Aerodynamic Performance of a Biologically Inspired Hybrid
Plasma-Mechanical Flow Control and Sensing Device

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Aerodynamic Performance of a Biologically Inspired Hybrid Plasma-Mechanical Flow Control and Sensing Device

Joseph P. Dygert

Dissertation submitted to the
Benjamin Statler College of Engineering and Mineral Resources
at West Virginia University
in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy
in
Aerospace Engineering

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Morgantown, West Virginia
2022

Keywords: Dielectric Barrier Discharge, Compliant Electrode Discharge, Plasma Aerodynamics, Active Flow Control

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ABSTRACT

Aerodynamic Performance of a Biologically Inspired Hybrid Plasma-Mechanical Flow Control and Sensing Device

Joseph P. Dygert

The continued high global demand for passenger and freight air traffic along with increased use of unmanned aerial vehicles operating in broader Reynolds number regimes has resulted in researchers examining alternative technologies, which would result in safer, more reliable, and superior performing aircraft. Aerodynamic flow control may be one of the most promising approaches to solving this problem, having already proven its ability to enable higher flow efficiency while simultaneously improving overall control of flow behavior such as laminar-to-turbulent transition. Recent research in aerodynamic flow control has seen a pronounced growth in the areas of biomimicry and plasma flow control actuators. Plasma actuators offer an inexpensive and energy efficient method of flow control. In addition, plasma actuator technology has the potential to be applied to a host of other aircraft performance parameters including applications in radar cross section mitigation and in situ wing deicing. Biomimetic researchers have studied large scale mechanics and phenomena such as flapping mechanics, and wing morphology, as well as small scale factors such as feather fluttering and microscale feather geometry. The proliferation of interest in these fields laid the foundation and inspiration for the development of a novel aerodynamic flow control and sensing device known as the compliant electrode discharge device, commonly referred to by the inventors as “plasma feathers”.

This study consists of an investigation into the behavior of the compliant electrode device and its aerodynamic characteristics and performance during its flapping mode operation. Three models of varying aspect ratio were constructed, characterized through a modal analysis, and then subsequently tested for behavioral characteristic and aerodynamic performance. The behavioral testing shows that there is clearly defined range of pulsing ratios and duty cycle combinations that will likely result in desired behavior. The aerodynamic performance was investigated via two-dimensional two-component particle image velocimetry. It’s shown in tunnel-on testing that the device can favorably affect a low Reynolds number flow and potentially be used as an active airbrake in higher Reynolds number flows. Testing in quiescent air demonstrated that flows with velocities on the order of the speed of the tip of the compliant electrode can be induced in two momentum jets that are similar to the superposition of a traditional dielectric barrier discharges induced jet (horizontally oriented jet) and a synthetic jet’s induced jet (vertically oriented jet) overlayed upon one another allowing for a broad range of low Reynolds number applications.
Dedication

I would like to dedicate my doctoral work to my mother Shannon Sterling. From my earliest days she has always allowed and encouraged me to pursue my curiosities often at great financial cost to her when I would destroy refrigerators, televisions, radios, and any other household items that I wanted to learn the inner workings of. I’ve been fortunate to have a mother that so selflessly puts her children before herself, arguably the greatest factor contributing to the person I am today.
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“No man is an island entire to itself” – John Donne

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Nomenclature

Abbreviations

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<td>.csv</td>
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<td>Amperes</td>
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<td>alternating current</td>
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<td>dielectric barrier discharge</td>
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<td>CCD</td>
<td>charge coupled device</td>
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<tr>
<td>CED</td>
<td>compliant electrode discharge</td>
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<td>CTA</td>
<td>constant temperature anemometer</td>
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<td>direct current</td>
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<td>FFT</td>
<td>fast Fourier transform</td>
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<td>FLIR</td>
<td>forward looking infrared</td>
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<td>electrical ground</td>
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1.0 Background and Introduction

This chapter provides the reader the background and motivations leading to the conception of a newly developed flow control device with sensing abilities as well as a brief description of the device’s operating physics and potential capabilities. This chapter includes a literature review as part of the motivation for the development of the device and lastly it outlines the specific research objectives of this dissertation.

1.1 Problem Statement

Pronounced growth in the use of unmanned aerial systems (UASs) or unmanned aerial vehicles (UAVs) over the past few decades has been a significant driving factor in the aerodynamics community to research and develop new and novel forms of flow control in the low Reynolds number regime ($10^4$ – $10^5$). Flow control schemes can typically be divided into two classes: passive devices, which require no power consumption to control or alter the flow, and active devices, which use power to control or alter the flow. In the field of active flow control there have been two particular areas which have seen increasing levels of interest; the first is the area of plasma-aerodynamics or plasma flow-control systems, and the second is the area of biomimicry or biomimetic flow-control devices. The need for new and efficient flow control and aerodynamic performance enhancing devices along with the proliferation of study in these two areas has laid the motivation for the problem to be studied. *The broader problem under study is whether a system that has been developed by the author that combines aspects of both plasma flow control techniques and biomimicry into a single device, has favorable aerodynamic characteristics such as thrust generation and/or low Reynolds number flow control or favorable flow alteration. Put in a simpler manner, answer the question of whether the device can produce some aerodynamically beneficial outcome and potentially be useful as an aerodynamic device.*
1.2 Motivation for Device Development with Literature Review

Perhaps the single most pronounced trend in the aerospace engineering community in recent decades is the growth in the use of UAVs in many civilian and military sectors. The UAV application space in regard to UAV size is wide ranging from the use of large UAVs such as the well-known Global Hawk or Predator UAVs, and the area of small and miniaturized UASs or UAVs such as the RQ-7 Shadow or the CyberQuad Mini. This pronounced growth in the use of UAVs, and more specifically the large growth in the use of small to nano-sized UAVs (sometimes referred to as Micro Air Vehicles, or MAVs) has sparked a renewed interest in low Reynolds number aerodynamics. Small to medium sized UAV’s size, typically bird sized, and slow cruise speed compared to traditional aircraft place the majority of these vehicles’ operating regimes in a low Reynolds number range of $10^4$ – $10^5$ [1]. With these vehicles operating in low Reynolds number regimes, they are susceptible to a variety of “aerodynamic problems” including the presence of leading-edge separation of the boundary layer at high angles of attack, unfavorable laminar to turbulent transitions, instability from gusts and other unsteady flow phenomena.

This renewed interest in low Reynolds number aerodynamics spurred on by the market trends has prompted many researchers to develop many new, and revisit several old, low Reynolds number flow control techniques. One of the newer areas of low Reynolds number flow control is plasma actuation or plasma flow control devices. Two of the most commonly studied forms of plasma flow control are Corona Discharge and Dielectric Barrier Discharge (DBD). Corona discharge is a direct current (DC) or very low frequency alternating current (AC) powered electrical discharge, which typically takes place between a sharp or pointed electrode and a flat or plate electrode when energized to the proper electric potential. A DBD is an AC powered electrical discharge which occurs between two flat or plate electrodes with a dielectric barrier placed in the discharge region, when energized to the proper electric potential. The DBD device produces non-thermal equilibrium plasma ($T_e >> T_i \approx T_n$) and is an electrohydrodynamic (EHD) device with dominant electric fields and dominant electric field related forces, in contrast to a magnetohydrodynamic (MHD) device which has dominant magnetic fields and the associated magnetic
forces. Many researchers have focused studies on various aspects of the DBD devices because of their physical simplicity, quick response time, and plethora of optimizable variables, as well as the long list of possible applications. A simple schematic of a DBD can be seen in Figure 1.1 and Figure 1.2 with an image depicting the two modes of discharge commonly found in a DBD device, filamentary (stable) and non-filamentary or diffuse (unstable), as seen in Figure 1.3.
Researchers have studied effects of varying geometric properties such as dielectric thickness, electrode gap distance, electrode widths, etc., on the performance of a DBD device. Many researchers have also performed studies on the effects that electrical operating parameters have on DBDs, such as potential (voltage), frequency, slew rate, waveform, and pulsed versus non-pulsed operations. The other set of characteristics that have been thoroughly studied are the material properties of both the dielectric barrier such as dielectric constant, dielectric strength, reactivity, and the electrodes’ material properties such as conductivity (thermal and electrical), work function of the material, and brittleness [3, 4, 5, 2, 6]. The high number of variables with a near infinite number of design permutations, and operational settings, allows for the DBD to be optimized for particular applications, some of which are: ozone generation, sterilization processes, plasma assisted combustion, material processing, and various aerodynamic applications [7, 8, 9, 10, 11]. The use of multiple DBD devices has also been studied in actuator array configurations to study the effects of using several actuators together and their interaction on induced flows. Due to limitations on single DBD actuator size and unfavorable aerodynamic characteristics of typical DBD actuator arrays, many researchers have developed variations of the DBD to allow for greater aerodynamic-surface coverage, ultimately improving performance. Researchers have studied using multiple electrodes in various designs, one of which utilizes a third electrode (second exposed electrode) with a DC bias to create what has become
known as the sliding discharge device, a schematic of which is shown below in Figure 1.4. There have also been other modifications to the standard DBD design to in essence create a new discharge device such as replacing the dielectric layer with a resistive layer creating the resistive barrier discharge [12, 13, 14].

![Slide Discharge Device Schematic](image.png)

**Figure 1.4: Diagram of a sliding discharge actuator setup [15]**

Another area of low Reynolds number research that has in a sense come full circle, since it was the initial source of guidance that inspired humans to take flight, is that of avian flight mechanics. Many researchers have been studying numerous aspects of avian flight phenomena such as flapping mechanics and wing compliance/morphology, as well as small scale factors such as feather fluttering and microscale feather geometry [16, 17, 18, 19]. Researchers have shown that there are still many insights into the realm of flight to be gained from the study of avian biomimetics, as well as other biological fluid-structure interaction propulsion methods utilized by bats, insects, fish, and bacteria [20, 21, 22]. The study of biologically inspired fluid-structure interaction has also played a key role in the development of thin flexible energy harvesting devices that convert the kinetic energy of a flow into usable energy, usually via piezo-electric devices [23, 24].

### 1.3 Device Overview (with Continued Literature Review)

This section gives a brief overview of the inspiration for the device followed by an overview of general configuration, operating characteristics, and behavioral traits. This section also discusses some similarities
of the device under study with other flow control systems. The aerodynamics research areas discussed in the previous section, plasma actuators and biologically inspired flight mechanisms, were the inspiration of the flow control device developed by the author and discussed in this dissertation. The newly developed device, known as the compliant electrode discharge device, combines aspects and characteristics of both previously discussed flow control techniques. Some of the general concepts or characteristics observed of the previously discussed flow control techniques that were the inspiration for the development of the device were: 1) flapping/fluttering mechanisms for propulsive and/or flow control purposes, 2) other low Reynolds number flow control via periodic fluid-structure interactions, and 3) the customizability of the DBD device.

The compliant electrode discharge device utilizes a setup similar to that of a DBD device but with a flexible electrode that protrudes from the surface at a shallow angle (~20 – 25°) in replacement of the planarly oriented exposed electrode. Figure 1.5 gives a general illustration of the setup of a compliant electrode discharge (CED) device that has come to be more commonly referred to as “plasma feathers.” The region of the plasma discharge in the schematic is exaggerated in size for depiction.

![Figure 1.5: Schematic of compliant electrode discharge device (side view)](image)

The physical setup of the CED depicted in Figure 1.5 allows for the device to operate in two modes. The first mode is when a steady AC signal of sufficient potential is applied to the CED device which forces the compliant electrode to lay flat on its dielectric barrier and then behaves like that of a simple DBD device.
(i.e., DBD mode of operation) which can be seen below in Figure 1.6. Here the plasma-fluid interaction is the primary mechanism for flow alteration.

Figure 1.6: Flow visualization of DBD mode of the CED

The second mode, which is the primary focus of this study, is when a pulsed AC signal is applied to the electrodes which results in a periodic “flapping” motion of the compliant electrode (i.e., flapping mode). The compliant electrode is attracted through electrostatic forces to the lower electrode during the signal-on part of the pulsed AC signal and then released to return to its original position during the signal-off part of the pulsed AC signal. Pulsing the AC signal at appropriate frequencies and duty cycles can lead to the compliant electrode exhibiting a flapping like behavior resulting in flow field alteration. Figure 1.7 below shows a simple illustration of the motion that the CED makes during flapping mode operation. Although plasma is present on a portion of the underside of the compliant electrode throughout each flap cycle, the physical movement of the electrode (i.e, the fluid-structure interaction) is the primary mechanism for flow alteration.

Figure 1.7: Simple depiction of electrode’s flapping motion
The group of figures below, Figure 1.8 through Figure 1.11, show the formation of a vortex on the electrode’s upstroke and the vortexes subsequent shedding at the beginning of the downstroke of the compliant electrode motion.

- **Figure 1.8:** Vortex forming
- **Figure 1.9:** Vortex is growing in size
- **Figure 1.10:** Compliant electrode starts down stroke pushing out the vortex
In this mode, the device operates similarly to other active flow control methods that rely upon periodic forcing methods such as synthetic jets, dynamic roughness, pulsed plasma discharges, and acoustic streaming; although these all have different fundamental physical mechanisms for inducing momentum or altering flow, they are similar in the respect that they all are periodically forced, zero net mass-flux devices. Zero net mass-flux devices do not introduce (or remove) mass from the flow field unlike techniques such as boundary layer blowing and suction, yet all these devices alter the momentum of a flow. The synthetic jet operates by utilizing a diaphragm in a sealed cavity to draw in and eject working fluid into the flow, ultimately introducing momentum into the flow. Figure 1.12 depicts the typical setup of a synthetic jet. Dynamic roughness consists of small-scale time-dependent surface perturbations driven in an active manner. Acoustic streaming is the generic term for flows that are dominated by their fluctuating components and usually are driven by propagation of ultrasonic sound waves in a pulsed fashion. All these flow control techniques operate in a periodic forcing or pulsing styles, similar to the CED device, although the underling physics of how the induced momentum or flow control is achieved is different for each method [25, 26, 27].
The CED devices physical setup is similar to another fluid-structure interaction system studied by researchers which is the periodic forcing or fluttering motion of a cantilever beam near a wall and its interaction with the surrounding fluid. Some studies that were reviewed were interested in the fluid-structure interaction effects as well as possible induced thrust, while others were concerned with wall-fluid-beam system interactions. The majority of the experimental tests conducted were in water channels with the thin cantilever beam (representative of the compliant electrode) being driven by a shaker mechanism, with the utilization of particle image velocimetry (PIV) for data acquisition [28, 29, 30, 31]. However, in nearly all the studies performed so far, whether experimental or analytical, the researchers assumed that the transverse displacement of the beam was always less than the stand-off distance from the wall to ensure that the beam never contacted the wall, which is different than the physical set up of the CED where the compliant electrode can easily come fully in contact with the wall or surface. Researchers have studied forcing a thin cantilever beam with an applied electrostatic force and applied airflow, oriented from the free end towards the fixed end of the thin beam (anti-parallel to the proposed orientation for the compliant electrode discharge device), and measured beam behavior as a function of the applied electric and aerodynamic forces [32]. This setup of having a thin lamina or cantilever beam oscillating near a surface with a small standoff distance is also very similar to that of an atomic force microscope or a micro-electrical-mechanical cantilever flow detection device [33, 34]. Many of these studies are in some way fundamentally
related to understanding aspects of the CED due to physical and behavioral similarities, as well as provide insight into methods of studying the CED device (e.g., PIVs use in studying flapping cantilever beams and their fluid structure interaction)

An attribute of the CED that makes it conceptually novel, in addition to its ability to operate in two modes (flapping mode and DBD mode), is that it could potentially be used as a sensor through detecting changes in electrical properties of the circuit during flapping mode operations. The use of flow sensors integrated with flow control techniques to develop biologically inspired flight techniques has become another area of increased interest of study. Researchers have investigated using various types of biologically inspired flow sensors and techniques such as micro-electrical-mechanical system (MEMS) devices, typically piezoelectric based, that mimic hairs or flexible wings with angular springs used for sensing to be integrated into UASs [35, 36]. The potential for the CED device to operate as both a sensor and a flow controller offers the possibility to have a distributed array of them working together to mimic bird feathers in their ability to both sense and control air flow [37]. The devices sensing capabilities are discussed further in section 1.5 Device’s Sensing Capability.

1.4 Device Operating Physics (Driving Forces and Resulting Moments)

In this section and the subsections contained within, the driving forces which dictate the behavior of the compliant electrodes motion will be discussed individually and then their combined effect, or interplay on the electrode’s behavior is discussed. The motion of the compliant electrode is dictated by the dynamic interplay of three forces resulting in moments acting on the electrode. The three moments and the fundamental forces that dictate the compliant electrode’s behavior are 1) the compliant electrodes plate bending moment, a resultant of its flexural rigidity and deformation by the other moments, 2) the aerodynamic moment resulting from the dynamic pressure of the fluid flow impinging on the compliant electrode, and 3) the electrostatic force and resulting moment which arises from the electrical potential difference between the high voltage applied to the compliant electrode and the grounded base plate. The following subsections look at the three forces individually in closer detail to help the reader gain insight
into what is fundamentally influencing the behavior of the compliant electrode and ways to calculate or estimate the forces and moments involved.

### 1.4.1 Flexural Rigidity and Resulting Plate Bending Moment

The first force and resulting moment to discuss is the compliant electrodes flexural rigidity and its bending moment. When the compliant electrode is displaced from its neutral position (shallow angle of ~20° from dielectric barrier) the flexural rigidity of the electrode results in a bending moment in the electrode which wants to return it to its neutral position. Flexural rigidity is generically described as a structure’s resistance to bending with units of a moment, [N-m], for a thin plate. The bending moment acting at the clamped edge of a structure, like the physical setup of the compliant electrode, is a function of both the flexural rigidity of the structure and its displacement from its neutral position resulting from the other forces acting on the structure. Although the compliant electrode’s dimensions categorize it as a membrane, as shown in Figure 1.13, where \( a \) is the length of a side, \( t \) is the thickness, and the \( a/t \) ratio for the compliant electrode is in the range of several hundred to several thousand, however due to it possessing some rigidity, it is more correctly classified as a thin plate.

