow responds to this single perturbation by producing a variety of frequency content. This is supported by CTA measurements in the following section. It is also notable (and perhaps supportive of the impulse response idea) that forcing at $F^+ \approx 0.15$ results in structures over the airfoil that

are of similar spatial scale and location as those produced by forcing at $F^+ \approx 0.46$ (Figure 28). It is also possible that the amplitude of the fluctuations becomes large enough such that nonlinear interaction takes place (Sato 1970).

Figure 27. Phase-averaged PIV for ns-DBD forcing at $F^+ \approx 0.15$ ($f_f = 20$ Hz) (a) Dimensionless Streamwise Fluctuating Velocity $\tilde{u}^*$ (b) Dimensionless Vertical Fluctuating Velocity $\tilde{v}^*$ and (c) Dimensionless Spanwise Vorticity $\tilde{\Omega}^*$.

The dimensionless phased-averaged streamwise and vertical velocity fluctuations and vorticity for $F^+ \approx 0.46$ ($f_f = 60$ Hz) are presented in Figure 28a, Figure 28b, and Figure 28c respectively. As opposed to the $F^+ \approx 0.15$ ($f_f = 20$ Hz) case, large coherent structures remain present in the wake throughout the entire field of view. This frequency produces the strongest and most organized fluctuations in the wake. Subsequent phases confirm the propagation of the organized regions along the airfoil chord and downstream. A pair of positive and negative regions corresponds to the outer edge of a clockwise rotating structure. Dimensionless vorticity (Figure 28c) is also useful for identifying this behavior,

but is in general subject to noise due to the gradient operator (when applied to PIV) and diffusion of vorticity downstream. Note that regions of positive vorticity are generally dominant over regions of negative vorticity. This is expected given that ns-DBD plasma excitation is applied near the leading edge on the suction surface and produces positive vorticity.

Figure 28. Phase-averaged PIV for ns-DBD forcing at $F^+ \approx 0.46$ ($f_f = 60 \text{ Hz}$) (a) Dimensionless Streamwise Fluctuating Velocity $\tilde{u}^*$ (b) Dimensionless Vertical Fluctuating Velocity $\tilde{v}^*$ and (c) Dimensionless Spanwise Vorticity $\tilde{\Omega}^*$.

The phased-averaged dimensionless streamwise and vertical velocity fluctuations and vorticity for $F^+ \approx 1.14$ ($f_f = 150 \text{ Hz}$) are presented in Figure 29a, Figure 29b, and Figure 29c respectively. In contrast to the $F^+ \approx 0.46$ ($f_f = 60 \text{ Hz}$) control case, the strength of the coherent structures in the wake is reduced significantly. However, organization over the airfoil chord is very apparent as would be expected for successful separation control. These coherent structures dominate the flow and their number and size is consistent with forcing

at $F^+ \approx 1.14$. It is well-established that these dynamic structures are effective for entraining freestream momentum and reattaching separated flow over the airfoil (Greenblatt et al. 2000). From Figure 23b, ns-DBD control at $F^+ \approx 1.14$ corresponds to the minimum C_p nearest the leading edge, translating to the best case for separation control. Control at $F^+ \approx 1.14$ creates a strong suction peak near the leading edge and reattaches the flow in the mean over nearly the entire suction surface (see Figure 24). Consistent with previous studies (Little et al. 2012), the control mechanism in this case is not due to laminar to turbulent transition, but rather due to the excitation of flow instability through ns-DBD produced thermal perturbations.

Figure 29. Phase-averaged PIV for ns-DBD forcing at $F^+ \approx 1.14$ ($f_f = 150 \text{ Hz}$) (a) Dimensionless Streamwise Fluctuating Velocity $\tilde{u}^*$ (b) Dimensionless Vertical Fluctuating Velocity $\tilde{v}^*$ and (c) Dimensionless Spanwise Vorticity $\tilde{\Omega}^*$.

Turbulent statistics (Reynold's stresses and turbulent kinetic energy (TKE)) are included in Appendix C, but are not considered here.

