Airfoil Leading Edge Flow Separation Control Using Nanosecond Pulse DBD Plasma Actuators

THESIS

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By

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Abstract

This work continues an ongoing development and use of dielectric barrier discharge (DBD) plasma actuators driven by repetitive nanosecond pulses for high Reynolds number aerodynamic flow control. These actuators are believed to influence the flow via a thermal mechanism which is fundamentally different from the more commonly studied AC-DBD plasmas. Leading edge separation control on an 8-inch chord NACA 0015 airfoil is demonstrated at various post-stall angles of attack (\(\alpha\)) for Reynolds numbers (\(Re\)) and Mach numbers (\(M\)) up to 1.15x10^6 and 0.26, respectively (free stream velocity, \(U_\infty = 93\) m/s). The nanosecond pulse driven DBD can extend the stall angle at low \(Re\) by functioning as an active trip. At post-stall \(\alpha\), the device generates coherent spanwise vortices that transfer momentum from the freestream to the separated region, thus reattaching the flow. This is observed for all \(Re\) and \(M\) spanning the speed range of the subsonic tunnel used in this work. A comparison of leading edge separation control between NS-DBD and AC-DBD plasma actuation demonstrates the increased control authority of NS-DBD plasma at higher flow speeds. The actuator is also integrated into a feedback control system with a stagnation-line-sensing hot film on the airfoil pressure side. A simple on/off type controller that operates based on a threshold of the mean value of the power dissipated by the hot film is developed for this system. A preliminary extremum seeking controller is also investigated for dynamically varying \(Re\). Several challenges typically associated with integration of DBD plasma actuators into a feedback...
control system have been overcome. The most important of these is the demonstration of control authority at realistic takeoff and landing $Re$ and $M$. 
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Fields of Study

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Chapter 1: Introduction

Flow separation from the an airfoil surface leads to stall, which decreases the airfoil lift and increases drag, causing complete loss of desired performance. Airfoils often utilize leading edge droops or slats to extend the stall angle for a given flow speed. These devices can be very effective, but they also often add weight or mechanical complexity to the overall system. Along with these detrimental effects, the devices can have a negative impact on performance when operated away from their design conditions. To reduce the negative effect that these passive devices have on airfoil performance, active flow control can be implemented as an alternative. Active flow control can be accomplished through a variety of techniques including both steady and unsteady blowing and suction. Dielectric Barrier Discharge (DBD) plasma actuators have also been studied for the purpose of active flow control on airfoils. AC-DBD plasma actuators, which use a high voltage AC input signal to produce plasma, have been extensively studied and have been shown to offer control authority through momentum addition to the flow (Corke et al. 2010). A newer type of plasma actuator is the nanosecond pulse (NS-DBD) plasma actuator. This device does not add momentum to the flow, but rather it affects the flow through rapid heating of the air near the actuator.
This work continues exploration of the use of dielectric barrier discharge plasma actuators driven by repetitive nanosecond pulses for aerodynamic flow control. The efficacy of NS-DBD pulses has previously been demonstrated on an airfoil leading edge up to Reynolds number ($Re = 1\times10^6$ (62 m/sec)) (Little et al. 2010). The current work extends the investigation to higher Mach numbers ($M$) (0.26, 93 m/s) and $Re$ ($1.15\times10^6$) using an 8 inch chord NACA 0015 airfoil commonly studied with active flow control. It also incorporates an actuator recessed in the airfoil surface which reduces discontinuities near the leading edge. A comparison of NS-DBD and AC-DBD plasma actuations is conducted at various $Re$ to demonstrate the difference in control authority between the two methods. The NS-DBD actuator is integrated into a feedback control system with stagnation-line-sensing hot films near the leading edge. These sensors can be used to identify critical points and have recently been implemented in AC-DBD plasma feedback control studies of lift enhancement (Poggie et al. 2010). Two types of closed-loop control systems are investigated. The first is a simple on/off type controller that operates based on thresholding the hot film signal for static $Re$ conditions. The second is an extremum-seeking controller that attempts to optimize the frequency of excitation with changing flow conditions. This latter controller is tested by dynamically varying $Re$. The practical utility of this feedback controller is not fully realized, due to the unfavorable location of the feedback sensor. However, several of the challenges typically associated with DBD plasma actuators have been overcome. The most important of these is the demonstration of control authority at $Re > 10^6$ and $M > 0.25$. Many remaining challenges are currently being addressed.
Chapter 2: Background

Flow separation occurs when a strong adverse pressure gradient is encountered by flow as it moves past a surface. This adverse pressure gradient along with viscous effects in the boundary layer of the flow can lower the momentum of the flow enough that a region of zero or reverse flow develops forcing the remaining flow to separate from the surface. This phenomenon can occur at or near the leading edge of an airfoil at high angles of attack. As a result of flow separation the velocity over the top surface of the airfoil is significantly reduced leading to increased pressure on the top surface. The increase in pressure leads to a large drop in the lift created by the airfoil, along with a corresponding increase in drag.

Separation Control

Separation control with periodic excitation is widely established as a successful actuation technique in many flow systems (Greenblatt and Wygnanski 2000). This active flow control technology can substantially decrease the manufacturing cost, weight and parasitic drag associated with many passive control systems that rely purely on geometric modifications to the aerodynamic surface (McLean et al. 1999). Practical active flow control systems should incorporate feedback for robust operation in the presence of uncertainties, and successful implementations have been demonstrated in various
aerodynamic systems (Becker et al. 2007; Patel et al. 2007; Pinier et al. 2007; Samimy et al. 2007a; Benard et al. 2010b; Poggie et al. 2010; Sinha et al. 2010).

The periodic excitation used for active flow control is often generated using oscillatory momentum devices that produce zero-net mass flux (Glezer and Amitay 2002). The most effective dimensionless frequency of actuation ($F^+$) has been found to be on the order of 1. This dimensionless frequency, or reduced frequency, is calculated as

$$ F^+ = \frac{f x_{sp}}{U_\infty} $$

where $f$ is the frequency of actuation, $U_\infty$ is the freestream velocity, and $x_{sp}$ is the length scale, which in this case is the length of the separated region (Seifert et al. 1996). Momentum can be introduced by a variety of techniques, but the most common are piezoelectric, electromagnetic and electrostatic. In all of these cases, an electromechanical driver creates the oscillatory flow used for excitation. These devices are controlled through electrical signals and, compared to passive control, offer a significant reduction in weight, mechanical complexity and parasitic drag. Unfortunately, they possess limited bandwidth and are subject to mechanical failure because the electromechanical driver is usually operated at resonance to produce the large amplitude perturbations necessary for realizing control authority at practical flight speeds. Even when operated in this fashion, amplitude requirements are often not met, especially for cruise conditions where actuator momentum requirements are high.
Plasma Actuation

Flow control with plasma actuation is appealing because these devices are entirely surface mounted, lack mechanical parts, and possess high bandwidth while requiring relatively low power. Dielectric Barrier Discharge (DBD) plasma actuators driven by AC waveforms (AC-DBD) are the most commonly used of these devices (Corke et al. 2009). They have been widely studied for controlling flow separation, particularly on the leading edge of airfoils in relatively low Re conditions ($Re \sim 10^5$ and $U_{\infty} \sim 30$ m/s) (Moreau 2007), but very few demonstrations of this technology exist at higher Re and $M$. The control mechanism for AC-DBD plasma actuators arises from an electrohydrodynamic (EHD) effect. Collisions between the charged species in the plasma and neutral particles near the surface generate a low speed ($U_{\text{max}} < 10$ m/s) near-wall jet in quiescent air (Forte et al. 2007). The momentum production of these devices is fundamentally restricted by ion density in the space-charge region of electric discharge (Macheret et al. 2004), which has limited their use at higher speeds to date, although continuous improvements are being made (Thomas et al. 2009).