![Diagram of plate bending theory](image)

**Figure 1.13: Depiction of which theory is generally applicable based on side-to-thickness ratio [38]**

The typically defined difference between a thin plate and membrane is that a membrane cannot resist bending, hence its flexural rigidity is zero. The compliant electrode requires the use of a material and geometry that does allow for some flexural rigidity; thus, the compliant electrode is treated as a thin plate and not a membrane. Classical thin plate theory developed by Kirchhoff relies on several assumptions, one
of which is the deflection of the thin plate, \( w \), is on the order of a tenth of the plates thickness, \( t \), or smaller \((w<0.1t)\). The typical deflections of the compliant electrode occurring during the operation of the device are typically around three orders of magnitude greater than the electrodes thickness, thus the bending moment acting on the clamped edge of the compliant electrode as a result of a deflection and the flexural rigidity, cannot be analytically calculated using classical thin plate theory. The theory for large deflections of thin plates was developed by Von Karmen and includes non-linearities in the stresses and strains due to nonlinear geometry of the deformed plate. This large deflection theory is generally assumed to be applicable for deflections on the order of the thickness of the plate or smaller \((w\leq t)\) [39]. The compliant electrode’s thickness is typically on the order of 0.001” and experiences a displacement typically around a few tenths of an inch which results in the displacement to thickness ratio lying outside of the applicable range of even the large deflection theory of thin plates. The large deflections of the compliant electrode occurring during device operations negates the applicability of typical analytical solutions for the compliant electrodes bending moment. Taking this into account along with the additional consideration that there will be deviations from the ideal case for any manufactured CED or model (e.g., for the models used in this study the electrodes have had a surface applique attached to a portion of the upper surface to reduce compliant electrode twist) further complicating determining the bending moment. The author suggests that if the bending moment is needed that it can be estimated through a mixture of computational modeling via programs such as ANSYS and/or experimental testing.

### 1.4.2 Aerodynamic Force and Resulting Moment

The aerodynamic forces and their resulting moment are the simplest to estimate which can be done through analytical calculation for an ideal case where the compliant electrode does not deform and remains straight and only rotates about its clamped edge. In the ideal case the aerodynamic force is just the drag force, a consequence of the dynamic pressure, \( q \), impinging on the frontal cross-sectional area, \( A \), of the compliant electrode. The equations shown below, Equation 1.1 and Equation 1.2 are for the dynamic pressure and cross-sectional area respectively; where \( \rho \) is the air density, \( U \) is the free stream velocity, \( W \) and \( L \) are the
width and length of compliant electrode respectively, and \(\theta\) is the angle of inclination of the compliant electrode from the base plate.

\[
q = \frac{\rho U^2}{2}
\]

Equation 1.1

\[
A = WL \sin \theta
\]

Equation 1.2

The dynamic pressure multiplied by the frontal cross-sectional area multiplied by the 3-D drag coefficient, \(C_D\), is the aerodynamic force acting on the compliant electrode which can be seen in Equation 1.3 below.

\[
F_{aero} = C_D q A = \frac{C_D \rho U^2 WL \sin \theta}{2}
\]

Equation 1.3

The moment that is created about the clamped edge due to the aerodynamic force is the aerodynamic force multiplied by the moment arm length which is half the length of the compliant electrode since the aerodynamic force ideally acts uniformly over the entire electrode. The resulting aerodynamic moment is shown below in Equation 1.4.

\[
M_{aero} = \frac{C_D \rho U^2 WL^2 \sin \theta}{4}
\]

Equation 1.4

This is useful for getting an approximation of the aerodynamic moment acting on the compliant electrode but there are many deviations from the ideal case that make this somewhat impractical. Some examples of the deviations that would affect the aerodynamic moment would be flow circulation occurring below the compliant electrode between the compliant electrode’s lower surface and the dielectric barrier’s upper surface, in the plasma formation region; suction over the upper surface by Bernoulli principle; and deformation of the compliant electrode throughout a flapping cycle. In addition to these deviations the drag coefficient, \(C_D\), would need to be experimentally determined. The motion of the compliant electrode from the interplay of the electrode’s bending moment from its flexural rigidity and the aerodynamic moment
from the impinging flow, is a problem well-suited for fluid structure interaction (FSI) computational studies to be done in the future. Studying various geometric and material variables and their impact on the electrode’s behavior will be an important field of study for the further development of the CED device and can be performed using FSI studies. Before meaningful FSI studies can be performed more studies need to be performed to gather detailed information on how the electrostatic force and its resulting moment affect the compliant electrode’s behavior in a wide range of variable settings so that the electrostatic moment can be used as an input forcing function into FSI models.

1.4.3 Electrostatic Force and Resulting Moment

The electrostatic force between two charged parallel plates is a common analytical introductory physics problem. This problem is also easily solved analytically for inclinations of one of the plates if the angle of inclination is kept small enough that the mathematical small approximation formulas still reside within acceptable error and the fringing field lines remain negligible compared to the overall field. It is suggested by B.R. Patla that small angle approximations are only acceptable for inclinations up to $10^{-2}$ radians or about less than a degree [40]. In a series of papers written by Y. Xiang devoted to the analytical description of inclined plate capacitors at arbitrary angles, the force acting on the inclined plate of an inclined plate capacitor is derived via three successive different conformal mappings to various coordinate planes. The three successive mappings more specifically are 1) simple mapping of the form shown in Equation 1.5, 2) a fractional linear transformation, and 3) a Schwarz-Crystoffel transformation.

$$t = Mz^\pi + M_0$$  \hspace{1cm} \text{Equation 1.5}$$

The successive conformal mappings essentially deform the electrodes and the space between them until they are equal in length and parallel resulting in the traditional parallel plate solution in the new coordinate space. The derived solution shown in Equation 1.6 is for the component of the force acting in the normal direction to the inclined plate which would be the contributing component to the electrostatic moment. The
solution relies on the calculation of the complete elliptic integral of the first kind, $K(k)$, which would need to be calculated numerically for the physical setup. The negative sign in the equation below indicates that the force is attractive towards the other plate and $\tau_1$ and $\tau_2$ are geometric quantities related to the original dimensions of the plates. [41]

$$ F_{elect} = -\frac{\pi^2 \varepsilon_0 V^2}{8 \theta \sin \theta K^2 (k)} (\tau_1 \cos \theta + \tau_2) $$

Equation 1.6

The necessity to numerically calculate the complete elliptic integral of the first kind for this geometric setup along with the following two considerations it is recommended to computationally simulate the electrostatic moment if it is needed to be determined by itself. The other two considerations for reasoning to resort to computer simulation is 1) the moment arm associated with the force to calculate the electrostatic moment would be mathematically intensive to calculate due to the force not being uniformly distributed over the entire compliant electrode, it being a function of inclination angle, and having to apply the three conformal mappings in reverse, and 2) the derivation of the electrostatic force is for a single continuous dielectric (i.e., vacuum) and would get significantly more complex for the inclusion of the glass barrier along with air present between the plates. These considerations lead to the best route for estimating the electrostatic moment via utilizing computational simulation software such as ANSYS Maxwell or ANSYS AIM.

### 1.4.4 Interplay of the Three Forces

There are three limiting cases for how the compliant electrode will behave depending on the magnitude of the three forces and their moments. First is in the limit that the rigidity of the beam is sufficient to dominate over the imposed aerodynamic and electrostatic forces. In this limit, the beam will tend to be stationary in its starting position and the electrostatic and aerodynamic forces will affect it negligibly. The second limiting case is when the aerodynamic force is dominant over the applied electrostatic force and more importantly the rigidity of the electrode. In this case, the electrode would be forced to be essentially flat along the boundary surface and could be operated in traditional DBD mode but not flapping mode. The
other limiting case is when the electrostatic force applied is dominant. If the signal applied is continuous the electrode will lay flat and operate like a traditional DBD and if the signal is appropriately pulsed it will result in the sought after periodic “flapping” behavior. It has been reported in the literature of other driven fluttering devices that when the driving force, in this case the electrostatic force, and the aerodynamic forces are of the same order of magnitude a periodic, quasi-chaotic behavior of the beam is often induced [32, 42]. If the electrostatic force is the strongest when applied and the desired flapping behavior is achieved, then the three forces involved, and their resulting moments all have significantly different magnitudes throughout a single flapping cycle of the compliant electrode. The plate bending moment can generically be referred to as the restoring force as it is always acting against the aerodynamic moment and electrostatic moment to return the electrode back to its neutral position. During the flap cycle as the electrode is pushed down by the aerodynamic moment and pulled down by the electrostatic moment, the bending moment increases due to its displacement from its neutral position, the aerodynamic moment decreases due to the decreasing cross-sectional area of the compliant electrode, and the electrostatic moment increases as the average separation of the highly charged compliant electrode and the grounded base plate becomes smaller. Figure 1.14 illustrates the flapping cycle and describes what is happening with each moment/force at that position in the flap cycle.
Figure 1.14: Diagram depicting the changing moments acting on the electrode throughout a flap cycle

1.5 Device’s Sensing Capability

The CED possesses a novel attribute in the potential ability for the device to be used as both a flow control device and sensing device. The potential for the CED to be a sensing device is derived from monitoring changes in the electrical circuits operating parameters due to changes in the flapping behavior from flow impinging on the device. As the compliant electrode passes through a flap cycle the capacitance of the device changes as the geometry changes which can be monitored. If flow is impinging on the device, then it will behave differently and its change in capacitance will be different from a flap cycle with no flow. It may also be possible for the device to be integrated with machine learning techniques to “learn” how certain
flow conditions correspond to specific changes in the capacitance ultimately allowing for an array of CED devices to work together similar to the feathers of a bird being used to simultaneously sense and control the flow. [37] When the device’s sensing capabilities were first being explored, electrical current monitoring was being investigated and then later a method to monitor the devices capacitance was implemented. Monitoring the device’s capacitance via charge-voltage (Q-V) cyclograms, also known as Lissajous diagrams, offers the most useful data for sensing capabilities but both methods will be discussed. The current monitoring method was the first method employed and was originally being employed as an attempt to monitor the devices power consumption. Electrical current was monitored directly using a current probe known as a Rogowski coil in conjunction with an oscilloscope, both of which are discussed in more detail in section 2.3 Data Acquisition Devices, while pulses of air were blown onto an operating CED model. It can be seen from Figure 1.15 that during an external gust event which forced the compliant electrode to behave differently (i.e., forced the electrode to lay flat on the dielectric barrier) the electrical current amplitude was changed as well, which is outlined by the red circle in Figure 1.15.

Figure 1.15: Change in the electrical current amplitude circled in red during a gust event
This change in current is measurable and usable as an indicator that an external wind gust has forced the electrode to change its flapping behavior. For the test performed from which the data for the above figure was collected the device was operating in quiescent air and experienced a gust of over 12 m/s. This specific prototype has a max effective flow speed at around 10 m/s, meaning that any flow speeds higher result in the compliant electrode being forced completely flat onto the dielectric barriers surface like operating in traditional DBD mode. The electrical current monitoring method has limited ability due to low signal-to-noise ratio inherent in these capacitive plasma devices. This limitation often leads to researchers relying on Q-V cyclograms to determine power consumption of these devices. A Q-V cyclogram is easily generated by installing an in-series capacitor on the grounded side of the actuator and monitoring the voltage drop across the capacitor. While implementing this method to monitor power consumption, which will be discussed in full detail in section 3.2.1 Powered Device Behavioral Analysis Methodology and Setup, of the powered device behavioral analysis, it was found to offer considerably more sensitivity to the position of the compliant electrode with less noise than the current monitoring method and thus offered improved sensing capabilities. This sensitivity can be seen in Figure 1.16: Growth in voltage amplitude on monitoring capacitor through half a flap cycle Figure 1.16, depicting the voltage amplitude on the monitor capacitor rising as the height of the compliant electrode decreases as it goes through the downward stroke of its flap cycle.

![Figure 1.16: Growth in voltage amplitude on monitoring capacitor through half a flap cycle](image)
This change in monitoring capacitor voltage as the compliant electrode travels downward through its flap cycle can be used to gain information on the state of the compliant electrode and essentially the flow. Due to this increase in the monitoring capacitor’s voltage from the changing geometry and thus changing capacitance of the device, the Q-V cyclogram of the CED rotates counterclockwise, giving another parameter to use in the development of the device’s sensing capabilities (e.g., rate of change of capacitance). Figure 1.17 below shows how the device’s Lissajous curves (an elongated ellipse) rotate counterclockwise during a flap cycle.

![Q-V Lissajous curve rotating counterclockwise through progression of a flap cycle](image)

The potential for the sensing capability of the device cannot be understated: the entire process whereby highly aerobatic natural flyers (e.g., pigeons in a formation flying through a complex bridge undergirding) begins with the flyer being equipped with a sensing skin able to detect local changes to air flow (for a bird this happens as each feather’s base wiggles on the bird’s skin) and rapidly respond to such detected events. You can vary the compliant electrodes geometry to “tune” it to operate in different flow speeds. This tuning process would also have been taken into consideration when developing the sensing aspects as the electrical characteristics would vary for different geometries and at different flow speeds.
1.6 Objectives

The overall goal of the study is to investigate the aerodynamic efficacy of a newly developed biomimetic flow control and sensing device by investigating the device’s operational behaviors and aerodynamic performance. The investigation of the device’s efficacy will be accomplished by achieving the following four objectives:

1. Measure the behavior of the compliant electrode as a function of electrode geometry and forcing signal.
2. Measure momentum changes and inspect flow pattern alteration in low Reynolds number flow.
3. Measure the speed of induced flow and inspect the flow pattern from the device while operating in quiescent conditions.
4. Calculate turbulent kinetic energy (tke) in low Reynolds number testing and quiescent testing.

Figure 1.18: Diagram of the fundamental elements used to comprise the motivation behind the development of the compliant electrode discharge device - "plasma feathers"
2.0 Model and Equipment

During the development of the CED device it was determined that the device can operate in two modes, discussed earlier in section 1.3 Device Overview (with Continued Literature Review), which are potentially useful for aerodynamic flow control. The first mode is the CED device’s ability to operate as a traditional DBD when a continuous AC signal of sufficient voltage to force the compliant electrode to lay flat on the dielectric barrier is applied between the compliant electrode and ground electrode. The second mode, the topic of focus for this study, is its “flapping mode” where the CED device is driven by applying a pulsed AC electrical signal to the compliant electrode and its ground electrode. The technical work undertaken was directed towards developing an understanding of the influence of electrical operating settings and electrode geometry on flapping behavior and aerodynamic flow control. The technical work is broken into three phases 1) modal analysis of the models, 2) powered device behavioral analysis, and 3) aerodynamic analysis. The modal analysis and the powered device behavioral analysis were aimed at understanding the electrical operating characteristics of the device in its flapping mode and how they correlate to mechanical behavior as well as finding an operational setting known as a treatment that is well behaved and thus favorable for aerodynamic analysis. This was accomplished using high frequency electrical probes, optical sensors, and MATLAB® analysis of high-speed video of the device operating. The aerodynamic testing was performed via flow measurement and visualization using particle image velocimetry (PIV) carried out in the Joseph Dygert Eifel-Type Variable Test-Section Geometry Benchtop Wind Tunnel at West Virginia University (WVU). The Variable Test-Section Wind Tunnel was designed and constructed specifically for the technical work carried out in this study. The design and construction of the tunnel is discussed in detail in Appendix A: Smoke Tunnel Design, Construction, and Qualification. The following subsections discuss in detail the models, the test stand, the model powering system, and the data acquisition devices used for the technical work performed in the Modal Analysis, Powered Device Behavioral Analysis, and the Aerodynamic Analysis.
2.1 Model and Testing Stand

For the technical work conducted three models of varying width were constructed and tested. The three models can be seen below in Figure 2.1 and Figure 2.2, resting on a wooden block.

![Figure 2.1: The three models used for testing resting on a wooden block (frontal view)](image)

A model comprises of a piece of copper foil for the ground plate, two pieces of glass, a piece of steel shim stock for the compliant electrode, Kapton polyimide tape, and two wires (one for ground and the other for high voltage). First the copper foil is sandwiched between two pieces of glass (one of which acts as the dielectric barrier) with its edges wrapped in Kapton polyimide tape to help prevent electrical arcing around the edges which has been previously studied by the researcher at WVU [43]. A piece of 0.001 in-thick steel
shim stock which acts as the compliant electrode was placed above the barrier glass plate and is slightly curved so that it raises from the surface of the glass dielectric barrier creating a shallow angle (~15° – 25°) from the dielectric surface. The radius of curvature of the steel shim stock used for the models was predetermined by packaging method of rolling the steel shim stock into tubes. The material properties of the compliant electrode are density (ρ=0.28 lb/in³), modulus of elasticity (E=29x10⁶ psi), and Poisson’s ratio (ν=0.29). The compliant electrode was secured to the dielectric surface along its leading edge with Kapton polyimide tape. Lastly a separate wire was attached to each electrode, the ground plate and compliant electrode, to be used as connections for the ground and high voltage lead wires, respectively. It was later found during several attempted runs of the behavioral testing that to limit twisting and other undesirable deformation of the compliant electrode, a thin compliant applique needed to be added to the upper surface of the electrode. Through several trial-and-error tests with various materials and application methods it was determined that using double-sided adhesive strips to attach a piece of card stock to a portion of the upper surface provided a simple and effective solution.

All three variations of the model have the same length of 1.25 inches from inflection point (clamped edge) to tip of electrode and three different widths were made corresponding to aspect ratios of 0.66, 1, and 2, defined below in Equation 2.1.

$$AR = \frac{W}{L} = \frac{\text{spanwise direction}}{\text{streamwise direction}}$$  \hspace{1cm} \text{Equation 2.1}

These three variations in width, or aspect ratio, where chosen to give a spectrum of geometric planform ranging from “narrow” corresponding to aspect ratio of 0.66, perfectly square corresponding to aspect ratio of 1, and “wide” corresponding to aspect ratio of 2. The definition of the aspect ratio for aeronautical/aerospace engineers may at first seem like the reciprocal for the typical definition due to the traditional definition for square wing planforms being length over width (chord) but the definition was chosen to keep the definition the same in respect to orientation to the flow (i.e., the definition in both cases is spanwise direction over streamwise direction). The nominal dimensions used for the design phase as well
as the measured dimensional values after construction of the compliant electrode for each model are shown below in Table 2.1.