4.4 Constant Temperature Anemometry

Hot wire data are collected over a range of forcing cases from $F^+ = 0.08 - 1.22$ ($f_f = 10 - 160$ Hz) in increments of $\Delta F^+ = 0.08$ ($\Delta f_f = 10$ Hz). To coincide with the PIV measurements, focus is placed on the cases of $F^+ = 0.15, 0.46$, and 1.14 ($f_f = 20, 60$, and 150 Hz respectively) as these cases best exemplify the behaviors being studied. All CTA data is acquired at $x/c = 7$ and $y/c = -0.08$.

Before characterizing the flow with the actuator on, it is important to establish the noise floor of the measurements with both the plasma on and the plasma off. To do so, the hot wire collects data with the tunnel and actuator off. The PSD of the data set is calculated to determine the noise level of the data acquisition over a range of frequencies. The process is repeated with the actuator set to $St = 1.14$ ($f = 150$ Hz) as an example case. This process was repeated for all frequencies tested and each exhibited similar behavior. The noise floor distribution is indicated in Figure 30. This is acquired with the probe placed at one-half span. The same process is used to find the noise floor for the probes at one-third and two-thirds span, which exhibited nearly identical behavior. This noise floor is used to evaluate the significance of changes in the spectra, as well as the effects of EMI on data acquisition. If the changes in the magnitude of PSD at a specific frequency are greater than the noise floor at that frequency, then the measurement can be identified as a change in the flow and not a product of noise or EMI.

Figure 30. PSD vs. Strouhal number for noise floor and actuation at $F^+ = 1.14$ ($f_f = 150$ Hz).

Figure 31 shows PSD and autocorrelations at the mid-span probe location for each forcing frequency. The frequency content in Figure 31a is consistent with PIV data from the previous section and a well-developed inertial subrange is apparent from the slope at high frequency. The frequency at which the inertial subrange becomes apparent is not appreciably different from the various forcing cases. The baseline case is absent a clear spectral peak as expected. The same can be said of the highest forcing frequency case ($F^+ = 1.14$). Recall that this forcing frequency resulted in the best performance in terms of separation control. PIV data indicate a very robust pattern over the airfoil (see Figure 29). However, this behavior diminishes quickly in the wake such that the forcing signal is no longer visible at the probe location, $x/c = 7$. Note that PSD values at high frequency are slightly reduced in this case. As previously indicated by PIV, forcing at $F^+ = 0.46$ results in a dominant peak in the spectrum while lower frequency forcing ($F^+ = 0.15$) resembles a potential impulse response with multiple harmonics. In fact, the first harmonic exceeds the fundamental in terms of PSD level. This behavior at low frequency ($F^+ \leq 0.15$) may also be attributed to the nonlinear evolution of fluctuations in the far wake (Papageorgiou 1988).

All forcing cases have higher broadband PSD levels at lower frequency with the $F^+ = 0.46$ being particularly dominant.

The autocorrelations of Figure 31b provide similar information as the spectra. Prior to correlations being performed, a low-pass filter of 200 Hz is applied to each data set in MATLAB so that the frequencies at which vortices are generated can be more effectively analyzed. Furthermore, time is made non-dimensional by multiplying time lag by U_∞/c . The baseline case displays near-zero correlation levels throughout after its initial zero crossing. Forcing at the highest frequency case behaves similarly, but indicates slightly greater integral time scale. The integral time scale is further extended in the $F^+ = 0.46$ forcing case as might be expected from the spectra and PIV data. Note also the oscillatory behavior of the $F^+ = 0.46$ case up to at least 10 convective times downstream. Finally the $F^+ = 0.15$ case shows some curious behavior that is interpreted as a by-product of a possible impulse response or nonlinear behavior in the far wake at $x/c = 7$. This case shows correlation levels and an integral time scale that closely resembles the baseline case. However, at approximately 6.5 convective times downstream the correlation values peak to almost 0.2. Inspection of the difference in convective times between correlation coefficient peaks indicate that this is the time associated the forcing at $F^+ = 0.15$.