Early reports suggest DBD plasma actuators driven by a different type of waveform could be a superior alternative in some systems (Roupasov et al. 2009). The construction of the device is analogous to the AC-DBD, but the discharge is driven by repetitive nanosecond duration pulses (NS-DBD). DBD plasma created using these waveforms has shown control authority for leading edge airfoil separation control up to transonic speed (Roupasov et al. 2009). The NS-DBD produces very low velocity in the neutral species and the control mechanism is believed to stem from rapid localized
heating of the near surface gas layer (Roupasov et al. 2009; Little et al. 2010). This mechanism is well-established for localized arc filament plasma actuators (LAFPAs) that have demonstrated control authority in high Reynolds number and high-speed (subsonic/supersonic, cold/hot) jets in both experiments (Samimy et al. 2010) and computations (Gaitonde and Samimy 2010).
Chapter 3: Experimental Facility and Techniques

Wind Tunnel

All the experiments are performed in a Gottingen-type, closed, recirculating wind tunnel at the Gas Dynamics and Turbulence Laboratory at The Ohio State University. This tunnel was manufactured by Engineering Laboratory Design, Inc. and is capable of producing velocities from 3-95 m/s (10-300 ft/s).

The tunnel flow is generated by an axial fan powered by a 200 hp variable speed AC induction motor. The speed of the fan is controlled by an operator control panel mounted on the tunnel wall. The wind tunnel has a symmetrical contraction section upstream of the test section with an area ratio of 6.25:1. Downstream of the test section there is a diffuser that expands at an angle of 6°. Upstream of the test section the air is conditioned and straitened with a hexagonal cell aluminum honeycomb. Each of the four right-angle turns of the wind tunnel use galvanized steel, high efficiency turning cascades to minimize losses. The tunnel is equipped with a high porosity screen downstream of the test section as a safety catch to avoid damage to turning vanes or the fan. The wind tunnel construction results in freestream turbulence levels on the order of 0.25% and ±1% variation of the mean freestream velocity across the span of the wind tunnel test section 15 cm (6 in) from the inlet.
The wind tunnel includes an aluminum fin/copper tube heat exchanger that regulates the flow temperature in the tunnel. This heat exchanger is capable of regulating the flow temperature to within ±1 °C of ambient temperature with proper cooling water supply. In the presence of excessive electromagnetic interference (EMI) from the plasma actuator the regulating valve that controls the flow of cooling water does not operate properly. Therefore, to ensure consistent temperature settings for a given flow condition, the valve is set to fully open by requesting maximum cooling. The flow temperature in the tunnel is measured downstream of the test section before the flow goes through any turning vanes.

The tunnel test section (Figure 3.1) has dimensions of 61 x 61 x 122 cm³ (2 x 2 x 4 ft³). The test section consists of walls made of 25.4 mm (1 in) thick optically accessible acrylic. The infield wall includes a 30.5 cm (12in) port centered 30.5 cm (12 in) from the test section floor and 61 cm (24 in) downstream from the entrance of the test section. This port includes a protractor for manual setting of angle of attack with an uncertainty of approximately ±1/4° and is used with interchangeable wall plugs depending on the experimental setup. A modified outfield wall includes a mirror of this port to allow for full-span 2D testing of airfoil models, as is performed in this work. The outfield wall is also hinged at the top to allow for full access to the test section. The test section floor can be removed to accommodate different testing requirements and includes two 44.45 mm (1.75 in) ports and ten 6.35 mm (0.25 in) mounting holes that are plugged when not in use. The test section ceiling includes a 12.7 mm (0.5 in) wide slot that runs along the
length of the centerline of the test section for instrument access. This slot is sealed using a high density nylon brush seal along the full length of the slot.

Figure 3.1: Wind tunnel test section.

The operating conditions of the tunnel are measured using two piezometer rings at the inlet and exit of the contraction section. Each piezometer ring consists of four static pressure taps with one located at the center of each of the tunnel walls. The measurements are taken with two sets of differential static pressure transducers (Omega Engineering, Inc. PX655-25DI and PX655-5DI). The static pressure measurements are
displayed and acquired by the data acquisition system using two process meters (Omega Engineering, Inc. DP-25-E-A).

Airfoil Design and Construction

The airfoil used for all experiments presented here is a symmetric NACA 0015 airfoil with a chord length of 20.32 cm (8 in). This chord length was chosen based on constraints including test section size and material requirements. The airfoil spans the full 61 cm (24 in) test section in a horizontal configuration. The airfoil is constructed of a non-conductive fiberglass material. This ensures adequate strength while keeping the material non-conductive makes certain the plasma actuators will not form an arc with the airfoil surface and cause damage.

The airfoil model is constructed in two sections; a trailing edge section and a leading edge section (see Figure 3.2). Steel alignment pins are used to hold the two sections together. The steel pins are sufficiently far from the actuator location to avoid any plasma arcing issues. The trailing edge section is a standard NACA 0015 trailing edge section which is the same for all airfoil setups, but there are two interchangeable leading edge airfoil sections. One leading edge section is a standard NACA 0015 airfoil leading edge for baseline measurements (LE-1), while a second leading edge is constructed with a 0.762 mm (30 mil) recess wrapping around the leading edge from 10% chord length on the pressure side to 35% chord length on the suction side (LE-2) as shown in Figure 3.3. This recess allows for the installation of a DBD plasma actuator to be flush-mounted near the leading edge to avoid significant discontinuities on the airfoil surface. The center of the airfoil is mostly hollow for ease of instrumentation and wire
management, with several support spars running chord-wise across the span of the airfoil support. Each of the airfoil leading and trailing edge sections also has a hollow spar that runs across the entire span of the airfoil used for routing wires and static pressure tubing out of the tunnel and supporting the airfoil on the walls of the tunnel. The seams produced by the mating of the leading and trailing edge sections are located at $x/c=75\%$ on the suction side and $x/c=30\%$ on the pressure side. This placement is used to minimize disturbing the developing boundary layer near the leading edge of the airfoil.

Figure 3.2: Two Section Airfoil Design with LE-1.

Figure 3.3: LE-2 with PCB actuator installed.
Flow Diagnostics

In order to determine the effect of plasma actuation on the flow around the NACA 0015 airfoil several flow diagnostic tools are used. Static pressure, dynamic pressure, and constant voltage hot film anemometer measurements are taken on surface of the airfoil. The wind tunnel also enables Particle Imaging Velocimetry and qualitative smoke flow visualization.

Figure 3.4: Instrumented airfoil schematic.
Static pressure measurements

The airfoil is equipped with 35 static pressure taps distributed around the chord of the airfoil near the center of the span (Figure 3.4). The static pressure measurements are acquired using three Scanivalve digital pressure sensor arrays (DSA-3217). These pressure signals are acquired at 5 Hz and 50 samples are used to calculate $C_p$ and $C_L$ values for the airfoil. The $C_p$ and $C_L$ values are calculated according to the following equations.

\[
C_p = \frac{p - p_\infty}{q_\infty}
\]

\[
C_L \approx \int_0^1 (C_{p, \text{pressure side}} - C_{p, \text{suction side}}) d \left( \frac{x}{c} \right)
\]

In these equations $p$ is the surface static pressure, $p_\infty$ is the freestream static pressure, $q_\infty$ is the freestream dynamic pressure and $x/c$ is the normalized chordwise position.