<table>
<thead>
<tr>
<th>Compliant Electrode Nominal Values</th>
<th>Measured Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (in)</td>
<td>Width (in)</td>
</tr>
<tr>
<td>1.25</td>
<td>0.825</td>
</tr>
<tr>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>1.25</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The cardstock applied to the upper surface was 0.75” in length, spanned the entire width of each of the three models and was placed so that their edge was 0.125” from the trailing edge of the compliant electrode (i.e., the free edge of the compliant electrode). The models are mounted in an adjustable width test stand to secure the models for the Modal testing and Powered Device Behavioral testing; the stand also acts as the test-section of the variable width test-section smoke tunnel. The adjustable width test stand constructed for the technical work was composed of two pieces of acrylic sheet for the side walls, with several simple features milled into them as shown in Figure 2.3, and four acrylic spacer or support posts for the four corners along with machine screws and washers for mounting the posts to the acrylic sidewalls. There are three sets of acrylic posts that match the width of the compliant electrode which allows for the adjustment of the width of the test stand.
Figure 2.3: Schematic of milled-out acrylic side walls of test stand for model (all dimensions are in inches)

On the side walls there are four holes drilled through the acrylic plates in the corners to insert the screws to hold the support posts. Both sidewalls have 3.25” long, 0.20” tall, and 0.10” deep pockets milled into them to allow for the edges of the model to sit in. One version of the side walls constructed has a 3.25” by 2.25” shallow pocket milled on the same side as the long-slit pocket for a location to place the optical sensor used in the behavioral testing. Figure 2.4 shows a depiction of the test stand assembled with a model present in the stand. The milled groove for mounting the optical distance sensor is not shown in Figure 2.4. The fully assembled model and test stand with the attached diffuser-entrance section and foam seals to enable use in the smoke tunnel can be seen in Figure 2.5.

Figure 2.4: Drawing of model in the test stand (milled groove on one side wall is not shown for clarity)
2.2 Model Powering System

The model powering system used to provide the pulsed AC signal to the model is comprised of a waveform/signal generator, an audio amplifier, and a step-up transformer. The waveform generator used for the experimental work was a BK Precision 4054 function/arbitrary wave generator which was used to generate the pulsed sine-wave signal which was fed to a Crown XTi 4002 audio power amplifier (3200 W bridged mono output) to increase the power of the signal. The signal generator and amplifier can be seen in Figure 2.6. The signal is then sent into the primary coil of the transformer to step-up the voltage to the necessary operating conditions. A custom high voltage step-up transformer with a turn ratio of 1:140 was purchased from Corona Magnetics and can be seen in Figure 2.7. A schematic of the system used for powering the CED device is shown in Figure 2.8.
Figure 2.6: Signal generator and amplifier

Figure 2.7: High voltage step-up transformer in its custom-built cooling stand
2.3 Data Acquisition Devices

This section discusses the data acquisition devices used in all the various testing. The electrical and mechanical characteristics of the CED device were monitored and recorded utilizing a series of electrical probes and optical measurement devices in conjunction with each other. The circuit driving voltage was measured using a BK Precision PR-55 AC/DC high voltage oscilloscope probe (10 KV, 50 MHz bandwidth) in conjunction with a Rigol DS1074z digital storage oscilloscope (70 MHz bandwidth 1 GSa/s sampling frequency). The electrical current was monitored with an inductive device known as a Rogowski coil which is used for measuring high frequency current and commonly used in electrical characterization of plasma discharge devices. The specific Rogowski coil used for this work was a Pearson Current Monitor Model Number 2877 (1 V to 1 A output) which was used in conjunction with the oscilloscope as well. For purposes of calculating power which will be discussed in further detail in the methodology section a capacitor was introduced into the circuit in series with the CED device. The voltage on this capacitor was monitored via a low voltage probe connected to the oscilloscope. The low voltage probe used was a BK Precision PR150B (1x or 10x 150 MHz bandwidth) oscilloscope probe. Mechanical behavior of the compliant electrode was measured using two optical devices: a photoelectronic distance sensor and a high-speed camera. The photoelectronic distance sensor used was a Wenglor OPT2001 High Performance Distance Sensor with a distance reading range of 30 – 80 mm with a resolution of approximately 8 µm.
with a (4 mA/0 V – 20 mA/10 V) response over the 50 mm working range. The distance sensor signal was also read through the Rigol oscilloscope. The high voltage probe, Rogowski coil, distance sensor, and low voltage probe can be seen in Figure 2.9 and the oscilloscope the four sensors were used with can be seen in Figure 2.10. The camera used to monitor the compliant electrodes behavior was an Edgertronic SC1 high-speed camera shown in Figure 2.11.

Figure 2.9: A) High voltage probe; B) Rogowski coil (with high voltage line through coil); C) Distance sensor; D) Low voltage probe

Figure 2.10: 4-channel digital storage oscilloscope
The flow visualization and measurement of the aerodynamic testing was carried out using a LaVision FlowMaster particle image velocimetry (PIV) system. The PIV system comprises four major components: the seeder, the illuminator, the camera(s), and the computer. The seeder used was a LaVision pneumatic atomizer, capable of generating aerosolized oil droplets of appropriate size range for use in air, which reflect light from the illumination source. Typical oils used in this system are diethylhexyl sebacate (DEHS) and olive oil. For the experiments presented, the selected seeding material was olive oil. The seeder can be seen below in Figure 2.12.
The illumination system used for the PIV is a Litron Nano T180-15 dual-pulsed Nd:YAG 1200 mJ laser which emits at a wavelength of 532 nm (green). Figure 2.13 below shows the main components of the illumination system including the laser, the cooling tower, and the blue laser guide arm.

![Figure 2.13: A) Litron nano laser; B) laser cooling tower; C) laser guide arm](image)

Because the aerodynamic testing described in this paper was largely 2-D in nature, a planar PIV arrangement requiring only a single camera was used. The specific camera used was a LaVision Imager Pro X 4M which has 14-bit depth and 4 MP resolution. The camera, which can be seen below in Figure 2.14, was equipped with a Nikon AF Nikkor 50 mm f/1.8D lens and a 532 nm filter was added to the front of the lens to reduce undesired excitation of the camera’s CCD by anything other than reflected light from the illumination laser. All tests were run with the camera’s aperture, focus, and, most importantly, its position relative to the model (thus also relative to the wind tunnel) constant to ensure that images taken from separate tests maintained an identical optical and geometric reference frame.
The computer used to control the entire imaging system and to compute the resultant flow fields is a custom-built LaVision system operating on a standard Windows OS. LaVision’s DaVis 8.0 imaging and processing software provided all the primary algorithms required to generate the resultant planar velocity flow fields for each individual test case, the most important of which was a multistep cross correlation algorithm, discussed in further detail in the methodology section of the Aerodynamic testing.
3.0 Methodology and Results

In the previous chapter, Chapter 2, the model and all the equipment used in testing was discussed in detail. This chapter, Chapter 3, will cover in detail the experimental setup and methodology for each of the three testing phases and their results. The testing was completed in three phases in which the results of a phase are inputs for the following phase. The first phase, modal analysis, is used to determine the fundamental frequency of each of the three compliant electrode models which is used to construct the driving electrical signal used in the second phase. The second phase looks at the behavior of the compliant electrode for a variety of inputs signals for each of the three model variations. The results of the powered behavioral testing of the CED are a set of experimental inputs (i.e., a treatment) that is well behaved and thus well suited for aerodynamic testing, which is the third phase of testing. The results from the aerodynamic testing will be answers to the objectives stated section 1.6 Objectives. Figure 3.1 depicts the flow chart for testing and the results from which phase feed into the next.

Figure 3.1: Experimental testing flow chart
3.1 Modal Analysis

Experimental modal analysis was performed to determine the fundamental or modal frequency of the first vibrational mode of each of the three compliant electrode configurations. The modal frequency is then used to calculate a pulsing frequency of the driving signal to be applied to each device in further testing of the electrical and mechanical behavior of the device and during the aerodynamic testing.

3.1.1 Modal Analysis Methodology and Setup

The modal testing of each electrode was performed by mounting each model into the test stand and physically striking the compliant electrode, subsequently measuring its movement via the Wenglor optical distance sensor while it freely vibrated until its motion ceased. The wide model mounted in the test stand with the optical distance sensor present can be seen below in Figure 3.2. The process of striking the compliant electrode and measuring its vibration was carried out for a total of three trials for each of the three configurations (i.e., nine total trials). MATLAB® was then used to perform a Fast-Fourier-Transform (FFT) of the recorded signal from the distance sensor to plot the transformed signal in the frequency domain and find the modal frequency of each configuration. The modal frequency, $f_{modal}$ is rounded to the nearest hundredth of a Hertz for use in developing the pulsed signals for powering the CED based on the fundamental frequency. The pulsing frequencies, $f_{pulse}$, of the pulsed driving signals are calculated using Equation 3.1 below and from selecting frequency ratios, $R_f$, that wish to be tested.

$$f_{pulse} = (R_f)(f_{modal})$$  

Equation 3.1

Once the pulsing frequency of the signal(s) are determined the signal can be constructed in the signal generator by programming in signals with the chosen base AC signal frequency (1000 Hz was used for all experiments in this study), the proper pulse frequency, and the selected duty cycles. Every unique combination of a pulsing frequency and duty cycle chosen for testing is a unique signal based on the model’s...
modal frequency. The constructed signals are the output of this phase of testing and are used in the second phase of testing described in the Powered Device Behavior Methodology section.

![Modal Testing Image](image.png)

**Figure 3.2: Wide model in testing stand during modal testing (model is not powered)**

The methodology of the modal testing is summarized as:

1) Mount model in test stand
2) Strike model while recording data with distance sensor
3) Repeat step 2 until three trials are completed
4) Repeat steps 1 through 3 for all three models
5) Fast Fourier Transform and graph data
6) Identify modal frequencies
7) Use modal frequencies, pulse ratios, and duty cycles to construct driving signals
3.1.2 Modal Analysis Results

As can be seen below, Figure 3.3, Figure 3.4, and Figure 3.5 show the transformed results of the distance sensor signal for the three trials for each of the three configurations. The fundamental frequency can be identified by observing the peak in each of the FFT figures below and identifying the corresponding frequency on the x-axis. Table 3.1 shows the tabulated data for each trial including the modal frequency and the difference in frequency between the peak (modal frequency) and the closest frequency bins on the left and right.

![Figure 3.3: FFT results of wide electrode](image)
Figure 3.4: FFT results of square electrode

Figure 3.5: FFT results of narrow electrode
The modal frequencies identified for the wide, square, and narrow compliant electrode configurations are 15.00 Hz, 17.27 Hz, and 16.36 Hz respectively. The pulsing frequencies, $f_{pulse}$ are calculated using Equation 3.1 and from selecting frequency ratios, $f_{ratio}$ both above and below 1 (i.e., pulsing frequencies will be both above and below the modal frequency). The chosen frequency ratios to be tested were 0.5, 0.75, 1, and 1.25; the resulting pulsing frequencies (rounded to the nearest tenth of a Hertz) for each model configuration is shown in Table 3.2 below.

### Table 3.1 Data of all 9 trials of the modal testing

<table>
<thead>
<tr>
<th>CED Aspect Ratio</th>
<th>Trial</th>
<th>Modal Frequency (Hz)</th>
<th>Bin to the left (-Hz)</th>
<th>Bin to the right (+Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR= 2 (Wide compliant electrode)</td>
<td>1</td>
<td>15.00</td>
<td>0.2175</td>
<td>0.1596</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>15.00</td>
<td>0.164</td>
<td>0.0853</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>15.00</td>
<td>0.1843</td>
<td>0.0906</td>
</tr>
<tr>
<td>AR= 1 (Square compliant electrode)</td>
<td>1</td>
<td>17.27</td>
<td>0.0991</td>
<td>0.2191</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>17.27</td>
<td>0.1255</td>
<td>0.2393</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>17.27</td>
<td>0.0996</td>
<td>0.2</td>
</tr>
<tr>
<td>AR=.66 (Narrow compliant electrode)</td>
<td>1</td>
<td>16.36</td>
<td>0.2255</td>
<td>0.2014</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>16.36</td>
<td>0.18</td>
<td>0.1675</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>16.36</td>
<td>0.203</td>
<td>0.191</td>
</tr>
</tbody>
</table>

The set of 12 pulsing frequencies are then multiplied by the chosen duty cycles of 33%, 50%, and 66% to give the 36 unique treatments to be tested in the powered behavioral testing discussed in the next section.

### Table 3.2 Table of pulsing frequencies for each modal frequency and pulsing frequency combination

<table>
<thead>
<tr>
<th>CED</th>
<th>Modal frequency (Hz)</th>
<th>$f_{ratio}$ of 0.5</th>
<th>$f_{ratio}$ of 0.75</th>
<th>$f_{ratio}$ of 1.0</th>
<th>$f_{ratio}$ of 1.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>15.00</td>
<td>7.50</td>
<td>11.25</td>
<td>15.00</td>
<td>18.75</td>
</tr>
<tr>
<td>Square</td>
<td>17.27</td>
<td>8.64</td>
<td>12.95</td>
<td>17.27</td>
<td>21.59</td>
</tr>
<tr>
<td>Narrow</td>
<td>16.36</td>
<td>8.18</td>
<td>12.27</td>
<td>16.36</td>
<td>20.45</td>
</tr>
</tbody>
</table>
3.2 Powered Device Behavioral Analysis

Powered device behavioral analysis was performed to investigate the influence of driving signal characteristics and geometric differences on the behavior of the compliant electrode. More specifically the objective of this phase of testing was to identify a set of input signals that allowed for continuous operation of the CED device in a steady state flapping operation with no undesired behavior exhibited by the compliant electrode (e.g., not flapping, unsteady flapping, etc.).

3.2.1 Powered Device Behavioral Analysis Methodology and Setup

For the powered device behavioral testing each model was mounted in the test stand and operated for a few seconds at each of the models 12 driving signal settings (four different pulsing ratios based on the fundamental frequency of the model and three different duty cycles) while having operational data collected. The behavioral testing was performed twice (i.e., two trials) to investigate and ensure repeatability of the devices operating behavior under the same input conditions with different operational conditions (i.e., a different day with different atmospheric conditions). The test matrix used for the powered device behavioral testing can be seen in Table 3.3. The columns labeled “Trial 1” and “Trial 2”, were used to write the name of the data file saved on the oscilloscope (e.g., File1, File2, File3, etc.) which contained all the measured electrical characteristics and the optical distance sensor data.
Table 3.3: Testing matrix for powered device behavioral testing

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Frequency ratio</th>
<th>Duty Cycle</th>
<th>Driving signal file</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>wide</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.5</td>
<td>Frequency ratio</td>
<td>33 duty cycle</td>
<td>SDG000</td>
</tr>
<tr>
<td>.5</td>
<td>Frequency ratio</td>
<td>50 duty cycle</td>
<td>SDG001</td>
</tr>
<tr>
<td>.5</td>
<td>Frequency ratio</td>
<td>66 duty cycle</td>
<td>SDG002</td>
</tr>
<tr>
<td>.75</td>
<td>Frequency ratio</td>
<td>33 duty cycle</td>
<td>SDG003</td>
</tr>
<tr>
<td>.75</td>
<td>Frequency ratio</td>
<td>50 duty cycle</td>
<td>SDG004</td>
</tr>
<tr>
<td>.75</td>
<td>Frequency ratio</td>
<td>66 duty cycle</td>
<td>SDG005</td>
</tr>
<tr>
<td>1</td>
<td>Frequency ratio</td>
<td>33 duty cycle</td>
<td>SDG006</td>
</tr>
<tr>
<td>1</td>
<td>Frequency ratio</td>
<td>50 duty cycle</td>
<td>SDG007</td>
</tr>
<tr>
<td>1</td>
<td>Frequency ratio</td>
<td>66 duty cycle</td>
<td>SDG008</td>
</tr>
<tr>
<td>1.25</td>
<td>Frequency ratio</td>
<td>33 duty cycle</td>
<td>SDG009</td>
</tr>
<tr>
<td>1.25</td>
<td>Frequency ratio</td>
<td>50 duty cycle</td>
<td>SDG010</td>
</tr>
<tr>
<td>1.25</td>
<td>Frequency ratio</td>
<td>66 duty cycle</td>
<td>SDG011</td>
</tr>
<tr>
<td><strong>square</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.5</td>
<td>Frequency ratio</td>
<td>33 duty cycle</td>
<td>SDG012</td>
</tr>
<tr>
<td>.5</td>
<td>Frequency ratio</td>
<td>50 duty cycle</td>
<td>SDG013</td>
</tr>
<tr>
<td>.5</td>
<td>Frequency ratio</td>
<td>66 duty cycle</td>
<td>SDG014</td>
</tr>
<tr>
<td>.75</td>
<td>Frequency ratio</td>
<td>33 duty cycle</td>
<td>SDG015</td>
</tr>
<tr>
<td>.75</td>
<td>Frequency ratio</td>
<td>50 duty cycle</td>
<td>SDG016</td>
</tr>
<tr>
<td>.75</td>
<td>Frequency ratio</td>
<td>66 duty cycle</td>
<td>SDG017</td>
</tr>
<tr>
<td>1</td>
<td>Frequency ratio</td>
<td>33 duty cycle</td>
<td>SDG018</td>
</tr>
<tr>
<td>1</td>
<td>Frequency ratio</td>
<td>50 duty cycle</td>
<td>SDG019</td>
</tr>
<tr>
<td>1</td>
<td>Frequency ratio</td>
<td>66 duty cycle</td>
<td>SDG020</td>
</tr>
<tr>
<td>1.25</td>
<td>Frequency ratio</td>
<td>33 duty cycle</td>
<td>SDG021</td>
</tr>
<tr>
<td>1.25</td>
<td>Frequency ratio</td>
<td>50 duty cycle</td>
<td>SDG022</td>
</tr>
<tr>
<td>1.25</td>
<td>Frequency ratio</td>
<td>66 duty cycle</td>
<td>SDG023</td>
</tr>
<tr>
<td><strong>narrow</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.5</td>
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During operation of each of the 12 signal settings, for all three models, the compliant electrodes motion was captured via the Wenglor optical distance sensor and high-speed video via the Edgertronic HS camera,
while its electrical characteristics were simultaneously monitored via the High voltage probe, low voltage probe on the in-line capacitor, and the Rogowski coil all connected to the Rigol oscilloscope for measurement capture and storage. The Edgertronic HS camera was operated using a standard laptop with an ethernet port and cable. The testing setup can be seen below in Figure 3.6 and Figure 3.7 shows the setup from the top view.