Figure 31. (a) Mid-span PSD for all Forcing Frequencies (b) Auto Correlations at all Forcing Frequencies. Hot wire probe is located at $x/c = 7$ and $y/c = -0.08$.

CTA surveys across a wide range of frequencies ($F^+ = 0.08 - 1.22$) in increments of $\Delta F^+ = 0.08$ indicate three approximate regimes of flow response. Forcing in the range of $0.92 < F^+ < 1.52$ results in separation control over the airfoil. There is also a subtle reduction of PSD levels in the inertial subrange. Excitation in the range of $0.23 < F^+ < 0.92$ produces a single dominant frequency in the wake that remains correlated for up to 10 convective times. $F^+ < 0.23$ shows behavior consistent with a possible impulse response in that fluctuations are produced, but the flow relaxes back to something resembling its initial baseline state in between pulses. PIV data in the previous section confirm these observations in all three regimes. In general (and perhaps not surprising), the wake can be excited at frequencies below the approximate onset of the inertial subrange. However, with decreasing forcing frequency, the onset of an impulse-like response and/or nonlinear behavior is observed.

Figure 32 shows plots of both the mid-span and outboard (one-third and two-thirds span) power spectra at each forcing frequency and the baseline. The baseline PSD is shown in Figure 32a. The distributions for one-third, one-half, and two-thirds span lie mostly on top of each other. However, the spectrum at two-thirds span shows a subtle peak around St

≈ 0.5 and slightly higher broadband behavior at low St . An even more subtle peak at similar frequency is observed in the one-third span case. This is accompanied by a slight reduction in the PSD at high St in comparison to its counterparts.

Figure 32b shows the dimensionless PSD for a forcing frequency of $F^+ = 0.15$ ($f_f = 20$ Hz). The spectrum contains several clear peaks in response to actuation frequency. The first peak occurs at $St = 0.15$ ($f = 20$ Hz) which is identical to the frequency of actuation. This implies that each pulse of the actuator is generating a disturbance which propagates downstream where it is detected by the hot wire probe. The peak at $St = 0.15$ agrees with phase-averaged PIV data which shows vortices being produced at the forcing frequency. The peaks in the spectrum at different spanwise locations coincide very closely in terms of St , but the relative amplitude between the fundamental and harmonics differ across the span. In some cases, the first harmonic is dominant over the fundamental. It is possible that the flow may be interacting with the boundary layer along the tunnel walls or with an endwall vortex system as the aspect ratio (AR) of the model is only three. The PIV data will be further examined to provide an explanation for this behavior. As discussed previously, the multi-frequency content is believed to be a manifestation of a possible impulse response or nonlinear effects. Papageorgiou et al. found that the initial conditions in the near wake play a critical role in the instability mechanisms (Papageorgiou 1988). This suggests that an investigation into stability theory might also be advisable for this work. The exact mechanism for this is a subject of further research.

Figure 32c shows the dimensionless PSD for a forcing frequency of $F^+ = 0.46$ ($f_f = 60$ Hz). Notice that, unlike the previous case, only one peak in PSD is present. Thus, it can again be inferred that the mechanism causing multiple peaks to occur at harmonics is

limited to low forcing frequencies. The vortices being generated by actuator pulses remain very coherent as they propagate downstream in this case. The single, high peak in PSD at the forcing frequency indicates a higher level of fluctuation in the wake. The visual evidence of large, coherent structures corresponding to $St = 0.46$ in the PIV further substantiate this claim. The peaks in one-third, one-half, and two-thirds span coincide with each other closely, suggesting these structures are present across the span. However, some endwall effects are likely present in that the mid-span data indicates higher PSD across the entire St range.

Figure 32d shows the dimensionless PSD for a forcing frequency of $F^+ = 1.14$ ($f_f = 150$ Hz). No discernable peaks in PSD occur at the forcing frequency, indicating that coherent structures are not sustained into the wake. This agrees with PIV data at $F^+ = 1.14$ (Figure 29), which shows visual evidence of coherent structures over the model, but not in the wake. Instead, the PSD at $F^+ = 1.14$ closely matches the baseline PSD. This behavior is expected given that the goal of separation control is to reattach the flow to the airfoil in the mean sense, not to produce strong perturbations in the wake. Note that some 3D effects are apparent in this case as well since some modest variations in PSD are observed at both low and high frequencies.