Dynamic pressure measurements

Dynamic pressure measurements are taken on the surface of the airfoil near the center of the span of the airfoil. Six high bandwidth 2.5 mm (0.1 in) diameter Kulite pressure transducers (XCQ-080-25A and XCQ-080-5D) are flush mounted along the chord length on the suction side of the airfoil as shown in Figure 3.4. The pressure transducers were placed sufficiently far away from the plasma actuators to avoid arcing between the actuator and the metal transducer.
The pressure transducers are powered with a signal conditioner that was produced in-house and amplifies the signal by 1000. A separate Kemo Benchmaster 21M filtering unit is used to low pass filter the signal before data acquisition takes place. This setup has been found to reduce the overall electrical noise interference on the data. The pressure data is acquired at 50 kHz by a National Instruments PCI-6143 data acquisition board. The pressure spectra presented are calculated using 32 blocks each consisting of 8192 samples, and a Hanning window function. The dynamic pressure, \( c_p \), is calculated as

\[
c_p(t_j) = C_p(t_j) - \overline{C_p}
\]

where \( \overline{C_p} \) is the time-averaged surface pressure and \( t_j \) is the time index of the specific measurement. The power spectral density (PSD) of the dynamic pressure is computed to indicate the frequency content of the surface pressure. The PSD is calculated using a Hanning window function and results in dimensionless units expressed as \( c_p^2/F^+ \).

**Hot Film measurements**

An array of Senflex® hot film sensors is adhered to the suction side of the airfoil from 37\% to 63\% chord length and on the pressure side from 11\% to 17\% chord length (Figure 3.5 and Figure 3.6). A four-channel constant-voltage anemometer (Tao Systems, Inc.) provides the necessary excitation and signal conditioning. The four-channel unit only permitted the use of four sensors, whose locations are shown in Figure 3.4. These devices respond to changes in the shear stress on the surface of the airfoil. The pressure side sensor at \( x/c = 11\% \) is used to track movement of the stagnation line during closed-loop control. Shifts in the stagnation line result in a change in the power dissipated by the hot film sensor near the leading edge. This shift in the stagnation line can be correlated to
changes in the static pressure distribution, and subsequently $C_L$ (Poggie et al. 2010). The power dissipated ($P_{HF}$) by the hot film sensors is calculated using the resistance of the sensor and the applied constant voltage across the sensor. The resistance ($R_{HF}$) is calculated using the excitation voltage ($V_w$) and the measured sensor output voltage ($V_s$), which is low-pass filtered at 8 kHz, along with constants $a$ and $b$ which are specific to the data acquisition and signal conditioning hardware. The relevant expressions for power dissipation and hot film resistance as specified by Tao Systems, Inc. are

$$P_{HF} = \frac{V_w^2}{R_{HF}}$$

$$R_{HF} = \frac{1}{a \left(\frac{V_s}{V_w}\right) + b}$$

Figure 3.5: Leading edge recess airfoil with leading edge actuator installed (LE-2) with pressure side hot film array (element nearest leading edge used for closed-loop control).
**Figure 3.6**: Leading edge recess airfoil with leading edge actuator installed (LE-2) with suction side hot film array (not used for closed-loop control).

**PIV measurements**

Two-component particle image velocimetry (PIV) is used to obtain quantitative measurements of the velocity field over the airfoil. Images are acquired and processed using a LaVision PIV system. Nominally submicron olive oil seed particles are introduced upstream of the test section contraction using a 6-jet atomizer. A dual-head Spectra Physics PIV-400 Nd:YAG laser is used in conjunction with spherical and cylindrical lenses to form a thin light sheet that allows 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 a LaVision 14 bit 2048 by 2048 pixel Imager Pro-X CCD camera equipped with a Nikon Nikkor 50 mm f/1.2 lens. For each
image pair, subregions are cross-correlated using decreasing window size (642-322 pixels) 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 3x3 Gaussian smoothing filter is also applied to the calculated velocity fields.

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 various phases of the actuator modulation frequency are investigated by stepping through the actuation period using time delays. The resulting phase-locked data sets are averaged over 100 images at each phase which is sufficient for resolving the primary features of the flow fields. Phase-locked PIV data is acquired at 5 Hz. The spatial resolution of PIV data for the airfoil is approximately 2.4 mm. The full-scale accuracy for all instantaneous velocity fields is found to be 0.9% assuming negligible laser timing errors and a correlation peak estimation error of 0.1 pixels.

Smoke Flow visualization

Smoke flow visualization was performed using a LeMaitre Special Effects Inc. G100 smoke generator and water based fog fluid. The generator was set up directly below the wind tunnel test section and metal tubing was run from the outlet of the smoke generator to near the leading edge of the airfoil through one of the two access ports on the tunnel floor. Although this setup prevented accurate pressure measurements on the airfoil due to flow disturbances caused by the required plumbing, qualitative flow visualization
was obtained and resulted in a clear visualization of the separated and attached flow states.

**Plasma Actuator Construction**

The DBD plasma actuators used in these experiments consist of asymmetric electrodes separated by a dielectric layer as shown in Figure 3.7. Two different types of actuators have been used. For consistency, all open-loop control work presented in this work is performed using plasma actuators constructed using a Kapton tape dielectric. These actuators have electrodes made of copper tape with a dielectric consisting of layers of Kapton tape. The covered ground electrode is 12.7 mm (½ inch) wide and the exposed high voltage electrode is 6.35 mm (¼ in) wide. Both electrodes have thickness of 0.09 mm (3.5 mil). The dielectric barrier is composed of 3 layers of Kapton tape. Each layer has thickness of 0.09 mm (3.5 mil) and dielectric strength 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 0.05 mm (2 mil). The total thicknesses of the dielectric and the device as a whole are 0.27 mm (10.5 mil) and 0.44 mm (17.5 mil), respectively. The dielectric is wrapped around the LE-2 recess to remove discontinuities.

A printed circuit board (PCB) actuator is used with the on/off controller demonstrated in this work. Open-loop experiments have also been performed with this type of actuator, and results are very similar to those obtained with the Kapton tape actuator. The PCB actuator is made of a 0.127 mm (5 mil) thick polyimide dielectric clad in 0.025 mm (1 mil) copper laminate on both sides (Dupont Part FR8555R). To construct the actuator the areas of the copper clad board on which the electrodes will be placed are
covered with tape. The entire actuator is then placed in a bath of ferric chloride etchant. The ferric chloride etches away the entire copper layer except for what is covered with tape resulting in the necessary electrode geometry (Figure 3.6). The PCB actuators are preferred for their improved repeatability of fabrication. Because both types of actuators are not as thick as the recess on LE-2, the substrate consists of layers of Kapton tape necessary to fill the leading edge recess. These passive dielectric layers are necessary to make the top of the actuator flush with the airfoil surface when installed. The recess is intentionally designed in this fashion so thicker dielectrics could be employed in the future. The interface for both types of plasma actuators is set at $x/c = 1\% \pm 0.49\%$ with the plasma forming on the upstream side of the exposed electrode for NS-DBD experiments and on the downstream side for AC-DBD experiments (see Figure 3.6).

![DBD plasma actuator schematic](image)

**Figure 3.7:** DBD plasma actuator schematic.
NS Plasma Hardware and Software

The waveform used as the input for NS-DBD plasma is generated using an in-house constructed pulse generator. The pulser creates short duration pulses of approximately 100 ns FWHM. A sample of this waveform along with the respective power and dissipated energy is reproduced in Figure 3.8 and Figure 3.9 from Little et al. (2010). The magnitude of the pulse varies with the input voltage to the pulser and DBD actuator load. In this work, peak voltage is approximately 8.4 kV. Figure 3.10 (Little et al. 2010) shows a phase-averaged schlieren image of a compression wave that is generated by the NS-DBD actuator. This compression wave is generated by the thermal effects of the plasma. The thermal effect is believed to be the main control mechanism in NS-DBD control, rather than the momentum addition in AC-DBD plasma actuation. The details of the plasma hardware and the physics of actuation have been discussed in the previous work from our laboratory (Little et al. 2010; Takashima et al. 2010). The shape of each pulse is determined by the internal hardware of the power supply, but the timing of the pulses is dictated by a rapid prototyped controller running on a dSpace DSP 1103 board.
Figure 3.8: Typical voltage and current traces for an NS-DBD plasma actuator on a 30 cm DBD load. (Little et al. 2010)