Figure 3.6: Testing setup for powered device behavioral analysis
Figure 3.7: Top view of testing setup for powered device behavioral analysis

A diagram depicting the configuration of the electrical probes and optical devices is shown below in Figure 3.8. It’s important to note that the device and all probes were grounded to the same electrical mains ground. It’s also important to note that all probes must be grounded at the same location on the ground wire. Failure to do so can potentially lead to electrical ground-looping.

Figure 3.8: Schematic of data acquisition setup for behavioral testing
The properties of the CED that were monitored were electrical current, driving voltage input, voltage over the in-line capacitor, height of the electrode at the location of the optical distance sensor, and high-speed video. With the raw data collected the results were processed to glean more information from the measurements. Using MATLAB®, the high-speed video was converted to black and white and then analyzed to determine the velocity of the tip of the compliant electrode during operation, as well as percent stroke of a flap, and type of behavior from graphed tip behavior versus time over several flapping cycles. The high-speed video and graphed data from the optical distance sensor provided the best results for investigating the steadiness or the lack of steady operation of the CED during a single treatment. The current was reported as both its raw value and its smoothed or filtered value. Due to the nature of the electrical discharges of the plasma, and the timescales on which they occur being orders of magnitude smaller than the time scale of a single flap of the CED, the current measurement is full of noise and not very useful for analysis beyond determining the compliant electrodes behavior relative to the time of pulse of current (e.g., at what point during the pulse does the electrode reach its max height or reach its max deflection).

The task of monitoring the power of capacitive discharges accurately for small lab bench-scale devices used in flow control such as the traditional DBD and the newly developed CED, has been an area of great interest and research by the academic community due to both its fundamental importance and difficulty in practical application. There are three methods that have been traditionally employed in the plasma aerodynamics community for power measurement of DBD devices which are the shunt resistor method, Rogowski coil method, and the monitoring capacitor method. Each method has its draw backs; however, the monitoring capacitor method has become the most popular due to its ability to provide more data about the nature of the discharge device and the plasma discharge itself such as capacitance of the device without electrical discharge occurring and capacitance when plasma is present. For this work the monitoring capacitor method was employed after several attempts using the Rogowski coil method failed, resulting in wildly sporadic results with no repeatability. This was likely due to the fast time scales of the electrical discharges carrying a large amount of current which if not fully captured via the data acquisition system would lead to errors in
integration of the product of the driving voltage and current used to calculate power in the Rogowski coil method. In the monitoring capacitor method employed for this work, a capacitor with capacitance several orders of magnitude greater than the capacitance of the CED device was placed in series with the CED and had the voltage drop across it monitored via the low voltage probe. The monitoring capacitor’s capacitance must be several orders of magnitude higher than the device’s to keep the equivalent circuit’s capacitance unchanged, as can be seen from Equation 3.2, and thus not significantly alter the current flowing through the CED.

\[
\frac{1}{C_{eq}} = \frac{1}{C_{device}} + \frac{1}{C_{monitor}}
\]

Equation 3.2

Since the capacitance of the CED device was unknown a review of literature was performed to find the capacitances of DBD devices of comparable size and construction. It was found from literature that capacitances for discharge devices of the bench scale size typically were in the $10^9 – 10^{10}$ Farad range and according to Peeters and Buttersworth a typical monitoring capacitor should have a capacitance in the range of 100 to 10,000 times larger than the discharge device being tested [44]. The monitoring capacitor that was selected and used in all the testing had a capacitance of 220 nF. The charge flowing through the capacitor at any time can then be calculated from Equation 3.3.

\[
Q(t)_{monitor} = (C_{monitor})(V(t)_{monitor})
\]

Equation 3.3

With charge known and the voltage measured via the high voltage probe the charge can be plotted versus the driving voltage to get a charge-voltage (Q-V) cyclogram, commonly referred to as a Lissajous diagram in the literature. An ideal Q-V cyclogram can be seen below in where the red portions of the cyclogram indicates plasma off portions of the AC cycle and the green represents the plasma on portions of the AC cycle. The slope of the red lines is equivalent to the capacitance of the device without plasma present and slopes of the green lines are equivalent to the capacitance of the device with plasma present.
Taking the derivative of Equation 3.3, knowing that the derivative of charge with respect to time is current, and inserting it into the well-known power is the product of voltage and current equation results in Equation 3.4.

\[ P(t) = V(t)i(t) = V(t)(C_{monitor}) \frac{dV(t)_{monitor}}{dt} \]  

Equation 3.4

The time averaged power over a single AC cycle can be found by integrating Equation 3.4 over one AC cycle of period, \( T \), and using the charge relationship from Equation 3.3 again, resulting in Equation 3.5.

\[ \bar{P} = \frac{1}{T} \int_0^T V(t)(C_{monitor}) \frac{dV(t)_{monitor}}{dt} \, dt = \frac{1}{T} \int_0^T V(t) \, dQ(t) \]  

Equation 3.5

It can be seen from Equation 3.5 that the average power dissipated in a full AC cycle is directly proportional to the area enclosed by the Q-V cyclogram with the constant of proportionality being the frequency of the driving AC signal. The power can then finally be found by numerically integrating the enclosed area of the cyclogram and multiplying by driving signal frequency in radians per second. The calculation of the enclosed area of the cyclograms were performed numerically using MATLAB®’s built in Boundary...
function. The *Boundary* function in MATLAB® takes a set of matched \( x \) and \( y \) locations as inputs as well as a shrink factor from 0 to 1 and then calculates the area encompassed by the \( x \) and \( y \) locations and the shrink factor. A shrink factor of 0 gives the convex hull based on the points and a shrink factor of 1 returns the most compacted area defined by the points. A shrink factor of 0.5, the default setting for MATLAB®, was chosen for all work performed after investigating other shrink factors. In the MATLAB® script the area for each AC cycle over an entire pulse is calculated using the *Boundary* function and then averaged over the number of AC cycles to get an average power over one flap cycle of the compliant electrode. The MATLAB® code used for analysis of the collected oscilloscope data (i.e., driving voltage, current, monitoring capacitor voltage, and distance sensor signal) and the high-speed video is in Appendix B: MATLAB® Codes.

In addition to calculating the percent stroke of a flap of the compliant electrode, calculating the average power use over a flap cycle, and reporting the raw and filtered electrical data, the high-speed video graphs and optical distance sensor graphs were visually inspected for each treatment to classify the behavior and for comparison between Trial 1 and Trial 2 for repeatability. Behavior could generally be broken into three distinct categories; vibrating (temporally symmetric low amplitude tip displacement – percent stroke typically less than 30%), oscillating (temporally symmetric medium amplitude tip displacement – percent stroke typically between 30%-60%), and flapping (non-temporally symmetric and large amplitude tip displacement – percent stroke typically above 60%). Figure 3.10 depicts a representation of the graphs of the CED’s trailing edge tip height for each type of general behavior classification. The results of the powered device behavioral testing are presented in the next section as well as the treatment that was chosen for further aerodynamic study in the smoke tunnel.
The methodology of the behavioral testing can be summarized as:

1) Mount model in test stand
2) Power model with signal 1 of 12 for each model
3) Record electrical and video data
4) Change signal to next signal to best tested
5) Record electrical and video data
6) Repeat steps 4 and 5 for all signals
7) Process electrical data and video data to get electrical parameters and identify behavior of each treatment
8) Down select a treatment that is stable and provides desired behavior for aerodynamic testing

### 3.2.2 Powered Device Behavioral Analysis Results

In this section first a table summarizing the results for the testing of all 36 treatments is presented followed by an in depth look at the graphed data for the treatment that was selected for further study in the
aerodynamic testing. The full set of graphs for each treatment is included in Appendix E: Full Results of Electrical and Mechanical Behavior of CED Device Tests. Table 3.4 shows a summary of all the results of the 36 treatments tested in the powered device behavioral testing. The columns labeled Vrms and Irms are the root mean square of the input voltage and the measured current, post filtering by a moving average filter with a window size of 13, respectively. The mean power is the average of the area enclosed in the cyclograms of the input voltage and the monitoring voltage, post filtering by a moving average filter with a window size of 13, over one entire pulse (i.e., an entire pulse is both AC signal on and off portions of a signal pulse). The column labeled Percent stroke is calculated using Equation 3.6 and is highlighted green if the value is the same for both days of trials and highlighted yellow if off by only 2% or less indicating repeatable behavior.

\[
\%\text{stroke} = 100 \left( \frac{\text{Max trailing tip height} - \text{Min trailing tip height}}{\text{Max trailing tip height}} \right)
\]

Equation 3.6

The behaviors V, O, and F stand for vibrate, oscillate, and flap, respectively. In the behavior column the code US stands for unsteady behavior, code HB stands for harmonic behavior, and “to F” means transitioning to flapping, all three of which are undesirable behaviors. Unsteady behavior is a non-repeating behavior, harmonic behavior is the existence of repeated behaviors over timescales longer than a single applied pulse duration, and the vibrating transitioning to flapping behavior is characterized by low amplitude displacement with some temporal asymmetry. Examples of the CEDs’ trailing edge tip height graph for harmonic behavior, unsteady behavior, and vibrating transitioning to flapping, can be seen in Figure 3.11.
Figure 3.11: Examples of unsteady behavior, harmonic behavior, and the vibrating transitioning to flapping behavior.
## Table 3.4: Full behavioral testing results

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<th>Vrms (kV)</th>
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<td>34%</td>
<td>V</td>
<td>3.58</td>
<td>1.11</td>
<td>0.58</td>
<td>30%</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>50</td>
<td>3.61</td>
<td>1.16</td>
<td>0.96</td>
<td>39%</td>
<td>V</td>
<td>3.59</td>
<td>1.24</td>
<td>0.89</td>
<td>33%</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>66</td>
<td>3.60</td>
<td>1.13</td>
<td>1.43</td>
<td>82%</td>
<td>V (US)</td>
<td>3.60</td>
<td>1.15</td>
<td>1.36</td>
<td>41%</td>
<td>V</td>
<td></td>
</tr>
</tbody>
</table>

52
Examining Table 3.4, it can be difficult to identify any trends and draw meaningful conclusions, so the data was condensed and rearranged into Table 3.5. If either day of the behavioral testing exhibited unsteady behavior or harmonic behavior it was noted in Table 3.5 as the observed behavior (i.e., if day 1 had oscillate, and day two had oscillate unsteady, it was condensed into the table as oscillate unsteady). Any treatment that results in unsteady behavior, harmonic behavior, or vibrating behavior was shaded red to indicate that it was either unable to be studied using the PIV system or its displacement was so low it would likely have little effect on the flow. Treatments where the exhibited behavior was classified as oscillating was shaded yellow due to there being large enough displacements to affect the flow but no temporal asymmetry in behavior. Behavior classified as flapping was highlighted in green to indicate a potentially suitable treatment for further aerodynamic study.

**Table 3.5: Condensed behavioral testing results**

<table>
<thead>
<tr>
<th>Frequency Ratio</th>
<th>Duty Cycle (%)</th>
<th>Wide</th>
<th>Square</th>
<th>Narrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>33</td>
<td>oscillate (harmonic behavior)</td>
<td>oscillate (harmonic behavior)</td>
<td>oscillate (unsteady-harmonic behavior)</td>
</tr>
<tr>
<td>0.5</td>
<td>50</td>
<td>vibrate (transitioning to flap)</td>
<td>vibrate (transitioning to flap)</td>
<td>flapping</td>
</tr>
<tr>
<td>0.5</td>
<td>66</td>
<td>vibrate (transitioning to flap)</td>
<td>flapping</td>
<td>flapping</td>
</tr>
<tr>
<td>0.75</td>
<td>33</td>
<td>oscillate</td>
<td>flapping</td>
<td>flpping</td>
</tr>
<tr>
<td>0.75</td>
<td>50</td>
<td>flapping</td>
<td>flapping</td>
<td>flapping</td>
</tr>
<tr>
<td>0.75</td>
<td>66</td>
<td>flapping</td>
<td>flapping</td>
<td>flapping</td>
</tr>
<tr>
<td>1</td>
<td>33</td>
<td>oscillate</td>
<td>oscillate</td>
<td>oscillate (unsteady)</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>oscillate</td>
<td>oscillate</td>
<td>oscillate (unsteady)</td>
</tr>
<tr>
<td>1</td>
<td>66</td>
<td>oscillate</td>
<td>oscillate</td>
<td>flapping (unsteady)</td>
</tr>
<tr>
<td>1.25</td>
<td>33</td>
<td>vibrate</td>
<td>vibrate</td>
<td>vibrate</td>
</tr>
<tr>
<td>1.25</td>
<td>50</td>
<td>vibrate</td>
<td>vibrate</td>
<td>vibrate</td>
</tr>
<tr>
<td>1.25</td>
<td>66</td>
<td>vibrate</td>
<td>vibrate</td>
<td>vibrate (unsteady)</td>
</tr>
</tbody>
</table>

The signal that was chosen for further study due to it resulting in steady behavior in all trials across all three models as well as exhibiting flapping behavior was the signal of pulsing ratio 0.75 and duty cycle of 66%. The treatment consisting of pulsing ratio 0.75 and duty cycle of 50% also exhibited these behaviors but the treatment with 66% duty cycle was chosen for further aerodynamic study due to the temporal asymmetry...
in the pulse signal with a 66% duty cycle. Figure 3.12 below depicts all the highspeed video data collected on the first day of testing for the wide model operated at the chosen treatment for further aerodynamic study. The “Height” subplot is depicting the vertical location of the tip of the trailing edge of the compliant electrode; the “Area” subplot is depicting the value for the cross-sectional area underneath the compliant electrode; the “Area/Height” subplot depicts the ratio between the cross-sectional area and the tip height; and lastly the “Velocity” subplot depicts the speed of the tip of the trailing edge of the electrode.

As discussed in the behavioral methodology section, graphing the compliant electrode’s trailing-edge tip height can be used to identify the behavior of the CED (e.g., vibrating, oscillating, flapping) and other related quantities such as percent stroke or qualities such as temporal asymmetry. Graphing the cross-sectional area allows for easy quantification of how close the compliant electrode comes to lying completely flat on the dielectric barrier while graphing the ratio of the cross-sectional area to height (i.e., Area/Height) gives insight to the convexity or concavity of the compliant electrode and its deformation throughout a
flapping cycle. The velocity of the tip is important due to it playing an important role in dictating the amount of momentum and energy being imparted on the flow. Figure 3.13 below depicts all the electrical data collected for the wide model during the first day of testing at the chosen operational treatment for further aerodynamic testing. The “V” subplot is the input voltage or driving voltage; the “I” subplot is the raw measured current colored in blue and the filtered current colored in orange; the “P” subplot is the instantaneous power colored in blue, calculated as the product of the input voltage and raw measure current, and the filtered power colored in orange calculated as the product of the input voltage and the filtered current; lastly the “Vm” and “height” subplot are the voltage measured across the monitoring capacitor colored in blue and the height of the electrode as measured by the laser interferometer. Figure 3.14 is a zoomed in look at the driving voltage waveform to show more detail to the reader. The raw input voltage data was used for calculating the root mean square of the voltage over a single on-phase of a single pulse. Figure 3.15 is a zoomed in look at the current waveforms. Figure 3.16 is a zoomed-in look at the power waveforms. Figure 3.17 is a zoomed-in look at the voltage on the monitoring capacitor and the compliant electrode height waveforms. The height waveform is smoothed via a moving average filter with a window size of 29 to eliminate noise in the form of electrical interference in the signal from the plasma ignitions.
Figure 3.13: Electrical data for wide model: pulsing ratio (0.75) and duty cycle (66%)

Figure 3.14: Zoomed in view of the measured input voltage waveform
Figure 3.15: Zoomed in view of the measured current waveform and the filtered current waveform

Figure 3.16: Zoomed in view of instantaneous power and filtered instantaneous power
Figure 3.17: Zoomed in view of measured voltage across monitoring capacitor and measured height from laser interferometer

Figure 3.14 through Figure 3.17 were included to give the reader a more granular look at the data measured and used for calculations for this specific treatment. Zoomed in versions of the graphs for every treatment are not presented in Appendix E: Full Results of Electrical and Mechanical Behavior of CED Device Tests, just the full subplots of the video data, the electrical data, and optical distance sensor data. The height data measured by the laser interferometer was transformed via FFT and plotted along with a black vertical line at the pulsing frequency, the frequency at which the compliant electrode is being driven. Figure 3.18 below depicts the transformed height data for the wide model on the first day of testing at the chosen treatment for further study. Figure 3.19 is a plot of the Q-V cyclogram of the entire recorded data set (i.e., multiple sets of rotating Lissajous from each pulse overlayed on each other). The high-speed video and electrical subplots along with the FFT plot and Q-V cyclogram are the four graphs that are provided for each day of testing for all 36 treatments in Appendix E: Full Results of Electrical and Mechanical Behavior of CED Device Tests.
Figure 3.18: FFT of interferometer reading for wide model: pulsing ratio (0.75) and duty cycle (66%)

Figure 3.19: Q-V cyclogram for wide model: pulsing ratio (0.75) and duty cycle (66%)
Figure 3.20 through Figure 3.23 are the graphs for the square model on the first day of testing, operating at the selected treatment for further aerodynamic study, consisting of the high-speed video data subplots, the electrical data sublots, the FFT of the interferometer data, and the Q-V cyclograms, respectively.