Figure 32. (a) Baseline PSD (b) PSD at $F^+ = 0.15$ ($f_f = 20$ Hz) (c) $F^+ = 0.46$ ($f_f = 60$ Hz) (d) $F^+ = 1.14$ ($f_f = 150$ Hz).

To analyze the two-dimensional nature of the generated vortices, the CTA data set taken at mid-span is cross-correlated with the data taken at one-third and two-thirds span. An autocorrelation is also performed for comparison.

Figure 33 shows the resulting correlations for the baseline and forcing frequencies of $F^+ = 0.15$, 0.46 , and 1.14 respectively. In Figure 33a, the baseline autocorrelation peaks at zero time lag and decreases to zero with no clear oscillations as discussed previously. The outboard correlations are in general agreement, but peak at a convective time of approximately 1. In Figure 33b, the autocorrelation of the one-half span data has a peak of one at zero time lag then displays an additional high level of correlation at $T^* \approx 6.5$ as discussed previously. There is a region in between the oscillation peaks in which the

autocorrelation is near zero. This shows that, at such a low forcing frequency, there is a time in between vortex generation in which the flow is unaffected by the actuator and behaves similar to the base line. This supports the suspicion that forcing at this low frequency is triggering a possible impulse response in the flow. The cross-correlations follow a similar pattern, but are phase shifted by a convective time of ~ 0.60 ($\sim 0.004s$) with the outboard vortices leading those at mid-span. Obviously, the structures are not purely two-dimensional and some 3D effects and smaller scale turbulence are playing a role.

Figure 33c shows the correlation data at a forcing frequency of $F^+ = 0.46$. There are several key differences between this case and the case with forcing frequency $F^+ = 0.15$. The autocorrelation again oscillates at the forcing frequency. However, there are no regions in between peaks in which the correlation coefficient remains close to zero. The autocorrelation oscillates continuously and does not display any features of an impulse response. Instead, forcing produces coherent structures in the wake which occur at the forcing frequency, leading to the single, dominant peak in the PSD. Visual evidence of large, robust structures from PIV data confirms this (Figure 28). The cross-correlations also oscillate near the forcing frequency, but do not have as high of an initial peak due to 3D effects and small scale turbulence. Furthermore, the cross-correlations move in and out of phase with one another and the autocorrelation. This requires further exploration. The cross correlations, suggest that the wake has 2D features, but this is somewhat distorted by 3D effects. The correlation curve oscillates at the forcing frequency with amplitude on the order of 0.1 in great contrast with the baseline case.

Figure 33d shows correlations at a forcing frequency of $F^+ = 1.14$. The correlation curves closely resemble the baseline, indicating no coherent structures are generated in the

wake at this forcing frequency. This agrees with the PSD, which did not have a peak at the forcing frequency as in the other cases. Furthermore, the PIV images showed no large structures being formed at this forcing frequency in the wake.

Figure 33. Correlation data at (a) No actuation (b) $F^+ = 0.15$ ($f_f = 20$ Hz) (c) $F^+ = 0.46$ ($f_f = 60$ Hz) (d) $F^+ = 1.14$ ($f_f = 150$ Hz).

5. Discussion and Conclusions

Control of boundary layer separation and the wake of a NACA 0012 airfoil has been examined experimentally with ns-DBD plasma actuators. The airfoil (including spacers) has an aspect ratio of 3 and is tested at $Re = 0.74 \times 10^6$, $\alpha = 18^\circ$. Measurements include pressure distributions along the airfoil surface, PIV from $x/c = 0$ to $x/c = 4.5$ and CTA measurements at $x/c = 7$ for various spanwise locations. Actuation is applied along the span of the model near the leading edge with energy deposition of 0.3 mJ/cm.