Figure 3.9: Typical power and energy traces for an NS-DBD plasma actuator on a 30 cm DBD load. (Little et al. 2010)
Figure 3.10: Phase-averaged schlieren image of a compression wave generated by NS-DBD plasma actuator viewed along the major axis of the actuator. (Little et al. 2010)

**AC Plasma Hardware and Software**

Input signals for the AC-DBD plasma are generated using the same dSpace hardware and software used for the NS-DBD plasma. The input signal is sent to a Powertron Model 1500S AC power supply and step-up transformer. The amplified signal is then sent to a low power (200W), high voltage (0-20 kV$_{\text{rms}}$) transformer designed to operate in a frequency range of 1-5 kHz. Voltage measurements are acquired and monitored at the secondary side of the high voltage transformer with a Tektronix P6015A probe. A sample waveform used to generate the AC-DBD plasma is shown in Figure 3.11 (Little et al. 2010). The AC signal uses a 2 kHz carrier frequency, $f_c$, to produce the
plasma. This signal is modulated at a lower frequency, $f_m$, to excite natural flow instabilities in certain flow regimes. No modulation is employed for the NS-DBD.

The maximum velocity generated by the AC-DBD actuator in quiescent air measured 20 mm downstream of the electrode interface is between 3 and 3.5 m/s for a 2 kHz carrier frequency with no modulation (Little et al. 2010). The velocity profile is affected by changes in supply voltage, carrier frequency, and any modulation of the signal. In contrast, 2 kHz operation of the NS-DBD produces only ~0.5 m/s. The power consumption of both types of DBD actuators used in this work is similar (~1 W/cm). However, the NS-DBD actuator requires a significantly larger peak power during the nanosecond pulse (see Figure 3.9). It is important to note that neither of these actuators have been fully optimized for aerodynamic performance or power.
Closed-loop Control Hardware and Software

The closed-loop controllers investigated in this work are developed using MATLAB’s Simulink interface. The implementation of the controllers is done using the same dSpace hardware and software that are used for open-loop control of both the AC and NS-DBD plasma actuators. The dSpace hardware and software have built-in compatibility with Simulink which allows for rapid prototyping and evaluation of the different closed-loop control strategies used throughout the work. All closed-loop control is performed using the power dissipation of the constant voltage hot film sensor located at 11% chord length on the pressure side as the ‘decision variable.’
Chapter 4: Results

Baseline Results

Baseline flow studies are performed on the NACA 0015 airfoil to determine the flow characteristics of the airfoil with no actuation. To determine the baseline characteristics LE-1 is used to obtain a complete $C_p$ profile for the airfoil at various Re’s and angles of attack ($\alpha$’s) as shown in Figure 4.1 and Figure 4.2. To determine where hysteresis effects are present, data is taken by starting at the lowest Re, sweeping up incrementally to the highest Re, and then sweeping back down to the lowest Re in the same increments at each $\alpha$. When the flow is attached at the leading edge, the $C_p$ distribution is characterized by a negative pressure peak near the leading edge on the suction side. Beyond this point the $C_p$ value gradually increases along the chord of the airfoil. On the pressure side of the airfoil, the $C_p$ value reaches a maximum of one at the stagnation line. This point is near the leading edge, but shifts slightly depending on Re and $\alpha$. Further down the chord length of the airfoil, the pressure side $C_p$ value increases gradually until it equals the suction side value at the trailing edge. In Figure 4.1 data is shown for $\alpha=14^\circ$ and hysteresis effects can be seen depending on whether the flow is initially attached or initially separated. The flow is initially separated at the leading edge at $Re=0.25\times10^6$ and $\alpha=14^\circ$ and as $Re$ is increased the flow becomes attached along much
of the airfoil chord. Once the flow becomes attached, $Re$ can then be decreased back to $Re=0.25\times10^6$ with flow remaining attached. This hysteresis effect is not seen at higher angles of attack, but can be used in conjunction with a closed-loop feedback controller to save energy in the flow regime shown here (Benard et al. 2010a). In Figure 4.1 the curves labeled as $Re$ increasing are taken as $Re$ is increased incrementally from $Re=0.25\times10^6$ to $Re=1.15\times10^6$, and the curves labeled as $Re$ decreasing are taken after the flow has been increased to $Re=1.15\times10^6$ and is then decreased incrementally to $Re=0.25\times10^6$.

![Figure 4.1: $C_p$ at $\alpha = 14^\circ$ curves demonstrating hysteresis effects present on NACA 0015 airfoil.](image)

Figure 4.1: $C_p$ at $\alpha = 14^\circ$ curves demonstrating hysteresis effects present on NACA 0015 airfoil.
Figure 4.2 shows the $C_p$ distribution at $Re=1.15 \times 10^6$ over the range of $\alpha$ tested. This figure shows that the flow remains attached to the suction surface up $\alpha=12^\circ$ after which flow begins to separate. The separation line starts near the trailing edge and moves forward toward the leading edge as $\alpha$ is increased. The flow becomes separated over almost the entire chord of the airfoil for $\alpha$ greater than $14^\circ$.

![Figure 4.2: $C_p$ curves for varying $\alpha$ at $Re = 1.15 \times 10^6$.](image)

Baseline $C_L$ measurements were calculated by integrating the $C_p$ distribution around the surface of the airfoil. The Prandtl-Glauert transformation is used to adjust for
compressibility effects although the necessary corrections are very small. For all \( Re \) tested, the maximum lift coefficient, \( C_{L,max} \) is at \( \alpha=12-13^\circ \), with the value of \( C_{L,max} \) being dependent on \( Re \), as expected. The post-stall lift curve strongly depends on \( Re \) due to slight variations in the LE separation location. It is shown in this work that the different flow regimes require different control strategies depending on \( Re \) and \( \alpha \).

Figure 4.3: Lift coefficient vs. angle of attack for various Reynolds numbers for the baseline case.
A comparison of $C_p$ distributions for the airfoil with LE-1 and with an actuator installed but not active on LE-2 is performed to determine the passive effect of the actuator. In Figure 4.4, four angles of attack are shown for both the Kapton tape actuator and the PCB actuator. No static pressure data is acquired over the electrodes, but away from the electrodes holes are made in the dielectric material to allow static pressure measurements by the underlying taps. In Figure 4.4 it is seen that although there are some minor variations in the LE baseline distribution, the overall differences are minor. Some of the difference may be attributed to the uncertainty in setting of angle of attack. This data establishes that the actuator is not functioning as a passive control device and any control authority provided by the actuator is due to the formation of plasma.
Figure 4.4: Baseline $C_p$ comparison for clean airfoil (LE-1) and airfoil with recess and actuator (LE-2) (a) $Re = 0.25 \times 10^6$, $\alpha = 12^\circ$, (b) $Re = 0.25 \times 10^6$, $\alpha = 14^\circ$, (c) $Re = 1.15 \times 10^6$, $\alpha = 14^\circ$, and (d) $Re = 1.15 \times 10^6$, $\alpha = 16^\circ$.

Dynamic pressure data is taken along the chord of the suction side of the airfoil using Kulite pressure transducers. These transducers can measure high-bandwidth changes in the pressure along the surface of the airfoil. From the dynamic pressure measurements in Figure 4.5 it is seen that the passive actuator has very little effect on the overall frequency content of the pressure spectrum. This confirms that any flow changes...
induced by the actuator are indeed due to plasma formation and not a passive trip of the boundary layer.

Figure 4.5: Baseline $c_p$ PSD for clear airfoil (LE-1) and airfoil with recess and actuator (LE-2) at $\alpha = 18$ and $Re = 1.15 \times 10^6$.