Figure 3.20: High speed video data for square model: pulsing ratio (0.75) and duty cycle (66%)
Figure 3.21: Electrical data for square model: pulsing ratio (0.75) and duty cycle (66%)

Figure 3.22: FFT of interferometer reading for square model: pulsing ratio (0.75) and duty cycle (66%)
As can be seen above by comparing the wide model’s results to the square model’s results, the behaviors and results are similar. Both models display similar behavior, both models have similar compliant electrode tip speed, and both fluctuate at frequencies just barely above the driving frequency, trending toward the modal frequency. The most pronounced difference between the two cases is the extent to which the Q-V diagram extends into the negative Q and positive Q directions (i.e., the total rotation of the cyclogram is less pronounced for the square electrode in comparison to the wide electrode). This is indicative of a greater change in capacitance for the wide model than the square model during a flap cycle as the electrode approaches the dielectric barrier which is intuitive based in capacitance being a function of total capacitor area.

Figure 3.24 through Figure 3.27 are the graphs for the narrow model on the first day of testing, operating at the selected treatment for further aerodynamic study, consisting of the high-speed video data subplots, the electrical data sublots, the FFT of the interferometer data, and the Q-V cyclograms, respectively.
Figure 3.24: High speed video data for narrow model: pulsing ratio (0.75) and duty cycle (66%)
Figure 3.25: Electrical data for narrow model: pulsing ratio (0.75) and duty cycle (66%)

Figure 3.26: FFT of interferometer reading for narrow model: pulsing ratio (0.75) and duty cycle (66%)
As can be seen from comparing the graphical data for all three models the behavior of the narrow electrode is similar to the other two; however, one can see the continued trend of a less pronounced rotation of the Q-V cyclogram for the narrow model. One can also see by comparing all three models’ FFT diagrams that the narrow model appears to behave slightly different regarding its fluctuating frequency, Figure 3.26 shows the frequency spike occurring at a slightly lower frequency than the driving frequency unlike the wide and square models. Even considering these slight apparent differences the models behaved similarly and thus the signal of pulsing ratio 0.75 and duty cycle 66% for each model is down selected to study further in the following section.

### 3.3 Aerodynamic Testing (Two-Dimensional Two-Component PIV)

The aerodynamic testing was done to gain further insight into the flow field characteristics while the device is operating in a driven flow (i.e., flow alteration or flow control investigation) and while the device is operating in quiescent air (i.e., thrust production investigation). Every step was taken to keep the wind
tunnel symmetric along the midline to allow for two-dimensional flow so that two-dimensional two-component particle image velocimetry (PIV) could be used to study the flow fields.

3.3.1 Aerodynamic Testing Results

The wind tunnel used for the aerodynamic experimental work was a small low-speed flow visualization tunnel that was specifically designed and constructed for this work. The test section width is variable to allow for the testing of various compliant electrode aspect ratios. The side walls of the diffusion section are hinged to allow for expansion or contraction of the diffusion angle to meet the width of the test section. There were three modular contraction sections designed and built for the testing corresponding to the three different aspect ratios of the compliant electrode. Each contraction section has the same nominal height, the same nominal contraction ratio of eight, and were all designed utilizing the same fifth order polynomial that was studied by Bell and Mehta [45]. With the models installed in the tunnel test section the blockage is approximately 10.7% (±3%), details on the blockage calculation can be found in Appendix C: Wind Tunnel Blockage Analysis. More on the design, construction, and qualification testing of the wind tunnel can be found in Appendix A: Smoke Tunnel Design, Construction, and Qualification. The wind tunnel setup with the inlet for the wide model, without the test section present, can be seen below in Figure 3.28 and in Figure 3.29 the test section is present with a model mounted for testing.

Figure 3.28: Wind tunnel setup for two-dimensional two-component PIV testing with wide inlet (test section is removed)
During the aerodynamic testing two-dimensional (i.e., \(x\) and \(y\) plane) two-component (i.e., \(x\)-axis component of velocity \(y\)-axis component of velocity) was gathered via the PIV system, while the input voltage and voltage drop across the monitoring capacitor were visually monitored to ensure consistent operational behavior during all portions of the aerodynamic testing where the device was powered on. Figure 3.30 below shows a schematic of the data acquisition setup for the aerodynamic testing. The laser plane from the PIV arm was oriented as a parallel plane with the test section side walls and positioned at the center of the test section to enforce symmetry and minimize any out of plane motion.
Figure 3.31 below shows the control center setup consisting of the computer for controlling the PIV system, the oscilloscope for monitoring the CED, and the signal generator inside the black faraday cage power stand.

![Figure 3.31: Control center setup](image.png)

For the aerodynamic testing each model had several sets of data collected. First a set of 100 resolved flow fields (equating to 200 actual dual-pulsed images collected) were captured with the tunnel on and no model present in the tunnel to get a baseline of flow behavior in the tunnel and check that all models are being tested at as close to a similar flow speed as achievable. Next the model was placed into the tunnel while leaving it running and then collecting another set of 100 flow fields with the tunnel on and the model in an unpowered setting. Next the model was turned on and powered by the driving signal selected from the powered device behavioral testing. In the tunnel on and model powered setting, a series of 100 flow fields were generated for each position in the flapping cycle, and a final averaging step was used to generate a time-averaged mean flow field for each flap position. This was repeated through a whole flapping cycle for a total of 11 instances of capturing 100 flow fields in 10 evenly temporally distributed locations with the first and 11\textsuperscript{th} capture sequence representing the same position in the flapping cycle. Next the tunnel was turned off, the voltage was increased to induce flapping behavior and the process of collecting another 11 sets of 100 flow fields at 10 evenly temporally spaced locations through the flap cycle to look at flow induced by the device in quiescent settings. This entire process was performed for all three models. At the
beginning of every test the room temperature and humidity were recorded along with the time difference between each of the two individual images per a flow field reported as $dt$. The appropriate $dt$ for the tunnel on testing and tunnel off testing were both determined using a mix of running the DaVis software’s $dt$ Optimizer that provides an optimized $dt$ based on input of desired pixel travel length and trial-error testing through a wide range of $dt$ settings and visually comparing the results. It was determined that for the tunnel on setting a $dt$ equal to 80 µs was preferred and for the tunnel off (i.e., quiescent testing) it was determined the best $dt$ was 500 µs. For each of the instantaneous flow field captures described, an initial three-step process was used to determine the most likely velocity vectors in the flow field through application of two 64 x 64-pixel square interrogation window cross-correlations with 50% overlap followed by a subsequent 32-pixel diameter circular interrogation window cross-correlations with 50% overlap. Aside from the standard cross-correlation, the only other subroutines employed to modify the statistically derived flow field vectors were the software’s image correction feature and high accuracy mode for the final pass. These settings in the Davis 8.0 software can be seen in Figure 3.32 below.

![Figure 3.32: PIV analysis settings on Davis 8.0](image)

It can also be seen from Figure 3.32 that a geometric mask was used to prevent the software from using any data from the area where the model baseplate rests inside the tunnel side walls, and flow does not actually occur. This masked area is outlined in red in Figure 3.33 below.
Once the cross-correlation algorithm was run on every set of collected images and produced a likely instantaneous flow field, the set of 100 flow fields collected for each setting were averaged together to create a time averaged flow field. The instantaneous velocity fields and time averaged velocity fields for each setting are exported as a “.dat” file and the data is stored in 4 columns in the form of “u” and “v” velocity components at sets of “x” and “y” locations covering the entire interrogation window seen in Figure 3.33 excluding the masked area. A MATLAB® code that can be found in Appendix B: MATLAB® Codes, was written to perform control volume analysis of all the time averaged flow fields collected and use the instantaneous flow fields to calculate turbulent kinetic energy in the flow. The following pages consist of a look at the conservation of mass, momentum, and energy equations for control volumes that come from the Reynolds Transport Theorem followed by a look at Turbulent Kinetic Energy. These fundamental theoretical equations were the basis for the MATLAB® code written to analyze the PIV data and the following pages show how each fundamental equation was modified with assumptions to apply to this setup and put into form for use in MATLAB® coding.
Conservation of Mass equations for Control Volumes

Conservation of mass is the principle that the time rate of change of mass in a control volume (CV) is equivalent to the mass flux across the CV boundary (i.e., control surface (CS)).

\[
0 = \frac{d}{dt} \left( \int_{CV} \rho dV \right) + \int_{CS} \rho (\vec{U} \cdot \hat{n}) dA \tag{3.7}
\]

Observing the chosen CV which can be seen below in Figure 3.34, it makes practical sense to break the CS up into four domains: the inlet, outlet, top, and base. The base is also a nonpermeable wall so there are no velocity components across its boundary meaning it can be neglected from the integral domain, leaving Equation 3.8 seen below.

![Figure 3.34: Illustration of the control volume and the control surface (gray box)](image)

\[
0 = \frac{d}{dt} \left( \int_{CV} \rho dV \right) + \int_{inlet} \rho (\vec{U} \cdot \hat{n}) dA + \int_{top} \rho (\vec{U} \cdot \hat{n}) dA + \int_{outlet} \rho (\vec{U} \cdot \hat{n}) dA \tag{3.8}
\]

For the inlet the normal vector and positive $x$-direction are parallel, so the dot product of the normal and velocity vectors simplifies to the scalar value of the $u$-component of the velocity. For the top the normal
vector and positive $y$-direction are parallel, so the dot product of the normal and velocity vectors simplifies to the scalar value of the $v$-component of the velocity. For the outlet the normal vector is anti-parallel to the positive $x$-direction, so the dot product reduces to the negative of the scalar value of the $u$-component. This may seem counterintuitive as the goal is to maintain that all outward oriented flow despite which boundary or surface is crossed is denoted as positive flow but with the flow being oriented in negative $x$-direction this will result in outward positive flow on all surfaces (e.g., $u$-components along the outlet boundary exiting the surface are parallel to the outward normal and are negative due to being in the negative $x$-direction, requiring another negative to result in positive outward flow). We are also assuming 2-D and it can be seen from Figure 3.34 that the inlet and outlet are aligned in the $y$-direction so the differential, $dA$, can be replaced with $dy$. Similarly, for the top $dA$ can be replaced with $dx$. This leads to

$$0 = \frac{d}{dt} \left( \int_{CV} \rho dV \right) + \int_{\text{inlet}} \rho(u) dy + \int_{\text{top}} \rho(v) dx - \int_{\text{outlet}} \rho(u) dy$$

Equation 3.9

There is also no net build up or decrease in fluid within the CV at any instant (i.e., density is constant) thus the first term can be neglected leaving Equation 3.10 below.

$$0 = \int_{\text{inlet}} \rho(u) dy + \int_{\text{top}} \rho(v) dx - \int_{\text{outlet}} \rho(u) dy$$

Equation 3.10

From Equation 3.10 it can see that theoretically the mass flux across the boundaries at every point during the flap cycle should be zero. Any departure from zero contains within it the same errors before of the errors associated with any non-planar flow, velocity vector estimation errors in the PIV process, and numerical integration and calculation errors. The departure from true conservation of mass gives us a quantitative bound on the potential accuracy of the results of the conservation of momentum and energy analysis discussed next (i.e., is the induced momentum and energy from the CED greater than the cumulative errors that can be quantified from departure from mass conservation). The mass flux across all boundaries and the
total mass flux deviation from continuity were graphed at each position in a flap cycle for all tests with the model operating for all models.

**Conservation of Momentum Equations for Control Volumes**

The principle of conservation of momentum can be written as the sum of the forces on the CV are equivalent to the summation of both the time rate of change of momentum in the CV and the momentum flux across the CS. In equation form this is written as Equation 3.11.

\[
\sum F = \frac{d}{dt} \left( \int_{CV} \rho \vec{U} dV \right) + \int_{CS} \rho \vec{U} (\vec{U} \cdot \hat{n}) dA \\
\text{Equation 3.11}
\]

Of interest is the average forces acting during one flap cycle which can be found by taking the average of both sides of the equation and then splitting the right-hand side of the equation into two averages.

\[
\left\langle \sum F \right\rangle_{avg} = \left\langle \frac{d}{dt} \left( \int_{CV} \rho \vec{U} dV \right) \right\rangle_{avg} + \left\langle \int_{CS} \rho \vec{U} (\vec{U} \cdot \hat{n}) dA \right\rangle_{avg} \\
\text{Equation 3.12}
\]

It is assumed that the flapping motion is periodic and that each flap is similar. This allows us to assume that no momentum from one flap cycle is stored within the control volume into the next flap cycle. This allows for the time derivative term to be neglected. This is confirmed by Shinde and Arakeri who showed in a similar flapping experiment that the momentum stored within a control volume surrounding a flapping device changes with time and oscillates around a zero mean [46]. To study the cycle averaged forces involved we are left with Equation 3.13

\[
\left\langle \sum F \right\rangle_{avg} = \left\langle \int_{CS} \rho \vec{U} (\vec{U} \cdot \hat{n}) dA \right\rangle_{avg} \\
\text{Equation 3.13}
\]

Using the same CV, which was used for the conservation of mass derivation so once again the CS can be broken up into three domains: the inlet, outlet, and top, leaving us with Equation 3.14.
\[
\langle \sum F \rangle_{avg} = \langle \int_{inlet} \rho \vec{U} (\vec{U} \cdot \hat{n}) dA + \int_{top} \rho \vec{U} (\vec{U} \cdot \hat{n}) dA + \int_{outlet} \rho \vec{U} (\vec{U} \cdot \hat{n}) dA \rangle_{avg}
\]

Equation 3.14

For the inlet the normal vector and positive \( x \)-direction are parallel, so the dot product of the normal and velocity vectors simplifies to the scalar value of the \( u \)-component of the velocity. For the top the normal vector and positive \( y \)-direction are parallel, so the dot product of the normal and velocity vectors simplifies to the scalar value of the \( v \)-component of the velocity. For the outlet the normal vector is anti-parallel to the positive \( x \)-direction, so the dot product reduces to the negative of the scalar value of the \( u \)-component. It is also assumed that the flow is on average 2-D, and it can be seen from the picture of the CV in Figure 3.34 that the inlet and outlet are aligned in the \( y \) direction so the differential, \( dA \), can be replaced with \( dy \).

Similarly, for the top \( dA \) can be replaced with \( dx \). This leads to

\[
\langle \sum F \rangle_{avg} = \langle \int_{inlet} \rho \vec{U} (u) dy + \int_{top} \rho \vec{U} (v) dx + \int_{outlet} \rho \vec{U} (-u) dy \rangle_{avg}
\]

Equation 3.15

Looking at the left-hand side it can be intuitively reasoned that the forces would comprise drag acting on the CED and any induced thrust imparted on the flow from the CED.

\[
\langle \sum F \rangle_{avg} = Drag + Induced Thrust
\]

Equation 3.16

Further insight can be gained into the nature of the induced thrust of the device by splitting the vector equation into the \( x \) and \( y \) components. The drag force will only be present in the \( x \)-direction and the velocity vector, \( \vec{U} \), will be split into its \( u \) and \( v \) components. This results in the following two equations.

\[
\langle \sum F_x \rangle_{avg} = \langle \int_{inlet} \rho \vec{u} (u) dy + \int_{top} \rho \vec{u} (v) dx + \int_{outlet} \rho \vec{u} (-u) dy \rangle_{avg}
\]

Equation 3.17

\[= Drag + Induced Thrust \text{ in } x\]
\[ \left\langle \sum F_y \right\rangle_{avg} = \left\langle \int_{inlet} \rho \ddot{v}(u) dy + \int_{top} \rho \ddot{v}(v) dx + \int_{outlet} \rho \ddot{v}(-u) dy \right\rangle_{avg} \]

\[ = Induced Thrust in y \]

Examining Equation 3.17 it can be seen that the time averaged x-direction momentum flux across the boundaries of the CV over one entire flap is equivalent to the sum of both the average induced thrust in the x-direction over one flap cycle and the drag present on the device. Examining Equation 3.18 it can be seen that the time averaged y-direction momentum flux across the boundaries of the CV over one entire flap is equivalent to the induced thrust in the y-direction over one flap cycle. However, when calculating these integrals there will still be errors as described in the conservation of mass and conservation of momentum discussions above. The x-direction and y-direction momentum are plotted for each position of the compliant electrode in a flapping cycle to show how momentum across the boundaries and total momentum fluxes change throughout one flap cycle.

**Conservation of Energy Equations for Control Volumes (CV)**

The basic energy conservation equation for this open system may be stated as the rate of heat addition into the CV less the rate of work done by system on the surroundings is equal to the time rate of change of energy within the CV combined with the integrated energy flux across the CV boundary (e.g., control surface (CS)). Mathematically, this is given as

\[ \dot{Q} - \dot{W} = \frac{d}{dt} \left( \int_{CV} \rho e dV \right) + \int_{CS} \rho e (\ddot{U} \cdot \hat{n}) dA \]

\[ \text{Equation 3.19} \]

Where \( e = e_i + \frac{\nu^2}{2} + gh \) and \( e_i \) is the specific internal energy, \( g \) is the acceleration due to gravity and \( h \) is the fluids height. Using a similar approach as used in the momentum equations of averaging both sides of the equation over one full flapping cycle and break the averages of sums into sums of averages.
\[\langle \dot{Q} - \dot{W} \rangle_{avg} = \left(\frac{d}{dt}\left(\int_{cv} \rho e dV\right)\right)_{avg} + \langle \int_{cs} \rho e (\vec{U} \cdot \hat{n}) dA \rangle_{avg} \]

Equation 3.20

Once again as shown by Shinde and Arakeri, all the energy stored within a control volume surrounding a flapping device changes with time and oscillates around a zero mean, so after averaging for a flap cycle the mean contribution of the stored energy is zero [46]. This leaves us with Equation 3.21 or Equation 3.22 in expanded form.

\[\langle \dot{Q} - \dot{W} \rangle_{avg} = \langle \int_{cs} \rho e (\vec{U} \cdot \hat{n}) dA \rangle_{avg} \]

Equation 3.21

\[\langle \dot{Q} - \dot{W} \rangle_{avg} = \langle \int_{cs} \rho \left( e_i + \frac{U^2}{2} + gh \right) (\vec{U} \cdot \hat{n}) dA \rangle_{avg} \]

Equation 3.22

Making a few assumptions Equation 3.22 can be simplified. The first assumption is that the rate of heat addition, \(\dot{Q}\), is negligible in comparison to the work done by the CED. The second assumption is to neglect the internal energy and potential energy of the flow. The internal energy is dependent upon temperature which any changes in temperature of the fluid over one flapping cycle would be negligible in affecting the airs internal energy. The fluid’s potential energy may be neglected because the change in height of the fluid is negligible. This results in a great simplification of Equation 3.22 into Equation 3.23.

\[\langle -\dot{W} \rangle_{avg} = \langle \int_{cs} \rho \left( \frac{U^2}{2} \right) (\vec{U} \cdot \hat{n}) dA \rangle_{avg} \]

Equation 3.23

The control volume simplifications that were performed for the conservation of mass and conservation of momentum equations can now be performed. This results in Equation 3.24.

\[\langle -\dot{W} \rangle_{avg} = \langle \int_{inlet} \rho \left( \frac{U^2}{2} \right) (u) dy + \int_{top} \rho \left( \frac{U^2}{2} \right) (v) dx + \int_{outlet} \rho \left( \frac{U^2}{2} \right) (-u) dy \rangle_{avg} \]

Equation 3.24
Here it is important to note that the work term on the left-hand side of the equation consists of work done by the CED and flow work. It’s also important to note that here \( U = \sqrt{u^2 + v^2} \). Like conservation of mass and momentum there will also be errors present. The energy fluxes across the boundaries are also plotted at for each position in the flapping cycle to show its evolution over one flap cycle.