Frequency sweeps are performed over a range of forcing cases ($F^+ = 0.08 - 7.62$ ($f_f = 10$ Hz – 1kHz)) and the C_P distributions are computed to evaluate the separation control authority over the airfoil. Of the forcing frequencies tested, $F^+ = 1.14$ ($f_f = 150$ Hz) is found to be the most effective at controlling separation. At this forcing frequency, actuation produces a minimum pressure coefficient of $C_P = -2.1$ at $x/c = 0.09$ and produces a large region of adverse pressure gradient over the airfoil indicating mean reattachment of the nominally separated flow. The flow over the model for this case is dominated by coherent structures which entrain freestream momentum into the separated region. The efficacy of ns-DBD plasma actuators for separation control is further supported by PIV data which shows that the size of the wake is considerably smaller than the baseline as expected. The wake is generally devoid of strong fluctuations for forcing frequencies that are effective for separation control. The effects of the ns-DBD plasma actuator on separation control are largely in agreement with previous studies (Rethmel et al. 2011, Little et al. 2012).

The results illustrate substantial effects of ns-DBD plasma actuation on the turbulent wake for forcing frequencies that are not optimal for separation control. PSD computed from CTA data shows that forcing frequencies in the range $0.23 < F^+ < 0.92$ produce coherent structures that persist well downstream. Spikes in the PSD are consistent with the forcing frequency. However, lower frequency cases display phenomena resembling a possible impulse response and/or nonlinear characteristics. Both autocorrelations of CTA data and PIV support PSD observations. Based on this data, three forcing regimes have been identified. Below $F^+ = 0.23$, a possible impulse response is observed due to a considerable length of time in between ns-DBD perturbations. This low frequency forcing is characterized by multiple peaks in PSD at harmonics of the forcing

frequency and may also be due to linear instabilities evolving in the far wake at $x/c = 7$. A second regime ($0.23 < F^+ < 0.92$) produces a single dominant frequency in the wake and very coherent fluctuations in both PIV and autocorrelations of CTA data. Phase-averaged vertical and streamwise velocity fluctuations and phase-averaged vorticity clearly show organized structures propagating over the airfoil and in the wake for several chord lengths (up to $x/c = 4.5$). The high frequency regime, as illustrated by the $F^+ = 1.14$ case, is characterized by a disappearance of the peak in PSD at the forcing frequency. In this regime, large perturbations are not present in the wake. Instead, the outcome is to reattach flow on the airfoil rather than create wake fluctuations. In general, it appears possible to excite the wake at nearly any frequency below the inertial subrange. However, at low frequencies ($F^+ < 0.23$) it is currently unknown if the behavior is due to an impulse response or other nonlinear effects in the wake. Higher frequency excitation ($0.92 < F^+ < 1.52$) is more aligned with separation control over the airfoil model and minimal coherent structures in the wake.

The two-dimensionality of the flow field is examined using pressure taps located at one-quarter, one-half, and three-quarters span and hot wire probes located at one-third, one-half, and two-thirds span at $x/c = 7$. The pressure data at the one-quarter and three-quarters span locations are in close agreement with the mid-span pressure data. Although there is greater spatial resolution at mid-span, it can be concluded that the effects of separation control over the airfoil exhibit some two-dimensional features in all cases. PSD and correlation data in the wake indicate that some of this 2D behavior is lost downstream presumably due to 3D effects, likely from the relatively low AR. Spectra of PSD are generally consistent for each spanwise location across the test matrix. However, cross-

correlations of different spanwise locations identify phase shifts and lower correlation values (compared to autocorrelations) as expected.

5.1 Future Work

The three approximate frequency regimes presented in this work require further evaluation to be more clearly defined. This will be done by expanding the range of flow speeds, frequencies, amplitudes, and airfoil angles of attack. More explicit investigation into the low-frequency regime is required to substantiate the claim of impulse-like behavior. Analysis of hot wire data at varying streamwise locations closer to the trailing edge (similar to that of Bourgoyne 2005) and excitation of the ns-DBD with a single pulse at $F^+ \leq 0.15$ will help to further characterize this regime.