The dynamic pressure data can also indicate the state of the flow over the airfoil. Figure 4.6 and Figure 4.7 show that there is a clear difference in the pressure spectrum between separated and attached flow. In the spectrum for the attached flow the magnitude of the low frequency content in particular is lower. It is also seen that there are specific
peaks in the separated flow near a reduced frequency of $F^+ = 1$ that appear to correspond with a natural flow instability of the airfoil.

Figure 4.6: Baseline $c_p$ PSD for $\alpha = 12^\circ$ and $Re = 1.15 \times 10^6$ on LE-1.
Time-averaged PIV data is taken to establish the general characteristics of the flow field. The vorticity field over the top of the airfoil at $Re=1.15\times10^6$ and $\alpha=18^\circ$ is shown in Figure 4.8. The vorticity is defined as

$$\Omega_z = \frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}$$

The figure shows that the flow separates very near the leading edge of the airfoil and a shear layer develops from this separation line. This results in low momentum flow near the airfoil surface and higher momentum flow above the shear layer. For the same
$Re$ at a lower $\alpha$ of $12^\circ$ it is shown in Figure 4.9 that the flow over airfoil surface remains attached and a shear layer does not develop away from the surface of the airfoil.

Figure 4.8: Baseline vorticity at $\alpha = 18^\circ$ and $Re = 1.15 \times 10^6$ showing a separated flow condition.
Figure 4.9: Baseline vorticity at $\alpha = 12^\circ$ and $Re = 1.15 \times 10^6$ showing an attached flow condition.

The closed-loop controllers demonstrated later in this work use a hot film sensor located at 11% chord length on the pressure side of the airfoil as the input to the controller. To determine how the hot film sensor will react to changes in the airfoil flow profile, baseline results are recorded across a range of $\alpha$. Figure 4.10 and Figure 4.11 show that the power dissipated by the hot films follows a similar trend as the $C_p$ value nearest to the leading edge on the suction side ($C_{p-LE}$) which can be used as an indication of the overall lift of the airfoil. The $C_{p-LE}$ value must be used instead of $C_L$ because $C_p$ measurements cannot be made over the plasma actuator and since the largest changes in $C_L$ result from the strong suction peak that forms near the leading edge, the $C_{p-LE}$ value is the best indication of changes in $C_L$ available. The changes in power dissipated by the
hot film are due to changes in the stagnation line of the airfoil, which has been shown to correlate with $C_L$ (Poggie et al. 2010). As the stagnation line shifts, so does the flow profile, including the shear stress profile, over the entire airfoil. Because the hot film sensors react strongly to changes in shear stress, a shift in the stagnation line will result in a change in shear stress over the hot film element. This change is severe very near the stagnation line, but becomes more gradual with increasing distance. For this reason it is expected that a better correlation and better closed-loop control results could be obtained by placing the hot film sensor closer to the stagnation line.

To assist in explanation of the hot film signal, we employ the analysis tool XFLR5, a successor to the popular code XFOIL. Figure 4.12 presents XFLR5 predictions of pressure side skin friction coefficient, $C_f$, near the leading edge of a NACA 0015 at $Re=1\times10^6$ for two sample $\alpha$. Predictions for the suction surface have been removed for simplicity. Note the large difference in $C_f$ gradient on either side of the stagnation line. Upstream of stagnation the $C_f$ gradient is substantial while downstream the gradient is quite small. As $\alpha$ and $C_L$ increase, the stagnation line moves downstream on the pressure side of the airfoil. At post-stall $\alpha$, the stagnation line moves back upstream corresponding to a decrease in $C_L$. These changes result in shifts of the shear stress profile allowing the hot film to track movement of the stagnation line. The performance of feedback control crucially depends on the quality of the measured signal employed as a surrogate for the performance objective. The curves of Figure 4.12 illustrate that for increased sensitivity, a hot film sensor should be located upstream of stagnation in the region of high $C_f$ gradient such that small movements of the stagnation line can be resolved. Unfortunately,
the actuator recess employed in this work requires sensors placed further downstream at \( x/c = 11\% \) to prevent damage due to actuator replacement. The data in Figure 4.12 qualitatively explain the poor sensitivity observed in Figure 4.10 and Figure 4.11. Based on this information, it is somewhat surprising that movement of the stagnation line can be tracked at all this far downstream yet useful results have been obtained. Increased sensitivity is expected if sensors could be placed upstream of the stagnation line in the region of strong shear stress gradient. For example, Poggie et al. (2010) reported that a hot film sensor placed at \( x/c = 0.17\% \) showed increasing shear stress with increasing \( C_L \) indicating it is on the upstream side of the stagnation line. In our case (\( x/c = 11\% \)), shear stress decreases with increasing \( C_L \), consistent with data of Figure 4.12. Thus, both the sensitivity and sign of the \( C_L-C_f \) correlation are dependent on the sensor location.

![Figure 4.10: Baseline \( C_p-LE \) and hot film power dissipated vs. \( \alpha \) for \( Re = 0.25 \times 10^6 \) for LE-2.](image)

Figure 4.11: Baseline $C_p$-LE and hot film power dissipated vs. $\alpha$ for $Re = 1.15 \times 10^6$ for LE-2.

Figure 4.12: XFLR5 predictions of pressure side skin friction near the leading edge of a NACA 0015 at $\alpha = 6^\circ$ and $10^\circ$ for $Re = 1.00 \times 10^6$. 
NS-DBD Open-Loop Results

To determine the control authority of the NS-DBD plasma actuator, open-loop control characterization is performed at various $Re$ and post stall $\alpha$. A comparison between the effectiveness of actuation with Kapton tape and PCB actuators is shown in Figure 4.13 and Figure 4.14. This comparison is performed to determine if any differences in control authority or performance exist between the two dielectric materials and if the results for the two types of actuators can be treated interchangeably. The figures show that the control authority is very similar for the two dielectric materials, especially at high $Re$ and $\alpha$.

Figure 4.13: Controlled $C_p$ comparison for airfoil with Kapton tape actuator and for airfoil with PCB actuator at $Re = 0.25 \times 10^6$, $\alpha = 14^\circ$. 

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Figure 4.14: Controlled $C_p$ comparison for airfoil with Kapton tape actuator and for airfoil with PCB actuator at $Re = 1.15 \times 10^6$, $\alpha = 20^\circ$.

To determine the efficacy of the NS-DBD plasma actuator for leading edge separation control, testing is performed over a range of $Re$ from $0.25 \times 10^6$ to $1.15 \times 10^6$ (20 m/s-93 m/s). Testing is performed up to $\alpha=20^\circ$ which resulted in a maximum tunnel blockage of approximately 20%. No adjustments are implemented for blockage effects in the wind tunnel.

Several techniques for separation mitigation over airfoils have been established. Examples of these include, boundary layer tripping, excitation of natural flow instabilities, and addition or removal of momentum through blowing or suction (Greenblatt and Wygnanski 2000). In recent research it has been shown that NS-DBD plasma actuators do not create significant amounts of momentum due to
electrohydrodynamic effects (Roupasov et al. 2009; Little et al. 2010), therefore ruling out any blowing type effect. Depending on the $Re$ and $\alpha$, both boundary layer tripping and instability excitation have been observed with the NS-DBD plasma actuator. An example of boundary layer tripping is shown at $Re=0.25 \times 10^6$ and $\alpha=14^\circ$. A sample $C_p$ distribution for this case as well as the response of the static pressure near the leading edge ($x/c=6\%$) of the suction side of the airfoil to different actuation frequencies is shown in Figure 4.15 and Figure 4.16. Figure 4.16 figure also shows the response of a hot film sensor at $x/c=11\%$ on the pressure side of the airfoil to changes in the actuation frequency. As shown in Figure 4.15, actuation at $F^+=2.5$ causes the flow to remain attached up to approximately $x/c=70\%$. In the present work, the hot film sensors are placed substantially aft of the stagnation line; yet a correlation with suction side $C_p$-LE can still be observed (Figure 4.16). The $C_p$ data in Figure 4.15 shows that the stagnation line is at $x/c < 5\%$; thus it is somewhat surprising that its motion is tracked at all so far downstream, especially with this low velocity flow. Examination of Figure 4.16 shows a negative correlation between suction side $C_p$ and pressure side hot film near the LE. Note that baseline values are shown at $F^+=0$. This perceived negative correlation comes from the inverted $C_p$ axis, and in actuality the correlation is positive. It is also important to recognize that the change in the hot film signal ($\sim 0.2$ mW) is quite small compared to the nominal value ($\sim 85$ mW). The response of $C_p$ to forcing frequency is relatively constant from $F^+=2$ to $F^+=12$, and no preferred frequency can be distinguished. At higher frequency, the LE-$C_p$ value increases slightly indicating reduced control authority. These flow conditions (low-$Re$, moderate $\alpha$) correspond to a case where a well-designed LE
boundary layer trip can reattach the flow to the surface. This, along with the lack of a preferred frequency in Figure 4.16, suggests that the actuator functions as an active trip. This behavior has previously been observed for a different airfoil (Little et al. 2010).