**Turbulent Kinetic Energy Mapping**

Specific turbulent kinetic energy (\( tke \)) is the energy associated with turbulent fluctuations per unit mass from the mean flow velocity field and is defined in Equation 3.25, where \( u' = U - u \), \( v' = V - v \), \( w' = W - w \)

\[
tke = \frac{1}{2} (u'^2 + v'^2 + w'^2)
\]

Equation 3.25

Since we are working with two-dimensional two-component velocity fields the \( w' \) component is neglected resulting in Equation 3.26 seen below which was used for mapping the turbulent kinetic energy in the flows.

\[
tke = \frac{1}{2} (u'^2 + v'^2)
\]

Equation 3.26

In the MATLAB® code the instantaneous flow fields were subtracted from the time averaged flow fields, squared, and then averaged and components summed to create a “\( tke \)” value at every combination of “\( x \)” and “\( y \)” locations which were subsequently plotted to via surface plot to create “\( tke \)” maps for observation and comparison of “\( tke \)” evolution throughout a flap cycle in both externally driven flow and quiescent flow.
Induced Flow Analysis

For the induced flow analysis, the measured velocity of the induced flow from the device operating in quiescent air (i.e., tunnel-off setting) is plotted versus flap position and the mean induced velocities are compared to the average measured speed of the tip of the compliant electrode for all three models operating at the 0.75 frequency ratio and 66% duty cycle.

The methodology of the aerodynamic testing can be summarized as:

1) Place the test stand/test section without the model present into the wind tunnel and power on the tunnel.
2) Collect data (100 sets of PIV images) at the speed chosen to perform all testing to gather baseline flow with no model present.
3) Leave the tunnel running, remove the test section, mount the model into the test section and place the test section back into the wind tunnel.
4) Leave the model unpowered.
5) Collect data (100 sets of PIV images) of the flow around the unpowered model to collect baseline flow of unpowered model.
6) Turn on powering signal chosen from behavioral testing to proper voltage to achieve desired behavior.
7) Collect data (100 sets of PIV images) at location one in the flap cycle via external triggering of the PIV system by a sync channel on the signal generator providing the signal to power the model.
8) Change the offset in the PIV timing by increasing the offset by the pulse period of the signal divided by ten to move to the next location in the flap cycle.
9) Collect another 100 sets of PIV images.
10) Repeat steps 8 and 9 until data has been collected for every location including two sets for the first location. At this point all data for the tunnel-on flapping testing is collected.
11) Turn off the tunnel and allow time for the flow to become purely driven by the operating device.
12) Adjust the voltage of the operating signal to obtain desirable flapping behavior.
13) Collect data (100 sets of PIV images) at location one in the flap cycle via external triggering of the PIV system by a sync channel on the signal generator providing the signal to power the model.
14) Change the offset in the PIV timing by increasing the offset by the pulse period of the signal divided by ten to move to the next location in the flap cycle.
15) Collect another 100 sets of PIV images.
16) Repeat steps 14 and 15 until data has been collected for every location including two sets for the first location. At this point all data for the tunnel-off flapping testing is collected.
17) Repeat steps 1 through 16 for the other two models. Make sure the correct inlet is being used for each model setup and the corresponding test section width.
18) Perform data analysis including control volume analysis (i.e., conservation of mass, momentum, and energy), kte analysis, and induced flow analysis.

### 3.3.2 Aerodynamic Testing Results

Aerodynamic testing was completed in two separate attempts. The first attempt, all three models had the “baseline: no model with tunnel-on” data set collected, the “baseline: model-unpowered with tunnel-on” data set collected and the “model-powered tunnel-on” and “model-powered tunnel-off” data sets as well. Once the data was exported and analyzed it became apparent that for the testing of the narrow model dust particles had accumulated on the side wall of the wind tunnel distorting the PIV results which prompted the author to repeat the narrow model testing two days later to gain a clearer usable set of PIV data. Here the results of the control volume analysis, turbulent kinetic energy mapping analysis, and induced flow analysis for all three models’ usable sets of data are presented. Here just the raw results of all the analyses on the PIV results are presented, the results will be discussed in further detail in section 4.0 Discussion of Results.
Wide Model

The first model tested was the wide model followed by the square and then narrow. First the results of the wide model will be presented followed by the results of the square and then narrow models. The first set of PIV data collected for each model, the “baseline: no model with tunnel-on” data set was used to calculate the operating Reynolds number for the model once placed into the freestream flow of the wind tunnel. The equation for calculating Reynolds number is seen below in Equation 3.27 where $\rho$ is the fluid density, $U$ is the freestream velocity, $L$ is the characteristic length, and $\mu$ is the dynamic viscosity of the fluid. The Reynolds number is reported based on both the length of the compliant part of the electrode and based on the length from leading edge of the model’s base plate to the trailing edge of the compliant electrode (i.e., the electrode tip). This is illustrated in Figure 3.35 where the red double ended arrow depicts the characteristics length scale associated with the compliant portion of the electrode and the green double ended arrow depicts the characteristics length associated with the distance from the leading edge to the compliant electrode tip. The Strouhal number is also reported based off both the length of the compliant part of the electrode and the height of the trailing edge of the electrode (i.e., tip height which would represent a full stroke height of a flap). This is illustrated in Figure 3.36 where the red double ended arrow depicts the characteristics length scale associated with the compliant portion of the electrode and the green double ended arrow depicts the characteristics length associated with the height of the tip of the trailing edge of the compliant electrode. Strouhal number can be calculated using the Equation 3.28 where $f$ is the frequency of flapping, $U$ is the free stream velocity, and $L$ is the characteristic length.
Figure 3.35: Characteristic lengths for calculation of Reynolds number

Figure 3.36: Characteristic lengths for calculation of Strouhal number

\[ Re = \frac{\rho UL}{\mu} \]  

\[ St = \frac{fL}{U} \]

Equation 3.27

Equation 3.28

The baseline data with no model present was used for tunnel qualification as discussed in Appendix A: Smoke Tunnel Design, Construction, and Qualification. In addition to being used for qualification of the tunnel the baseline data set also had a control volume analysis performed to get baseline numbers for mass flux, momentum fluxes, and energy flux. Figure 3.37 below depicts a quiver plot of the velocity field of the baseline testing for the wide tunnel configuration with no model present. The large black box on the quiver
plot depicts the boundaries of the control volume used for the control volume analysis and the small black box near the right side of the large black box is the area that was used to calculate the average flow speed for use in calculating the Reynolds number of the flow. For all tests on all three models the locations are consistent for the control volume and the location of the “Reynolds Window” (i.e., the location where the velocity is sampled to calculate Reynolds number and Strouhal number).

![Quiver plot of mean velocity field](image)

**Figure 3.37: Quiver plot of mean velocity field with no model present for the wide tunnel configuration**

Table 3.6 depicts the results from the control volume analysis of the baseline testing with no model present. Theoretically the values for each of the calculated metrics should be exactly zero for the baseline case with no model present. The deviation from zero for the mass flux, momentum, fluxes, and energy flux, gives a quantitative estimate of the errors involved from non-planar flow, estimation of the velocity vectors, discretization of the field, and calculation or numerical processing errors. For all the control volume analyses, a negative number for the mass flux indicates a net mass moving into the CV or “mass destruction” is occurring to suit continuity and positive numbers indicate a net mass moving out of the CV or “mass creation;” by convention of outward flow being positive due to the dot product with the normal vector.
Clearly mass is not being created or destroyed however it can appear so from an aggregation of the errors listed above which will result in perceived deviations from continuity. A positive number for $x$-momentum indicates drag is dominant over any potential thrust production while a negative number indicates thrust is being produced. A positive number for $y$-momentum indicates air being pushed upward resulting in a downward force on the device whereas a negative number indicates an upward force on the device or generation of lift. A positive number for energy indicates net flow of energy out of the control volume and negative numbers indicate net energy flow into the CV. For the results seen in Table 3.6 no device is present and thus all deviations from zero are from various errors and not from the device altering the flow.

<table>
<thead>
<tr>
<th>Baseline: No Model Present</th>
<th>Wide model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Mass Flux (Kg/m-s)</td>
<td>0.00038</td>
</tr>
<tr>
<td>Baseline X-Mom Flux (N/m)</td>
<td>-0.00057</td>
</tr>
<tr>
<td>Baseline Y-Mom Flux (N/m)</td>
<td>-0.0025</td>
</tr>
<tr>
<td>Baseline Energy Flux (J/m-s)</td>
<td>-0.0015</td>
</tr>
</tbody>
</table>

After the baseline data with no model present was collected next the model was placed in the tunnel at the same flow speed with the model remaining unpowered followed by collection of another set of baseline data. Figure 3.38 depicts the quiver plot of the mean flow field of the model-off baseline data set and Table 3.7 gives the mean values for the control volume analysis of the model-off baseline dataset for the wide model.
After collection of the no model present baseline data set and the unpowered model baseline data set the model was turned on, driven with the chosen treatment from the behavioral testing of frequency ratio of 0.75 and duty cycle of 66%, and the collection of 11 separate data sets at 10 temporally spaced locations throughout a flap cycle were collected where positions 1 and 11 are repeats of the data collection at the same place to show cyclic behavior. Figure 3.39 below depicts the mean flow fields for positions 1, 3, 5, 7,
9, and 11 (i.e., position 1 repeated) in the flap cycle. The black boxes depict the areas that the data is sampled to monitor mean velocity versus flap position and turbulent kinetic energy versus flap position.

**Figure 3.39: Mean flow field in flap positions 1, 3, 5 across the top and 7, 9, 11 across the bottom**

The upper black box in the quiver plots in Figure 3.39 is “Window 1”, and its location was chosen to capture data related to the perpendicularly induced jet that will be seen in the quiescent testing; the second back box is “Window 2” and was chosen to be placed near the wake region of the outlet and located to capture data of the horizontally induced jet that will be seen in the quiescent testing. Table 3.8 below depicts the mean values of the CV analysis for the tunnel on and model on testing and Figure 3.40 depicts the plots of the mass flux, changes in $x$ and $y$ momentum and the changes in energy for every position in the flap cycle.
Table 3.8: CV analysis flap-cycle averaged results for wide model powered and tunnel on

<table>
<thead>
<tr>
<th>Flap average-Tunnel on</th>
<th>Wide model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strouhal Number (Compliant Length)</td>
<td>0.08</td>
</tr>
<tr>
<td>Strouhal Number (TE Tip Height)</td>
<td>0.03</td>
</tr>
<tr>
<td>Mass Flux (Kg/m-s)</td>
<td>-0.013</td>
</tr>
<tr>
<td>X-Mom Flux (N/m)</td>
<td>0.082</td>
</tr>
<tr>
<td>Y-Mom Flux (N/m)</td>
<td>-0.166</td>
</tr>
<tr>
<td>Energy Flux (J/m-s)</td>
<td>-0.226</td>
</tr>
</tbody>
</table>

Figure 3.40: Control volume analysis results for wide model powered with tunnel on

It should be noted that the mean mass flux should be zero at every position within the flap cycle and thus any departure from zero represents a manifestation of cumulative sources of errors. It can also be easily
seen that the $x$-momentum and mass flux subplots are almost identical mirror images of each other. Unfortunately, this makes interpreting the data of the $x$-momentum difficult due to calculated changes in the momentum being explainable by deviations from continuity. The $y$-momentum did not suffer from the same problems as analyzing the $x$-momentum and it can be seen from the $y$-momentum subplot that there exists nearly zero $y$-momentum flux across the top boundary as would be expected in an $x$-axis directed flow. There is also a constant negative $y$-momentum value at the inlet from flow rounding the leading edge of the model baseplate and there is a cyclic behavior to the $y$-momentum at the outlet where at the top of the compliant electrodes flap cycle (near positions 1 and 11) the flow is oriented in the negative $y$-direction almost equally mirroring the $y$-momentum at the inlet resulting in a flow like that over an airfoil. This can be seen in Figure 3.41

For the tunnel driven flow, the $x$-axis velocity component dominates over the $y$-axis velocity component resulting in the energy flux subplot succumbing to the same problems as the $x$-momentum subplot. This difficulty in gaining measurable and significant results from control volume analysis of the raw data along with observations of two induced jets in the quiescent testing data, discussed later, prompted the exploration of monitoring the mean velocities and the turbulent kinetic energy in the defined observation areas referred
to as Window 1 and Window 2, which became the induced flow analysis and turbulent kinetic energy mapping analysis. Figure 3.42 below depicts the calculated mean values of velocity and Figure 3.43 depicts the calculated mean values for turbulent kinetic energy in the two windows chosen for monitoring. The velocities and turbulent kinetic energies are cyclical in nature as would be expected. At position three in the flap cycle the mean velocity in Window 2 has reached a minimum but conversely the turbulent kinetic energy has reached its highest point in the flap cycle for Window 2. This is likely due to vortices being forced out from underneath the compliant electrode’s trialing tip into the wake region where Window 2 is placed resulting in a high turbulent kinetic energy but low mean velocity over time (i.e., averaged over hundreds of vortices). It can also be seen that the turbulent kinetic energy in Window 1 is essentially zero which is expected for a tunnel driven flow at this location.

Figure 3.42: Mean velocities in Window 1 and Window 2 versus flap position for wide model tunnel on
After all tunnel-on model-on data collection was completed, the tunnel was turned off and given time to come to quasi steady state with only the model driving the flow and the model’s voltage was increased until desirable flapping behavior was achieved. Figure 3.44 below shows a quiver plot of the induced flow field from just the model operating in quiescent test settings at position seven in the flap cycle. It can be seen on the right-hand side of the quiver plot that flow is being entrained towards the CED device and then shot out into two jets, one oriented vertically like that of a synthetic jet device, and the other oriented horizontally like that of traditional dielectric barrier device. The discovery of the tendency for the CED to produce a flow field similar to that of the superposition of a synthetic jet overlayed with the flow field from a traditional DBD is a defining step towards aerodynamically characterizing the devices and exploring their full potential for application. Table 3.9 below shows the mean values of the CV analysis for the quiescent testing and Figure 3.45 shows the flux versus flap positions.
Figure 3.44: Quiver plot of mean velocity field with model present at flap position 7 with the wind tunnel off for the wide tunnel configuration

Table 3.9: CV analysis flap-cycle averaged results for wide model powered and tunnel off

<table>
<thead>
<tr>
<th>Flap average-Tunnel off</th>
<th>Wide model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds number</td>
<td>0</td>
</tr>
<tr>
<td>Strouhal number</td>
<td>Infinity</td>
</tr>
<tr>
<td>Mass Flux (Kg/m-s)</td>
<td>0.0076</td>
</tr>
<tr>
<td>X-Mom Flux (N/m)</td>
<td>-0.0021</td>
</tr>
<tr>
<td>Y-Mom Flux (N/m)</td>
<td>0.0013</td>
</tr>
<tr>
<td>Energy Flux (J/m-s)</td>
<td>0.0004</td>
</tr>
</tbody>
</table>
Figure 3.45: Control volume analysis results for wide model powered with tunnel off

Like the tunnel-on testing the results of the CV analysis are difficult to glean clear results from due to the deviations from zero total mass flux and the similarities between the mass flux and x-momentum plots. The most notable of the results from the control volume analysis of the quiescent testing is that for all models there was a small amount of y-momentum flux that was cyclic in nature through the upper surface from the induced jet oriented in the vertical direction. The mean x-directed momentum shows a small amount of thrust production, but the mass flux shows mass creation which could account for the perceived increase in momentum. More on the CV analysis of the three models will be covered in section 4.0 Discussion of Results. Like the tunnel-on testing the mean velocities and turbulent kinetic energy content within Window 1 and Window 2 are plotted versus flap position in Figure 3.46 and Figure 3.47 respectively. There are once again cyclic patterns for the mean velocities and turbulent kinetic energy as would be expected from a
flapping devices cyclic behavior. The average velocity in Window 2 is increasing around position three in the flap cycle and reaches a maximum in position four, unlike where the velocity reached a minimum at position three in the tunnel on testing. This is likely due to two different factors, the first being difference in velocity resolution for the two different test settings (i.e., for tunnel on testing window 2 is a slow-moving region of fluid compared to the rest of flow field with the PIV tuned to capture high speed motion and for tunnel-off Window 2 is a fast-moving region of fluid relative to the rest of the tunnel with the PIV tuned to resolve the Window 2 area.) and the second being that the vortices traveling near the Window 2 region are traveling at or below the speed of the trailing edge tip of the compliant electrode making the region a slow fluid region for the tunnel on testing and a faster fluid region for the quiescent testing. More on the relation between the electrode’s trailing edge tip speed and the induced speeds will be discussed in section 4.0 Discussion of Results. It should also be noted here and will be seen in the results for the induced flow speeds for the square and narrow models that the mean velocity over a flap cycle in Window 2 is approximately double that of the mean velocity over a flap cycle in Window 1.