Additional work is required to better determine the two or three-dimensional nature of the airfoil wake. The capability of AFC as a disturbance generator in comparison to more traditional methods will rely heavily on the ability to consistently reproduce specific conditions for the study of unsteady aerodynamics and VBI. Therefore, it will be necessary to demonstrate repeatability of the work presented here.

Alternative actuation techniques for the ns-DBD must also be explored to fully understand the ability to control boundary layer separation and the wake. For example, altering the construction of the actuator to excite 3D forcing will have different implications for both separation and wake control. This might also be achieved by configuring multiple ns-DBD's for smart actuation, as explored by (Post et al. 2004) as opposed to the existing arrangement using a single ns-DBD. Current results will be expanded by conducting an increasingly thorough hot wire “mapping” of the wake in all three axes.

References

- Abbott, I., et al. (1945). Summary of Airfoil Data. NACA Technical Report: 266.
- Alexandria, H. o. (1851). The Pneumatics of Hero of Alexandria. London, Taylor Walton and Maberly.
- Booth, E., Yu, J. (1986). "Two-dimensional blade-vortex flow visualization investigation." AIAA Journal 24(9): 1468-1473.
- Bourgoyne, D. A., Ceccio, S. L., Dowling, D. R. (2005). "Vortex shedding from a hydrofoil at high Reynolds number." Journal of Fluid Mechanics 531: 293-324.
- Cattafesta, L., et al. (2011). "Actuators for Active Flow Control." Annual Review of Fluid Mechanics 43: 247-272.
- Corke, T., et al. (2010). "Dielectric Barrier Discharge Plasma Actuators for Flow Control." Annual Review of Fluid Mechanics 42: 505-529.
- Corke, T., et al. (2009). "Single Dielectric Barrier Discharge Plasma Enhanced Aerodynamics: Physics, Modeling and Applications." Experiments in Fluids 46: 1-26.
- Darabi, A., et al. (2004). "Active management of naturally separated flow over a solid surface. Part 1. The forced reattachment process." Journal of Fluid Mechanics 510: 105-129.
- Dawson, R., et al. (2013). "Characterization of nanosecond pulse driven dielectric barrier discharge plasma actuators for aerodynamic flow control." Journal of Applied Physics 113(10): 103302.
- Dengler, M. (2015). Examination of the wake of an airfoil actuated by nanosecond pulse driven dielectric barrier discharge (ns-DBD) plasma. Bachelor Technical University of Berlin.
- Enloe, C. (2008a). "Surface Potential and Electric Field Structure in the Aerodynamic Plasma Actuator " AIAA Journal 46(11): 2730-2740.
- Esfahani, G., Singhal, A., Clifford, C., Samimy, M. (2016). Flow Separation Control over a Boeing Vertol VR-7 using NS-DBD Plasma Actuators. AIAA SciTech. San Diego, CA.
- Favier, D., Castex, A., Maresca, C. (1985). Unsteady characteristics of an airfoil interacting with a vertical wake. AIAA.
- Gad-el-Hak, M. (2000). Flow Control: Passive, Active, and Reactive Flow Management. Cambridge, UK, Cambridge University Press.
- Glezer, A., et al. (2005). "Aspects of Low- and High-Frequency Actuation for Aerodynamic Flow Control." AIAA Journal 43(7): 1501-1511.
- Greenblatt, D., et al. (2008). "Dielectric Barrier Discharge Flow Control at Very Low Flight Reynolds Numbers." AIAA Journal 46(6): 1528-1541.
- Greenblatt, D., et al. (2000). "The Control of Flow Separation by Periodic Excitation." Progress in Aerospace Sciences 36: 487-545.