Figure 4.15: $C_p$ curves for baseline and with control at $F^+$ of 2.5 for $Re = 0.25 \times 10^6$, $\alpha = 14^\circ$. 
Figure 4.16: Hot film dissipated power and $C_p$-LE for various forcing frequencies for $Re = 0.25 \times 10^6$, $\alpha = 14^\circ$.

Figure 4.17 and Figure 4.18 demonstrate the case of high $Re$ ($1.15 \times 10^6$) and high $\alpha$ ($18^\circ$). In this flow regime the baseline flow is characterized by deep stall with a nearly flat $C_p$ distribution along the entire suction side of the airfoil. Actuation at a variety of frequencies results in reduction of the separated region over the airfoil. The frequency sweep shown in Figure 4.18 is quite different from that previously examined for low $Re$ (Figure 4.16). A clear preference is seen for $F^+ = 1.9$, which is consistent with dimensionless frequencies observed in literature for most effective instability excitation ($F^+ \approx 1$) (Seifert et al. 1996). This indicates a different physical mechanism, which is confirmed in the PIV results section. This is an important result which shows the efficacy of the NS-DBD plasma for controlling flow separation at $Re = 1.15 \times 10^6$ and $M = 0.26$.
($U=93$ m/s), associated with practical takeoff and landing conditions for transport aircraft, where the more common AC-DBD actuators are yet to show effectiveness. It is also in agreement with the results of Roupasov et al. (2009), who used a shorter pulse width NS-DBD waveform with similar success. Correlation between suction side $C_p$-$LE$ and the hot film signal is substantially less apparent for these conditions. While the minimum for $C_p$ occurs at $F^+ = 1.9$, the corresponding minimum for the hot film signal is near $F^+ = 3$-4, but there is substantial scatter in this hot film data. It is unclear if this is a result of the control mechanism or a characteristic of the hot film reaction to changes in the shear stress distribution.

![Figure 4.17: $C_p$ curves for baseline and with control at $F^+$ of 1.9 for $Re = 1.15 \times 10^6$, $\alpha = 18^\circ$.](image)


The frequency sweep results presented in Figure 4.16 and Figure 4.18 show that two different control mechanisms are at play. In the low Re, low-\(\alpha\) case, the frequency of actuation is not critical. This behavior indicates that flow instabilities are not being excited and the actuator is acting as an active boundary layer trip. The excitation of natural flow instabilities is largely dependent on the frequency of excitation. This is shown in Figure 4.18 where a clear frequency preference of around \(F^+ = 1.9\) is seen. This indicates that the primary method of control in these high Re, high-\(\alpha\) conditions could be the generation of large scale structures through the excitation of natural flow instabilities.

The presence of structures in the flow is confirmed by PIV. Coherent spanwise vortices can be identified using the phase-averaged fluctuating component of the vertical
velocity together with the swirling strength, as discussed by Little et al. (2010). The normalized phase-averaged fluctuating \( v \)-velocity is calculated as

\[
\tilde{v} = \frac{\bar{V} - \bar{V}}{U_\infty}
\]

where \( \bar{V} \) and \( \bar{V} \) are phase and time-averaged quantities respectively. The swirling strength, \( \lambda_{ct} \), is the imaginary component of the eigenvalues of the two-dimensional velocity gradient tensor of the phase averaged vector field, \( \tilde{W} \).

\[
\nabla \tilde{W} = \begin{pmatrix}
\frac{\partial \tilde{U}}{\partial x} & \frac{\partial \tilde{U}}{\partial y} \\
\frac{\partial \tilde{V}}{\partial x} & \frac{\partial \tilde{V}}{\partial y}
\end{pmatrix}
\]

The normalized swirling strength, \( \lambda_{ct}^* = \lambda_{ct} c / U_\infty \), is used to differentiate between regions of flow rotation and pure shear. This is based on critical point analysis of the velocity gradient tensor and its eigenvalues (Adrian et al. 2000). Figure 4.19(a) shows the normalized phase-averaged fluctuating \( v \)-velocity component, where a coherent structure is indicated by alternating regions of positive and negative \( v \)-velocity. Swirling strength contours presented in Figure 4.19(b) confirm that adjacent pairs of these alternating regions constitute distinct vortices in the flow (seen at approximately \( x/c = 20\% \) and \( 50\% \)). These vortices entrain and transfer high momentum fluid into the separated region near the airfoil surface. This mechanism is widely established in the literature for controlling separation in many flows (Greenblatt and Wygnanski 2000). However, this behavior has not been demonstrated at these \( Re \) and \( M \) using more common AC-DBD
plasma actuators. It should also be noted that spanwise vortices have previously been visualized over a range of actuation frequencies in a similar airfoil, which suggests that this device has high bandwidth (Little et al. 2010). As mentioned above, this mechanism stems from rapid localized heating of the near-surface flow by the plasma. This produces local compression waves similar to another type of short pulse width, high amplitude plasma actuator (localized arc filament plasma actuator) which has shown control authority for various high $Re$ and high Mach number jets (Samimy et al. 2007b, 2010).
The effect of NS-DBD plasma actuation can also clearly be seen in the time-averaged vorticity field. As was shown in the Figure 4.8 the baseline separated flow has a clear separation point from which a shear layer develops. When the NS-DBD plasma actuator reattaches the flow at the leading edge, the area of high vorticity moves toward
the airfoil surface (Figure 4.20), indicating that there is increased mixing between the high momentum fluid and the low momentum fluid in the previously separated region.

![Time averaged vorticity field](image)

**Figure 4.20**: Time averaged vorticity field at $\alpha = 18^\circ$ and $Re = 1.15 \times 10^6$ for $F^* = 2.75$ showing a shift in shear layer compared to baseline (Figure 4.8).

Smoke flow visualization was used to record videos of the transition from separated to attached flow as a result of plasma actuation. In Figure 4.21 and Figure 4.22 frames from the smoke flow visualization are shown. Figure 4.21 shows baseline separated flow at $Re=1.15 \times 10^6$ and $\alpha=18^\circ$ while Figure 4.22 shows a frame in which the NS-DBD plasma actuator is on and the flow is attached over some of the leading edge before separating further downstream.
Figure 4.21: Smoke flow visualization at $Re = 1.15 \times 10^6$ and $\alpha = 18^\circ$ with no actuation.