![Figure 3.46: Mean velocities in Window 1 and Window 2 versus flap position for wide model tunnel off](image-url)
Square model

The square model testing was performed exactly like the wide model testing with the collection of a single baseline data set with no model present, the collection of a baseline data set with the model present and unpowered followed by the collection of 11 data sets throughout a flap cycle with the tunnel on and another 11 data sets throughout a flap cycle with the tunnel off. Figure 3.48 below depicts the quiver plot of the baseline data set with no model present and Table 3.10 shows the results for the control volume analysis on the baseline data set. All values should theoretically be zero so any deviation from zero is the consequence of the aggregation of errors previously discussed.
Figure 3.48: Quiver plot of mean velocity field with no model present for the square tunnel configuration (Black Box is area average speed is calculated to determine Reynolds number)

Table 3.10: Baseline results of CV analysis for square tunnel configuration with no model present

<table>
<thead>
<tr>
<th>Baseline: No Model Present</th>
<th>Square model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Mass Flux (Kg/m-s)</td>
<td>0.0017</td>
</tr>
<tr>
<td>Baseline X-Mom Flux (N/m)</td>
<td>-0.0143</td>
</tr>
<tr>
<td>Baseline Y-Mom Flux (N/m)</td>
<td>-0.0034</td>
</tr>
<tr>
<td>Baseline Energy Flux (J/m-s)</td>
<td>0.0477</td>
</tr>
</tbody>
</table>

After collection of the baseline data set with no model present the square model was placed into the tunnel at the same free stream speed and baseline data set with the model present but unpowered is collected. Figure 3.49 below shows the quiver plot of the velocity field for the unpowered model dataset and Table 3.11 shows the results of the control volume analysis.
After collection of both baseline data sets the model is powered on and driven at the chosen treatment of pulsing ratio 0.75 and duty cycle 66%. A series of 11 data sets were collected at 10 even temporally spaced intervals through the flap cycle of the device. Figure 3.50 below shows the subplots of the mass, momentums, and energy from the control volume analyses versus position in flap cycle. Table 3.12 shows...
the mean results from the control volume analyses over one flap cycle. The problem with the patterns of the mass flux subplot and the $x$-momentum subplot being similar to one another like the wide model shows up in the data for the square model. The pattern of the $y$-momentum is almost identical to that of the wide model and the energy is once again dominated by the $x$-component of the velocity.

Table 3.12: CV analysis flap-cycle averaged results for square model powered and tunnel on

<table>
<thead>
<tr>
<th>Flap average-Tunnel on</th>
<th>Square model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strouhal Number</td>
<td>0.09</td>
</tr>
<tr>
<td>(Compliant Length)</td>
<td></td>
</tr>
<tr>
<td>Strouhal Number</td>
<td>0.03</td>
</tr>
<tr>
<td>(TE Tip Height)</td>
<td></td>
</tr>
<tr>
<td>Mass Flux (Kg/m-s)</td>
<td>-0.003</td>
</tr>
<tr>
<td>X-Mom Flux (N/m)</td>
<td>0.011</td>
</tr>
<tr>
<td>Y-Mom Flux (N/m)</td>
<td>-0.135</td>
</tr>
<tr>
<td>Energy Flux (J/m-s)</td>
<td>0.016</td>
</tr>
</tbody>
</table>
The evolution of the average velocities and turbulent kinetic energies in the observation Window 1 and Window 2 for the square model in tunnel driven flow with the model powered on follow the same pattern as the wide model results. The average velocity in the observation windows can be seen in Figure 3.51 and the average turbulent kinetic energy can be seen in Figure 3.52. Window 1 shows a steady average velocity out in the far field area with a near zero turbulent kinetic energy. Like the wide model there exists a minimum average velocity in Window 2 occurring in position three in the flap cycle where a maximum turbulent kinetic energy also occurs.
Figure 3.51: Mean velocities in Window 1 and Window 2 versus flap position for square model tunnel on

Figure 3.52: Mean tke in Window 1 and Window 2 versus flap position for square model tunnel on
After collection of the 11 datasets with the tunnel on the tunnel was turned off with the square model remaining powered on. Once the tunnel came to quasi steady state with the flow being driven by only the model, 11 datasets were collected at 10 evenly temporally spaced intervals. Similar to the wide model it was observed that two induced jets were created appearing as the superposition of the jet created by a synthetic jet device (i.e., a vertically oriented jet) and the jet created by a traditional DBD (i.e., a horizontally oriented jet). The two jets can be seen in Figure 3.53, a quiver plot of the velocity field at position seven in the flap cycle, along with the location of observation Window 1 and Window 2 outlined in black boxes on the plot. Table 3.13 shows the mean results of the CV analysis over the flap cycle and Figure 3.54 shows the results at each position in the flap cycle. Like the wide model there exists a cyclical and always positive flux of $y$-oriented momentum out the upper surface of the control volume due to the vertical induced jet. Unlike the wide model the mean mass flux over the cycle for this model shows up as negative indicating mass destruction to suit continuity and yet there is still some small amount of the thrust production like in the wide model.

![Figure 3.53: Quiver plot of mean velocity field with model present at flap position 7 with the wind tunnel off for the square tunnel configuration](image-url)
Table 3.13: CV analysis flap-cycle averaged results for square model powered and tunnel off

<table>
<thead>
<tr>
<th>Flap average-Tunnel off</th>
<th>Square model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds number</td>
<td>0</td>
</tr>
<tr>
<td>Strouhal number</td>
<td>Infinity</td>
</tr>
<tr>
<td>Mass Flux (Kg/m-s)</td>
<td>-0.0018</td>
</tr>
<tr>
<td>X-Mom Flux (N/m)</td>
<td>-0.00011</td>
</tr>
<tr>
<td>Y-Mom Flux (N/m)</td>
<td>0.00019</td>
</tr>
<tr>
<td>Energy Flux (J/m-s)</td>
<td>0.00002</td>
</tr>
</tbody>
</table>

Figure 3.54: Control volume analysis results for square model powered with tunnel off

For the induced velocities which can be seen below in Figure 3.55 the patterns in the velocities are similar to those seen in the wide model testing but approximately half the magnitude as the wide model and cyclical
in nature. The values for the turbulent kinetic energy do not appear to be cyclical in nature or comparable to the wide model results. This is likely due to the small value of the turbulent kinetic energy for the square model which is an entire order of magnitude smaller in value than the values for the wide model. This same trend of the low values with a non-cyclical pattern for turbulent kinetic energy will be seen in the narrow model as well to be discussed next.

![Graph showing mean velocities in Window 1 and Window 2 versus flap position for square model tunnel off](image)

**Figure 3.55:** Mean velocities in Window 1 and Window 2 versus flap position for square model tunnel off
Narrow model

Testing the narrow model proved to be difficult due to continued buildup of dust particles on the tunnel walls during operation distorting the PIV results. This resulted in the attempt of collection of the data several times before a sufficiently optically data set could be utilized. Figure 3.57 depicts the quiver plot of the baseline no model present data set with the control volume shown as the large black box and the observation area to calculate Reynolds number is outlined via the smaller black box. Table 3.14 shows the results of the CV analysis of the baseline data. It should be noted that theoretically the mass flux, momentum values and energy flux should all be equal to zero. Departure from zero represents an aggregation of errors previously discussed.
Figure 3.57: Quiver plot of mean velocity field with no model present for the narrow tunnel configuration

Table 3.14: Baseline results of CV analysis for narrow tunnel configuration with no model present

<table>
<thead>
<tr>
<th>Baseline: No Model Present</th>
<th>Narrow model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Mass Flux (Kg/m-s)</td>
<td>-0.0022</td>
</tr>
<tr>
<td>Baseline X-Mom Flux (N/m)</td>
<td>0.0133</td>
</tr>
<tr>
<td>Baseline Y-Mom Flux (N/m)</td>
<td>0.0037</td>
</tr>
<tr>
<td>Baseline Energy Flux (J/m-s)</td>
<td>-0.0375</td>
</tr>
</tbody>
</table>

Like the wide and square model after the collection of the first baseline dataset with no model present and the tunnel on the tunnel is left operating while the model is placed into the test section so that the second set of baseline data can be collected. Figure 3.58 shows the quiver plot of the second baseline dataset with the tunnel-on and the model unpowered. Table 3.15 shows the control volume analysis results of the unpowered model baseline dataset.
Like the wide and square models, the tunnel-on model-on control volume analysis for the narrow model was plagued by the perceived deviations from continuity. More on the control volume analysis will be discussed in section 4.0 Discussion of Results. Table 3.16 shows the mean results of the CV analysis over a flap cycle and Figure 3.59 shows the results at each position in the flap cycle.
Table 3.16: CV analysis flap-cycle averaged results for narrow model powered and tunnel on

<table>
<thead>
<tr>
<th>Flap average-Tunnel on</th>
<th>Narrow model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strouhal Number (Compliant Length)</td>
<td>0.08</td>
</tr>
<tr>
<td>Strouhal Number (TE Tip Height)</td>
<td>0.03</td>
</tr>
<tr>
<td>Mass Flux (Kg/m-s)</td>
<td>-0.016</td>
</tr>
<tr>
<td>X-Mom Flux (N/m)</td>
<td>0.110</td>
</tr>
<tr>
<td>Y-Mom Flux (N/m)</td>
<td>-0.100</td>
</tr>
<tr>
<td>Energy Flux (J/m-s)</td>
<td>-0.320</td>
</tr>
</tbody>
</table>

Figure 3.59: Control volume analysis results for narrow model powered with tunnel on

After performing the control volume analysis like the wide and square models the narrow model also had the velocities in the observation windows recorded and the turbulent kinetic energy analysis performed.
The evolution of the average velocities, which can be seen in Figure 3.60, and turbulent kinetic energies, which can be seen in Figure 3.61, in the observation Window 1 and Window 2 for the narrow model in tunnel driven flow follow the same pattern as the wide and square models. Window 1 shows a steady average velocity out in the far field area with a near zero turbulent kinetic energy. Like the wide and square models there exists a minimum average velocity in Window 2 occurring in position three in the flap cycle where a maximum turbulent kinetic energy also occurs.

![Figure 3.60: Mean velocities in Window 1 and Window 2 versus flap position for narrow model tunnel on](image-url)
After collection of the 11 tunnel-on mode-on data sets, the 11 data sets that comprise the tunnel-off model-on testing (i.e., quiescent testing) were collected. Figure 3.62 below depicts the quiver plot of the velocity from the model in position seven of the flap cycle with the field showing both induced jets. Table 3.17 shows the mean results of the control volume analysis for the quiescent testing of the narrow model and Figure 3.63 shows the results plotted at each flap position.
Figure 3.62: Quiver plot of mean velocity field in with model present at flap position 7 with the wind tunnel off for the narrow tunnel configuration

Table 3.17: CV analysis flap-cycle averaged results for narrow model powered and tunnel off

<table>
<thead>
<tr>
<th>Flap average-</th>
<th>Narrow model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds number</td>
<td>0</td>
</tr>
<tr>
<td>Strouhal number</td>
<td>Infinity</td>
</tr>
<tr>
<td>Mass Flux (Kg/m-s)</td>
<td>0.0013</td>
</tr>
<tr>
<td>X-Mom Flux (N/m)</td>
<td>-0.00021</td>
</tr>
<tr>
<td>Y-Mom Flux (N/m)</td>
<td>0.00011</td>
</tr>
<tr>
<td>Energy Flux (J/m-s)</td>
<td>0.00002</td>
</tr>
</tbody>
</table>
The evolution of the average velocity in the observations windows for the narrow model powered on in quiescent tunnel settings matches the results for the square model with there being a cyclical nature to both average velocities and a minimum in Window 2 at position six in the flap cycle. For the turbulent kinetic energies calculated in the observation windows for the narrow tunnel there was no observed cyclical behavior or similarity between the other models, likely due to the low value in comparison to the wide model’s turbulent kinetic energy production. The evolution of the velocities in both observation windows over a flap cycle can be seen in Figure 3.64 and the turbulent kinetic energies can be seen in Figure 3.65.
Figure 3.64: Mean velocities in Window 1 and Window 2 versus flap position for narrow model tunnel off

Figure 3.65: Mean tke in Window 1 and Window 2 versus flap position for narrow model tunnel off
4.0 Discussion of Results

This section discusses further in depth the key takeaways from the results of the three phases of testing. From the modal testing there are two key takeaways. The first is that the modal frequency of the compliant electrode is a key characteristic governing the behavior of the compliant electrode which needs to be identified or the device needs to be designed for a desirable modal frequency. The second key takeaway is that the width of the compliant electrode does not affect the modal frequency. This may not be obvious from the data presented but through the construction and testing of approximately 20 CED devices for their modal frequency it was observed that there was hardly ever a difference of more than 3 Hz between the models, and several had the exact same modal frequency despite having considerably different widths or aspect ratios. The variation of 3 Hz in the modal frequency of the models likely comes from variations in construction of the models. Slight differences in the length of the compliant electrode, the location of the surface applique for restriction of twisting and warping, and other imperfections could lead to slight variances in the modal frequency. The non-dependence of modal frequency on width can also potentially be inferred from the equations from thin plate bending theories. The width of the electrode still plays an important role in the stability of the flapping behavior of the compliant electrode as was seen in the powered device behavioral analysis likely due to fringe electric field effects around the edge of the electrode. For narrower electrodes the fringe or edge effects become more relevant due to the increased perimeter to area. For the behavioral testing several meaningful insights can be gained into the behavior of the compliant electrode as a function of pulsing signal. The first and perhaps the most obvious is that if the pulsing frequency of the driving signal is greater than the modal frequency of the compliant electrode then the electrode will vibrate near the driven frequency of the signal due to the electrode not having enough time to complete half of its natural flapping cycle during the power-off phase of the pulse (i.e., the time between the power-on phase of the pulses is shorter than half the natural oscillation period of the electrode. The other extreme of operation is pulsing slow enough with a duty cycle that gives the electrode enough time to complete an entire natural oscillation in-between power-on phases of the pulsing signal (i.e., the time
between the power-on phases of the pulses is longer than the entire natural oscillation period of the compliant electrode; this is what gives rise to harmonic behavior. The signals that performed the best were those with power-on phases longer in duration than half the natural period and a power-off phase that is shorter in duration than half the natural period but still gives the electrode enough time to complete almost half a natural oscillation. These bounds greatly limit the value space for the parameters of pulse ratio and duty cycle for future study. They can be summarized as Equation 4.1 and Equation 4.2. It is important to note that every combination in the value space bounded by the provided equations will result in desirable behavior. This is simply the region where favorable behavior is more likely to occur.

\[ 0.5 < R_f < 1 \]  
\[ 50\% < DC < 100\% \]

The bounds as specified by Equation 4.1 and Equation 4.2 along with the inference that compliant electrode width has no influence on modal frequency and thus is only a factor in stability of the electrode effectively completes the Objective 1 of this dissertation; measure the behavior of the compliant electrode as a function of electrode geometry and forcing signal. The aerodynamic testing and subsequent control volume analysis, turbulent kinetic energy mapping, and induced flow analysis were performed in effort to answer the remaining three dissertation objectives. Objective 2; measure momentum changes and inspect flow pattern alteration in low Reynolds number flow, was the objective to be answered by control volume analysis but as discussed in the results section the control volume analyses suffer from an aggregation of errors including, uncertainty in vector estimation by the PIV, non-planer flow, velocity field discretization, flap cycle discretization into 10 steps, computational or numerical calculation errors, etc. Table 4.1 below depicts a summary of all the tunnel on testing consisting of the baseline data set with no model present, the baseline data set with the model unpowered and the mean for the 11 datasets from the tunnel-on model-on testing.
For the mean results for all three models from the tunnel-on model-on testing it can be seen that it appears as if mass is being destroyed or stored in the CV which cannot happen and results in the perception of there being drag, however even if you multiply the mean deviation of the mass flux from continuity by the free stream velocity and subtract it from the change in x-momentum (i.e., suppose the mass that appears to be disappearing is carrying the most probable momentum value and subtract it from the results) then there is still drag being produced for the wide and narrow models with a small net thrust production in the square model. It can also be seen from the Strouhal number based on the compliant length of the electrode that a single air particles residence time along the active part of the device is less than one flap cycle which is known to generally be an ineffective range. It is probable that the device at these operating conditions is

<table>
<thead>
<tr>
<th>Table 4.1: Summary of CV results (except tunnel off results)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>dt=80us</strong></td>
</tr>
<tr>
<td><strong>Baseline Mass Flux (Kg/m-s)</strong></td>
</tr>
<tr>
<td><strong>Baseline X-Mom Flux (N/m)</strong></td>
</tr>
<tr>
<td><strong>Baseline Y-Mom Flux (N/m)</strong></td>
</tr>
<tr>
<td><strong>Baseline Energy Flux (J/m-s)</strong></td>
</tr>
</tbody>
</table>

| **dt=80us** | **Baseline: Model Off** | **Reynolds number (compliant length)** | 9000 | 9000 | 9000 |
| **Baseline Mass Flux (Kg/m-s)** | -0.032 | 0.00027 | -0.0022 |
| **Baseline X-Mom Flux (N/m)** | 0.113 | -0.048 | 0.1494 |
| **Baseline Y-Mom Flux (N/m)** | -0.112 | -0.092 | -0.0964 |
| **Baseline Energy Flux (J/m-s)** | -0.191 | 0.259 | -0.3712 |

| **Flap average-Tunnel on** | **Strouhal Number (Compliant Length)** | 0.08 | 0.09 | 0.08 |
| **Strouhal Number (TE Tip Height)** | 0.03 | 0.03 | 0.03 |
| **Mass Flux (Kg/m-s)** | -0.013 | -0.003 | -0.016 |
| **X-Mom Flux (N/m)** | 0.082 | 0.011 | 0.110 |
| **Y-Mom Flux (N/m)** | -0.166 | -0.135 | -0.100 |
| **Energy Flux (J/m-s)** | -0.226 | 0.016 | -0.320 |
producing more drag than thrust which is not necessarily a negative aspect. Comparing the x-momentum for the model unpowered with model powered-on it can be seen for the wide and narrow models the drag is reduced from the unpowered testing to the model powered-on testing. For the narrow model the deviation from continuity is greater for the model powered-on testing than the unpowered testing so the reduction in drag could be accounted for in the deviation from continuity increasing but for the wide model the deviation from continuity is actually less for the powered-on testing and shows a reduction in drag, providing a good indicator that the device experiences less drag while powered-on. The square model comparison of the unpowered testing to the powered-on testing actually shows an increase in drag, however the unpowered testing showed a positive deviation from continuity while the powered-on testing showed a negative deviation indicating that the change increase in drag is likely from the change in continuity deviation. This makes physical sense as for half the flap cycle the cross-sectional area of the model decreases lowering pressure drag. It can be inferred, and evidence has been presented to support, that the CED is likely only effective as a thrust generating device at low Reynolds numbers and above some critical Reynolds number the drag produced by the presence of the compliant electrode would be greater than the benefit gained from thrust production or flow alteration, at which point the CED can be switched to operate into traditional DBD mode by applying a non-pulsed AC cycle of sufficient voltage. While operating beyond this critical Reynolds number the flapping mode is now able to be employed or turned back on to be used as a method for drag creation like that of an air brake which in conjunction with the device’s ability to sense in flapping mode offers the ability for a distributed smart air brake actuator. If a need arrives for increased drag on an object, for example landing an aircraft, then the flapping mode could be effective in providing a drag producing device in that regime with the ability to sense in real time the flow characteristic allowing for a dynamic air brake actuator with potential for increased control. Inspecting Table 4.2, the mean results of the model-on tunnel-off (i.e., quiescent testing), it can be seen that for the wide and narrow model it appears that mass is being created from within the CV and for the square it appears that mass is being destroyed yet all three models show thrust production in the x-direction from the horizontally induced jet and a consistent downward force on the model from the upward directed induced jet.
Objective 3 of the dissertation was to measure the speed of induced flow and inspect flow patterns from device while operating in quiescent conditions. It was discovered that the CED tends to drive flow into two jets similar to the overlay of the jets of a synthetic jet device and a traditional DBD. The speed of these induced jet streams is an important operating characteristic of the CED. Figure 4.1 shows the induced velocity in Window 1 versus flap position for all three models and Figure 4.2 shows the induced velocity in Window 2 versus flap position for all three models.