- Gregory, J., et al. (2007). Switching Behavior of a Plasma-Fluidic Actuator. AIAA 45th Aerospace Sciences Meeting. AIAA Paper: 11.
- Gursul, I., Rockwell, D. (1990). "Vortex street impinging upon an elliptical leading edge." *Journal of Fluid Mechanics* 211: 211-242.
- Hoskinson, A., et al. (2008). "Force measurements of single and double barrier DBD plasma actuators in quiescent air." *Journal of Physics D: Applied Physics* 41(245209): 1-9.
- Huang, J., et al. (2006). "Plasma Actuators for Separation Control of Low-Pressure Turbine Blades." *AIAA Journal* 44(1): 51-57.
- Jolibois, J., et al. (2008). "Application of an AC Barrier Discharge Actuator to Control Airflow Separation above a NACA 0015 Airfoil: Optimization of the Actuation Location Along the Chord." *Journal of Electrostatics* 66: 496-503.
- Joslin, R. a. M., D. (2009). *Fundamentals and Applications of Modern Flow Control*. Reston, Virginia, American Institute of Aeronautics and Astronautics, Inc.
- Kelley, C., Bowles, P., Cooney, J., He, C., Corke, T. (2014). "Leading-Edge Separation Control Using Alternating-Current and Nanosecond-Pulse Plasma Actuators." *AIAA* 52(9): 1871-1884.
- Koochesfahani (1989). "Vortical Patterns in the Wake of an Oscillating Airfoil." *AIAA Journal* 27(9): 1200-1205.
- Lee, T. (2011). "Flow past two in-tandem airfoils undergoing sinusoidal oscillations." *Experimental Fluids* 51: 1605-1621.
- Lehmann, R., Akins, D., and Little J. (2015). Effects of Ns-DBD Plasma Actuators on Turbulent Shear Layers. 7th AIAA Flow Control Conference.
- Leishmann, J. (2000). *Principles of Helicopter Aerodynamics*. Cambridge, UK, Cambridge University Press.
- Little, J. (2010). High-Lift Airfoil Separation Control with Dielectric Barrier Discharge Plasma Actuators. Ph.D., The Ohio State University.
- Little, J. (2010). High-Lift Airfoil Separation Control with Dielectric Barrier Discharge Plasma Actuators. Doctor of Philosophy in the Graduate School of The Ohio State University, The Ohio State University.
- Little, J. (2010). High Lift Airfoil Leading Edge Separation Control with Nanosecond Pulse Driven DBD Plasma Actuators. AIAA 5th Flow Control Conference. Chicago, Illinois.
- Little, J., et al. (2010). "High-Lift Airfoil Trailing Edge Separation Control Using a Single Dielectric Barrier Discharge Plasma Actuator." *Experiments in Fluids* 48: 521-537.
- Little, J., et al. (2012). "Separation Control with Nanosecond-Pulse-Driven Dielectric Barrier Discharge Plasma Actuators." *AIAA Journal* 50(2): 350-365.
- Meier, G., Timm, R. (1985). *Unsteady vortex airfoil interaction in Unsteady Aerodynamics - Fundamentals and Applications to Aircraft Dynamics*.