Figure 4.22: Smoke flow visualization at $Re = 1.15 \times 10^6$ and $\alpha = 18^\circ$ with NS-DBD plasma actuation at $F^* = 2.75$. 
AC-DBD Open-Loop Results

A comparison of NS-DBD and the more common AC-DBD plasma actuators is performed. All AC-DBD plasma actuation experiments are performed using Kapton tape actuators because the lifetime of the PCB dielectric is too short for practical use with AC plasma. For AC-DBD actuation the actuator is placed with the electrode interface at \( x/c = 1\% \) just as in the NS-DBD experiments. However, the actuator is mirrored about the electrode interface so that plasma forms on the downstream side of the exposed electrode. This ensures that the momentum generated by the AC-DBD plasma is in the downstream direction, thereby adding momentum to the flow over the airfoil. It should be noted that for the AC-DBD plasma tests the \( C_p \) value could not be measured as close to the leading edge as compared to the NS-DBD plasma due to the differences in actuator orientation and plasma extent. With the AC-DBD actuator installed the static pressure located at \( x/c = 10\% \) is the closest available for pressure measurements on the suction side of the airfoil.

The AC-DBD experiments are performed at \( \alpha = 18^\circ \) while varying \( Re \). The AC signal is approximately 18 kV\(_{pp}\) for all testing. The carrier frequency of the AC-DBD actuator is 2 kHz and the signal is duty-cycle modulated at different frequencies with the best case for each flow regime shown in Figure 4.23. The response to changes in frequency of actuation for both AC- and NS-DBD plasma actuators was found to be very similar. Varying the duty cycle was found to have very little effect on control authority, and the data presented is for a 20% duty cycle.
A comparison of the $C_p$ curves in Figure 4.23 and Figure 4.24 shows that the effectiveness of the AC-DBD actuator drops off significantly as $Re$ is increased, with almost no discernible control authority beyond $Re=0.50 \times 10^6$ (39 m/s) which is consistent with the results in the literature (Moreau 2007). The AC-DBD actuator creates a strong suction peak near the leading edge of the airfoil similar to the NS-DBD actuator at $Re=0.25 \times 10^6$. However, at $Re=0.50 \times 10^6$ the $C_p$ curve shows a much smaller change with AC-DBD plasma actuation, indicating a reduction in effectiveness of the actuator. At $Re=0.75 \times 10^6$ and above the AC-DBD actuator exhibits almost no control authority on the separated flow. The reason for this reduction in control authority at higher flow velocities is that the control mechanism of the AC-DBD actuator is an electrohydrodynamic effect that creates a wall jet like effect on the airfoil surface. This wall jet adds momentum to the flow which mitigates separation, but as the flow velocity is increased the relative effect of adding the same momentum is reduced, thereby limiting the velocity at which AC-DBD plasma actuation is effective for flow control. The NS-DBD plasma actuator, by comparison shows similar control authority to that seen at $Re=0.25 \times 10^6$ with the AC-DBD actuator up to the maximum speed of the wind tunnel ($Re=1.15 \times 10^6$). These results are in agreement with our previous experiments on a different airfoil (Little et al. 2010).
Figure 4.23: $C_p$ curves at $\alpha = 18^\circ$ and varying $Re$ for AC-DBD actuation.

Figure 4.24: $C_p$ curves at $\alpha = 18^\circ$ and varying $Re$ for NS-DBD actuation.
Closed-Loop Results

Closed-loop control is investigated over a range of $Re$ and $\alpha$. Two types of closed-loop control are explored in this work, both of which use the power dissipated by the hot films as the ‘decision variable’. A mean value is used to address the stochasticity of power dissipated by the hot film. There is only a small change in signal when going from a separated to a controlled state as shown in Figure 4.16 and Figure 4.18. This small change results in a low signal to noise ratio for the ‘decision variable’ of the closed-loop controller, and taking a mean value over a short time period increases this signal to noise ratio.

On/Off Closed-Loop Control

The first type of closed-loop controller used is a simple on/off controller whose schematic is shown in Figure 4.25. A nominal threshold and a dead zone width are set based on experience gained in previous open-loop experiments. These settings are such that a reading of dissipated power above the dead zone indicates separated flow, whereas one below it indicates attached flow. A dead zone is used rather than a single threshold value to avoid unsteadiness for measured values very near the nominal threshold. The actuator, if it is indeed commanded to operate, runs at a preset frequency $f$ that is determined based on open-loop control results. The responsiveness of the controller is determined by the length of time over which raw hot-film voltage measurements must be accumulated for the necessary statistics (mean of dissipated power, in this case) to converge. This time interval is typically a function of the flow time scale, but in all the experiments reported here, it was set to 0.1 s (10 to 45 flow time scales, depending on
$Re$). The processed value is held over this interval, while a running sum of the raw sensor signal is accumulated. At the end of each interval, the processed value is refreshed, and the running sum is reset to 0.

![On/Off Controller Diagram]

**On/Off Controller Steps**
1. Acquire processed measurement, Input
   a. If Input > Threshold + DeadZone/2, Output = ON
   b. Else if Input < Threshold – DeadZone /2, Output = OFF
   c. Else Output = Previous Output
2. Wait for Input
3. Go to 1st step

Figure 4.25: The on/off control scheme.

On/off control is demonstrated at $Re = 0.25 \times 10^6$ and $\alpha = 14^\circ$ using an actuation frequency of $F^+ = 2.5$. As discussed earlier, hysteresis effects are significant in this flow regime, meaning that once flow is attached by actuation it can remain attached for some time even with the actuator switched off (Benard et al. 2010a). When this is the case, it is advantageous to temporarily turn the actuator off to conserve power and then reinitiate the plasma when the flow is once again beginning to separate. This behavior is achieved with the on/off controller, as demonstrated in Figure 4.26. The dSpace controller clock is
running at 50 kHz, so that the raw sensor voltage is sampled at this rate and the decision step (Step 1 in Figure 4.25) is performed in 20 µs. The sensing and its online processing are initiated before time $t = 0$ on the graph. When the controller is activated at $t = 1.5$ s, this processed measurement is found to be above the dead zone, and the actuator is enabled within 20 µs. The flow gets attached within the next 0.2 s, and sensing the corresponding drop in the dissipated power, the controller switches off the actuator (indicated by the flat-lining pulser input signal). From $t = 1.5$ s to 2.75 s, the hysteresis effect causes the flow to remain attached, which is continuously verified by the controller. The flow starts to separate again at $t = 2.75$ s, at which time the controller turns the actuator on to keep the flow attached to the airfoil, and the cycle is repeated. This behavior is consistent with the control mechanism of turbulent transition discussed in connection with Figure 4.16.

![Figure 4.26](image_url)

**Figure 4.26:** On/off controller at $Re = 0.25 \times 10^6$, $\alpha = 14^\circ$, $F^* = 2.5$. 

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The on/off controller is also tested in the deep stall regime at $Re=1.15\times10^6$ and $\alpha=18^\circ$. In this flow regime hysteresis effects are not present, therefore to keep the flow attached to the airfoil the NS-DBD actuator must run continuously. If the actuator is switched on and off repeatedly the disruption of the large-scale vortex pattern would create large unsteady forces on the airfoil. Therefore, the threshold for the controller is set intentionally low in these flow conditions. This causes the controller to determine that the flow is separated at all times and the actuator remains enabled until it is manually stopped.

Figure 4.27: On/off controller at $Re = 1.15\times10^6$, $\alpha = 20^\circ$, $F^\prime=2.75$. 