- Melton, L., Pack, et al. (2005). "Active Control of Flow Separation from Supercritical Airfoil Leading-Edge Flap Shoulder." *Journal of Aircraft* 42(5): 1142-1149.
- Moreau, E. (2007). "Airflow control by non-thermal plasma actuators." *Journal of Physics D: Applied Physics* 40(3): 605-636.
- Opaits, D., et al. (2009). "Electrodynamic Effects in Nanosecond-Pulse-Sustained Long Dielectric-Barrier-Discharge Plasma Actuators." *Applied Physics Letters* 94(061503): 3.
- Papageorgiou, D. T., Smith, D.T. (1988). Nonlinear Instability of the Wake Behind a Flat Plate Placed Parallel to a Uniform Stream. *Proceedings of the Royal Society of London, Royal Society*.
- Patel, M., et al. (2008). "Scaling Effects of an Aerodynamic Plasma Actuator." *Journal of Aircraft* 45(1): 223-236.
- Peng, D., Gregory, J. (2015). "Vortex dynamics during blade-vortex interactions." *Physics of Fluids* 27.
- Post, M. L., et al. (2004). "Separation control using plasma actuators - stationary and oscillating air foils." 42nd AIAA 2004-0841: 12.
- Rethmel, C., et al. (2011). "Flow Separation Control Using Nanosecond Pulse Driven DBD Plasma Actuators." *International Journal of Flow Control* 3(4): 213-232.
- Rival, D., Manejev, R., Tropea, C. (2010). "Measurement of parallel blade-vortex interaction at low Reynolds numbers." *Experiments in Fluids* 49: 89-99.
- Rockwell, D. (1998). "Vortex-Body Interaction." *Annual Review of Fluid Mechanics* 30: 199-229.
- Roth, J., et al. (2000). "Electrohydrodynamic Flow Control with a Glow-Discharge Surface Plasma." *AIAA Journal* 38(7): 1166-1172.
- Roupassov, D., et al. (2009). "Flow Separation Control by Plasma Actuator with Nanosecond Pulsed-Periodic Discharge." *AIAA Journal* 47(1): 168-185.
- Samimy, M., et al. (2007). "Active Control of High-Speed and High-Reynolds-Number Jets Using Plasma Actuators." *Journal of Fluid Mechanics* 578: 305-330.
- Sato, H. (1970). "An experimental study of non-linear interaction of velocity fluctuations in the transition region of a two-dimensional wake." *Journal of Fluid Mechanics* 44(4): 741-765.
- Seifert, A., et al. (1996). "Delay of Airfoil Stall by Periodic Excitation." *Journal of Aircraft* 33(4): 691-698.
- Seifert, A., et al. (2009). Fixed Wing Airfoil Applications. *Fundamentals and Applications of Modern Flow Control*. R. Joslin and D. Miller. Reston, VA, AIAA Inc. 231: 231-257.
- Simonich (1993). "Active Aerodynamic Control of Wake-Airfoil Interaction Noise - Experiment." *AIAA Journal* 31(10): 1761-1768.
- Sosa, R., et al. (2007). "Stall control at high angle of attack with plasma sheet actuators." *Experiments in Fluids* 42(1): 143-167.

- Starikovskii, A., et al. (2009). "SDBD plasma actuator with nanosecond pulse-periodic discharge." *Plasma Science and Technology* 18: 17.
- Wilder, M., Telionis, D. (1998). "Parallel Blade-Vortex Interaction." *Journal of Fluids and Structures* 12: 801-838.
- Wu, J., et al. (1998). "Post-stall Flow Control on an Airfoil by Local Unsteady Forcing." *Journal of Fluid Mechanics* 371: 21-58.
- Wynanski, I. (2004). The Variables Affecting the Control of Separation by Periodic Excitation. AIAA 2nd Flow Control Conference. Portland, Oregon, June 28-July 1. AIAA Paper: 30.
- Zaman, et al. (1989). "A natural low-frequency oscillation of the flow over an airfoil near stalling conditions." *Journal of Fluid Mechanics* 202: 403-442.
- Zhang, P., et al. (2009). "Aerodynamic Modification of a NACA 0012 Airfoil by Trailing-edge Plasma Gurney Flap." *AIAA Journal* 47(10): 2467-2474.

Appendix A

Technical Data For Gold-plated Wire Sensors	
Medium	Air
Sensor material	Platinum-plated tungsten
Sensor dimensions	5 μm dia, 1.25 mm long
Sensor resistance R20 (approx)	3.5 W
Temperature coefficient of resistance (TCR) a 20 (approx.)	0.36%/°C
Max. sensor temperature	300°C
Max. ambient temperature	150°C
Max. ambient pressure	Depends on the type of mounting
Min. velocity	0.05 m/s *
Max. velocity	500 m/s
Frequency limit fcpo (CCA mode, 0 m/s)	90 Hz
Frequency limit fmax (CTA mode)	400 kHz

Table 2. Technical Specifications for gold-plated Hot wire Sensors.

Appendix B

Supplemental Pressure Data

C_L at $Re = 740,000$

Appendix C

Supplemental PIV Data

Re XX

Re XY

Freq

Phase

0

1

2

3

Freq

20Hz

40Hz

60Hz

100Hz

150Hz

Phase 0 1 2 3

Freq

Appendix D

Supplemental Hot wire Data