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**Extremum-Seeking Closed-Loop Control**

Some preliminary investigations into extremum-seeking closed-loop control are also performed. This controller searches for an extremum (a maximum or a minimum) in the performance objective by continuously adjusting a chosen parameter of the actuation. The extremum-seeking controller is based on the Modified Nelder-Mead Algorithm implemented previously in a high Reynolds number high-speed jet forced with localized arc filament plasma actuators (Sinha et al. 2010). In brief, after each update of the actuation parameter of interest, the measured change in the performance objective is used to decide the sign and magnitude of the next update. In the present implementation, the objective is to keep $C_L$ maximized by optimizing the forcing frequency of the NS-DBD plasma actuator, even when the flow speed is dynamically varied. Since $C_L$ cannot be measured in real-time, one has to improvise with the surrogate objective of minimizing the power dissipated by the leading edge hot film sensor (see Figure 4.16 and Figure 4.18). However, it is shown in Figure 4.16 and Figure 4.18 that the minimum of this quantity does not necessarily correspond directly to the minimum of the $C_P$ value near the leading edge. This means that although using the extremum-seeking controller with the hot films may result in an increase in $C_L$ compared to the baseline case, one cannot guarantee convergence to the optimal forcing frequency determined from the open-loop frequency sweep. The hot film data also shows that, in the range of control frequencies explored, there are several local minima and areas of relatively flat frequency response. This leads to inconsistency in the extremum-seeking control action because it is difficult for it to navigate through these frequency ranges.
The behavior of the extremum-seeking controller is shown in Figure 4.28 and Figure 4.29. In these cases, the angle of attack is held at 18° and the Reynolds number is varied during the run from \( Re = 0.25 \times 10^6 \) to \( Re = 1.15 \times 10^6 \) and back. These changes occurred over a time period of 90 seconds, and this is determined by the responsiveness of the wind tunnel flow control system. It should be noted that separation control via boundary layer transition has not been observed at this angle of attack and a preferred frequency does exist in the sweep data (see Figure 4.18). These two figures correspond to two consecutive runs with the same controller parameters and flow conditions. The extremum-seeking controller is unable to produce repeatable results, presumably due to the limited sensitivity of the hot film at its present location. In both runs, at a time of approximately 350 seconds the controller loses control authority as a result of a spike in the actuation frequency. In Figure 4.29, the controller is able to navigate through this spike and ultimately settle upon the optimal forcing frequency, but in Figure 4.28 the controller continues forcing at a frequency which is too high. We postulate that if the hot film sensor used for closed-loop control could be placed closer to the stagnation line, the consistency of the controllers could be improved. This has been previously shown for simple on/off controllers with sensors located at \( x/c = 0.17\% \) (Poggie et al. 2010). In our experiments, this is not possible due to the location of the actuator recess, which is designed to provide adequate spacing between the hot films and electrodes to prevent equipment damage. If these fragile sensors were mounted on the dielectric even away from the electrodes they would be irrevocably damaged by physically changing the actuator. Despite the implementation issues with extremum-seeking control, it is
encouraging to see control authority at the $Re$ and $M$ conditions considered here, which represent the maximum capabilities of the employed wind tunnel.

Figure 4.28: Extremum-seeking control: $Re$ varied from $0.25 \times 10^6$ to $1.15 \times 10^6$ to $0.25 \times 10^6$, $\alpha = 18^\circ$.

Figure 4.29: Performance of extremum-seeking control during a different run using the same parameters as in Figure 4.28.
Several of the issues typically encountered in closed-loop flow control have been addressed in this work. However, several issues have been encountered in the process. The mean value of the hot film power dissipation slowly drifts to lower values over long periods of time at constant flow conditions as shown in Figure 4.30. The reason for this drift is unknown as it occurs regardless of whether the plasma is on or off and persists throughout the testing. This is especially problematic since the sensitivity of the hot film to $C_L$ changes at $x/c=11\%$ is quite small. Consequently, the threshold of the on/off controller had to be manually set for each control run, although the dead zone width could be retained constant. Due to the nature of the extremum-seeking control, the hot film drift did not have a significant effect on this controller.

Figure 4.30: Example of drift in Hot Film power dissipation value over time.
Another issue that occurs with the use of NS-DBD plasma actuators in closed-loop flow control is the presence of substantial electro-magnetic interference (EMI) created by the pulses. This phenomenon can be seen in Figure 4.31 as impulse-like spikes in the hot film time trace which are not due to any physical flow events. These EMI pulses correspond to each NS pulse used to produce plasma. These unphysical spikes are removed using a 12-point median filter in the time domain to minimize the effect on the hot film signal. An example of this is shown in Figure 4.31. This median filter was implemented within both closed-loop controllers studied in the work. Before any of the signal processing is performed, all cabling and connections are carefully shielded and multiple ferrites are employed to minimize the effect of the pulses, but the median filtering is still required to obtain suitable data for closed-loop control.
Figure 4.31: Hot Film unfiltered signal and median filter signal processing example.
Chapter 5: Conclusions and Future Work

This work presents our continued development and use of dielectric barrier discharge (DBD) plasma actuators driven by repetitive nanosecond pulses in high Reynolds number aerodynamic flow control. Leading edge separation control on an 8-inch chord NACA 0015 airfoil is demonstrated at various post-stall angles of attack ($\alpha$) for Reynolds numbers ($Re$) and Mach numbers ($M$) up to $1.15 \times 10^6$ and 0.26 respectively ($U_\infty = 93$ m/s). The control mechanism of the NS-DBD actuators is not momentum addition, unlike the case with AC-DBD plasmas. Instead, rapid localized heating of the fluid near the surface of the actuator is believed to provide the control effect. The signature of this localized heating is a compression wave that propagates into the flow with each pulse. Two control mechanisms are found, depending upon the $Re$ and $\alpha$. At low $Re$ ($0.25 \times 10^6$) and angles of attack just beyond stall, the NS-DBD actuator acts as an active boundary layer trip. At higher flow speeds ($Re = 1.15 \times 10^6$, $M = 0.26$) and angles of attack, the NS-DBD plasma actuator excites natural shear layer instabilities that develop into large coherent structures. These structures increase the momentum in the near-wall fluid by entraining high momentum fluid from the freestream. The efficacy of this control mechanism is dependent on the frequency of actuation with the best results obtained around $F^+ \approx 2$. A brief comparison with the more common AC-DBD plasma actuation is
presented to demonstrate the difference in control authority over a range of $Re$. The AC-DBD and NS-DBD actuators have similar control authority at $Re = 0.25 \times 10^6$. The NS-DBD actuator maintains very similar control authority up to the maximum $Re$ tested ($1.15 \times 10^6$), but the control authority of the AC-DBD plasma actuator decreases as $Re$ is increased with effectively zero control authority at or above $Re = 0.75 \times 10^6$.

NS-DBD plasma actuators are used in conjunction with surface-mounted constant voltage hot film anemometers in closed-loop on/off separation control. Two types of closed-loop control are demonstrated. On/off control uses the mean value of power dissipated by a hot film on the pressure side of the airfoil near the leading edge ($x/c = 11\%$). This serves as an input to the controller by sensing changes in the stagnation line location which correlate with $C_L$. The on/off controller is most useful at low $Re$ and moderate $\alpha$. In this case, the control mechanism is an active boundary layer trip. This logic allows the controller to turn off the plasma for periods of time where hysteresis effects keep the flow attached to the airfoil, thereby reducing power consumption. The on/off controller is also used in flow conditions where the excitation of flow instabilities is necessary (high $Re$, high $\alpha$). In this regime the actuator must remain on constantly to avoid high unsteady loading on the airfoil. Extremum-seeking control is used to optimize the forcing frequency of the actuator during dynamic variation of $Re$. In this preliminary work, the controller performance is not consistent, presumably due to sub-optimal hot film sensor location. The mixed success of the closed-loop controllers notwithstanding, several challenges typically associated with integration of DBD plasma actuators into a feedback control system have been overcome. The most important of these is the
demonstration of control authority at realistic takeoff and approach $Re$ and $M$. Many remaining challenges are currently being addressed.

There is still much work that can be done to expand the research presented here. Although some success was achieved with closed-loop control, this area still has significant room for improvement. Along with improving the controllers used in this work, more advanced methods of closed-loop control could be used along with optimization of sensing techniques and placement. The leading edge separation control can also be expanded to higher flow speeds. The only limitation to the speed at which control was obtained in this work was the limit of the facility used. If possible, testing should be done in a different facility that is capable of testing at speeds higher than the 93 m/s tested on the current airfoil.
References