<table>
<thead>
<tr>
<th>dt=500us</th>
<th>Flap average- Tunnel off</th>
<th>Wide model</th>
<th>Square Model</th>
<th>Narrow Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds number</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Strouhal Number</td>
<td>Infinity</td>
<td>Infinity</td>
<td>Infinity</td>
<td></td>
</tr>
<tr>
<td>Mass Flux (Kg/m-s)</td>
<td>0.0076</td>
<td>-0.0018</td>
<td>0.0013</td>
<td></td>
</tr>
<tr>
<td>X-Mom Flux (N/m)</td>
<td>-0.0021</td>
<td>-0.00011</td>
<td>-0.00021</td>
<td></td>
</tr>
<tr>
<td>Y-Mom Flux (N/m)</td>
<td>0.0013</td>
<td>0.00019</td>
<td>0.00011</td>
<td></td>
</tr>
<tr>
<td>Energy Flux (J/m-s)</td>
<td>0.0004</td>
<td>0.00002</td>
<td>0.00002</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.1: Induced velocity in Window 1 versus flap position for all three models
Figure 4.2: Induced velocity in Window 2 versus flap position for all three models

In wind turbine design and other rotary aerodynamic device design a common parameter for quantifying the efficiency of the turbine is the tip to speed ratio, a measure of the ratio between the velocity of the incoming air and the tip speed of the rotor blades. An analogous set of dimensionless parameters can be developed for the compliant electrode devices’ induced flows which would be a ratio of the induced wind speeds to the tip speed of the compliant electrode. Equation 4.3 and Equation 4.4 below show the proposed definition of the two tip speed ratios for the induced jets in the two respective observation windows.

\[
R_{ts1} = \frac{\text{Mean Induced Velocity in Window1}}{\text{Mean Velocity of trailing edge of Compliant Electrode}}
\]

Equation 4.3

\[
R_{ts2} = \frac{\text{Mean Induced Velocity in Window2}}{\text{Mean Velocity of trailing edge of Compliant Electrode}}
\]

Equation 4.4

The tip speed ratio dimensionless parameters are a measure of efficacy and is related to efficiency, essentially describing the relationship between the transfer of momentum from the electrode to the surrounding flow. We don’t have direct measure of the mean velocity of the trailing edge speed (i.e., tip speed) from the PIV testing but we do have the mean speeds from the powered device behavioral analysis.
The models in the quiescent PIV testing and the powered device behavioral testing were operated using the same signal waveform (i.e., frequency ratio of 0.75 and duty cycle of 66%) but the potential applied for the behavioral testing was approximately 5 kV to -5 kV where the measured potential for the quiescent PIV testing was approximately 4 kV to -4 kV so the tip speed would not be identical but a close estimate. Filling in the average tip speed from the behavioral analysis and the measured man velocities from the observation windows into Equation 4.2 and Equation 4.3 results in the values shown in Table 4.3 seen below.

<table>
<thead>
<tr>
<th></th>
<th>Wide</th>
<th>Square</th>
<th>Narrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Velocity Window 1 (m/s)</td>
<td>0.186</td>
<td>0.062</td>
<td>0.061</td>
</tr>
<tr>
<td>Mean Velocity Window 2 (m/s)</td>
<td>0.333</td>
<td>0.143</td>
<td>0.117</td>
</tr>
<tr>
<td>Mean Trailing Edge Speed (m/s)</td>
<td>0.356</td>
<td>0.309</td>
<td>0.291</td>
</tr>
<tr>
<td>Tip Speed Ratio 1</td>
<td>0.52</td>
<td>0.20</td>
<td>0.21</td>
</tr>
<tr>
<td>Tip Speed Ratio 2</td>
<td>0.94</td>
<td>0.46</td>
<td>0.40</td>
</tr>
</tbody>
</table>

It can easily be seen that the ratio of the two tip speed ratio parameters results in another dimensionless parameter, a ratio of the induced velocities to each other which is defined below in Equation 4.5, essentially describing the preferred directionality of the device (i.e., does it push more air in the x-direction or y-direction).

\[
R_{V_{\text{induced}}} = \frac{\text{Mean Induced Velocity in Window 1}}{\text{Mean Induced Velocity in Window 2}}
\]

Equation 4.5

For all three models the induced velocities and the resulting induced velocity ratios can be seen below in Table 4.4. It can easily be seen that the Induced Velocity Ratios, \( R_{V_{\text{induced}}} \) for all three models fall within the range of 0.43 to 0.56 indicating the average velocities in Window 1 were always approximately 50% the average induced velocities in Window 2.
Table 4.4: Mean induced velocities and the induced velocity ratios

<table>
<thead>
<tr>
<th></th>
<th>Wide</th>
<th>Square</th>
<th>Narrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Velocity Window 1 (m/s)</td>
<td>0.186</td>
<td>0.062</td>
<td>0.061</td>
</tr>
<tr>
<td>Mean Velocity Window 2 (m/s)</td>
<td>0.333</td>
<td>0.143</td>
<td>0.117</td>
</tr>
<tr>
<td>Induced Velocity Ratio</td>
<td>0.56</td>
<td>0.44</td>
<td>0.52</td>
</tr>
</tbody>
</table>

The combination of the three dimensionless parameters for the induced velocities, $R_{ts1}$, $R_{ts2}$, and $R_{v\text{-induced}}$, can be used to characterize a CEDs aerodynamic behavior in quiescent settings, a first step in complete aerodynamic characterization and an answer to Objective 3 of the dissertation. Objective 4 of the dissertation was to calculate the turbulent kinetic energy in low Reynolds number testing and quiescent testing. Like the induced velocities, the turbulent kinetic energy was monitored in the two observation windows and plotted versus flap position. Figure 4.3 shows the evolution of the turbulent kinetic energy in both observation windows for all three models for the tunnel-on model-on testing. Figure 4.4 shows the evolution of the turbulent kinetic energy in both observation windows for all three models for the tunnel-off model-on testing. The general observable from both the tunnel-on and tunnel-off testing is that on the downward portion of the stroke approximately positions 2 through 6 is where the maximum amount of turbulent kinetic energy passes through observation Window 2 which supports that the vortex shedding through the wake region is occurring during the downward portion of the stroke.

![Figure 4.3: Mean turbulent kinetic energy in the observation windows of the wide (left) square (middle) and narrow (right) models with the tunnel-on and model-on](image_url)
In addition to the results summarized from the modal, behavioral, and aerodynamic analyses, the use of the rotating Q-V cyclograms, which is unique to the CED, as a method for sensing changes in the compliant electrodes behavior from changing aerodynamic environments is another key take away from this research. The ability of the device to act simultaneously as a flow controller and flow sensor while operating in flapping mode in addition to the device’s ability to operate as a traditional DBD offers a wide range of applications. In addition to the observations related to the objectives of the dissertation and the sensing aspects of the device there were several other important observations made that should also be reported on as well. One of these observations is the tendency of the plasma discharge to corrode the underside of the compliant electrode. In Figure 4.5 the corrosion on the electrode can be seen which is the brownish reddish rust spots.
In addition to the corrosion, which is intensified by the plasma discharge, CEDs also degrade due to fatigue of the electrode and due to breakdown of the dielectric barrier from the plasma discharge as well. The breakdown of the dielectric barrier leads to short circuiting of the device and typically results in the device igniting. The plasma discharge also affected signals in the measurement devices and the timing circuit for the PIV system sometimes causing the camera and laser to run out of sync with each other. Problems due to electromagnetic interference from the plasma were limited by adding insulative coverings to all the probes wires leading to the oscilloscope and performing wire/cable management of all the PIV systems cables to ensure no wires or cables were touching any conductive surfaces or objects. In conclusion the objectives of this dissertation have been achieved along with the provision of several key takeaways related to the device’s behavior and efficacy and key considerations for researchers when performing similar work in the future.
5.0 Conclusions and Proposed Future Work

This section provides proposed future work for further development and study of the compliant electrode discharge device as well as the author’s final observations and conclusions.

5.1 Future Work

Due to the CEDs dual mode operation capabilities (i.e., flapping mode and DBD mode) as well as its ability to act as an active sensor during flapping mode operations provide for ample avenues of further investigation and work to be done in the future. Fundamental work in a wide range of multiple disciplines including research on the stability of the compliant electrode, the fluid-structure interaction and how to increase the mechanical energy to fluid momentum transfer, the materials used, the plasma-fluid interaction and how to increase the electrical energy to fluid momentum transfer, as well as the sensing abilities can all be investigated at a much deeper level than pursued here and offer a plethora of research topics worthy of masters and doctoral level study. Improved understanding of the fundamental areas listed, and others would help in the process of developing the CED to operate effectively as a flow controller at higher Reynolds numbers. In addition to fundamental studies for future work there is ample room for applied investigations as well. CEDs could potentially play a role in some UAV or UAS platforms, could enhance the efficiency of some wind energy capture devices (e.g., large wind turbine loading stabilization), or potentially be implemented as an active sensor in various situations. In the device’s sensing capabilities section, it is stated how natural flyers utilize their feathers or hairs in flight as sensors to improve flight performance which the CED has potential to be an electro-mechanical analog of that which can be deployed in large arrays of CEDs to act as a distribution of bird feathers on a wing or aerodynamic surface. CEDs could be placed in an array and connected with thin compliant nonconductive webbing allowing for the array to resemble a bat wing or other webbed flapping natural analog. Many different alterations or adjustments to the basic design could be implemented to achieve a wide range of desired flow effects which could be investigated further. In addition to attempting to alter the flow for improved flight efficiency the
CED can also be employed as an active airbrake system with simultaneous sensing capabilities allowing for a wide range of maneuverability augmentation of flight systems like UAVs. The use of the CED for an airbrake has a biological analog as well as its similar to birds altering their wing morphology during landings. There exist ample opportunities to study the use of a CED device as an airbrake instead of as an active flow controller.

5.2 Final Observations and Conclusions

In conclusion, all four of the objectives of the dissertation have been answered or addressed to some level with insight gained into the behavior of the device, its aerodynamic characteristics, its capabilities as a sensor and some potential applications. It has been demonstrated that while operating in flapping mode the device’s behavior relies heavily on the modal frequency of the compliant electrode, the pulsing ratio (i.e., pulsing frequency), and the duty cycle. A bound for the pulsing frequency and duty cycle have been established for the value space that is likely to lead to desirable compliant electrode flapping behavior. It has also been established that the device can alter flow in a driven flow field as well as produce an induced flow field in quiescent air. The induced flow field has also been shown to be similar in structure to the superposition of the induced flow fields caused by a traditional DBD and synthetic jet overlayed with one another. Dimensionless parameters for characterizing the effects on the induced flow field have been proposed and the values for these tests provided. The tunnel driven flow fields showed the generation of a cyclical amount of turbulent kinetic energy being introduced to the flow likely via vortex shedding from the trailing tip. In all it has been shown that the CED device has potential for broad aerodynamic applications. The devices broad operational capabilities (i.e., can do anything a DBD can do and then more) are what makes it so novel and potentially useful for so many applications.
Works Cited


6.0 Appendices

Appendix A: Smoke Tunnel Design, Construction, and Qualification

Design

The design and subsequent construction of the wind tunnel was an iterative process. The initial design criteria and limitations for the tunnel were 1] must be usable with the PIV system (i.e., clear test section with minimal reflective surfaces), 2] length restrictions to approximately 7 ft for use in laboratory space, 3] minimize cost, and 4] variable test-section widths needed for testing the various compliant electrode aspect ratios and the need for the model to span the entire width of test-section to help maintain two-dimensional flow. With the design criteria established, next, four Nidec 12 V 77 CFM computer fans were acquired as a power source to build a prototype tunnel to investigate the flow speeds needed to affect the CED device. The computer fans were mounted together onto a 9in x 12in board that had a 7.25 in x 7.25 in square cut out of it for the collection of the four fans, the fan bank, to be inserted into and fastened to. This can be seen in the picture of the finished fan bank assembly in Figure 6.1 below.

![Figure 6.1: Finished fan bank for wind tunnel](image-url)
With the fan bank constructed, known approximate length restrictions and a model-stand that could double as a test-section, a cardboard prototype of the tunnel, absent the contraction/inlet sections, was constructed to test the CED device in externally driven flow for the first time ever. A picture of the cardboard prototype with no cover to the diffusion section can be seen below in Figure 6.2. The length of the contraction section for the cardboard prototype pictured was approximately 28 in and the test section side walls in this configuration were separated by approximately 1 in with a 5 in height.

![Figure 6.2: Early-stage wind tunnel design constructed from cardboard](image)

Figure 6.3 shows the completed cardboard prototype that was used to test out the CED device's behavior in externally driven low-speed flow. In Figure 6.3 the test section side walls were replaced with replicants of the same size side walls from Figure 6.2 but with the protective brown paper coating removed. In Figure 6.3 the test section walls are separated by approximately 3 inches with the model spanning the entire test section. In Figure 6.3 a crude inlet to the test section was constructed with a piece of clear plastic pipe that was cut in half down its z-axis and fixed to the front with duct tape.
Figure 6.3: Completed cardboard prototype being powered on

From the cardboard prototype it was determined that the height of test section should be increased to the same height of the fan bank to help improve blockage from about 12% to about 10% and simplify construction. From the cardboard prototype testing it was also found that the four fans with a combined volumetric flowrate of 308 CFM provided a high enough flow speed to cover all testing regimes for the current CED device prototypes. From the prototype tunnel it was also found that the size restraints and imposed geometries from other requirements resulted in a half diffusion angle of approximately 6° which is above what is generally aimed for (~3°) but below what had been seen referenced in literature to as “wide angle diffusers”. At this point in design and construction of the tunnel it was decided that if any flow separation that occurred took place in the diffuser sufficiently far downstream to not have any recirculation entering the test section, then it would be acceptable to keep the steeper diffusion angle. Since flow separation was not able to be observed in the cardboard prototype it was decided to proceed with the rest of the design and construction since extending the diffusion section if needed would not alter any other part of the tunnel.

Next the contraction section needed to be designed. It was decided to create three contraction sections, one for each of the different span models, that were all designed using the same contraction polynomial. Through a literature survey it was found that a common contraction polynomial used for low-
speed tunnels was a fifth order polynomial that was studied by Bell and Mehta. They found that for a two-dimensional contraction section on a small low-speed wind tunnel that out of a third order, fifth order, and seventh order polynomial the fifth order with a contraction ratio of about eight and a length to half inlet-height ratio \((L/H_i)\) of between 0.67 and 1.8 was the least likely to have flow separation and produced clean uniform flow. For the design of this tunnel a nominal contraction ratio of eight was used and a length to half inlet-height ratio \((L/H_i)\) of one was used. The chosen contraction ratio, length to half inlet-height ratio \((L/H_i)\), and known half exit-heights \((H_e)\) which are equivalent to half the span of each model, can be used along with Bell & Mehta’s fifth order polynomial seen below in Equation 6.1, to come up with the equation describing the contraction curve for each of the three sections, one for each model width. [45] Figure 6.4 below shows the contraction curves.

\[
Y = H_i - (H_i - H_e) \left( 6 \left( \frac{X}{L} \right)^5 - 15 \left( \frac{X}{L} \right)^4 + 10 \left( \frac{X}{L} \right)^3 \right)
\]

Equation 6.1
Next a CAD model of the tunnel was drawn up in SOLIDWORKS based on the cardboard prototype and the large contraction section corresponding to the widest test section setting. A picture of the CAD design can be seen below.
With the test section, diffuser, and inlets, designed and the fan bank already constructed work began on constructing the rest of the wind tunnel.

**Construction & Final Tunnel**

The final wind tunnel was constructed using mostly clear acrylic and medium density fiber (MDF) board. The tunnel consists of one base board for the tunnel to sit on, the fan bank, the test section, the diffusion section, and the three different contraction sections. The base board is an approximately 2.5 ft by 4 ft piece of MDF board that was painted flat black to minimize laser reflection from the PIV system. The baseboard acts as the floor of the tunnel through the test section back through the diffusion section and fan bank. The fan bank consists of the original four fans from the carboard prototype still mounted onto the same board. A copy of the board the fans were mounted to was cut out and used along with 2 side walls of acrylic, a thin piece of aluminum flashing for the bottom, and a small board for the top cover to create a fan bank box that can be seen below in Figure 6.6. The Box was used to mount 3-D printed pyramidal shaped cones on the walls and center of the fans to help improve flow quality and reduce flow circulation near the fan section of the diffuser at the exit. In Figure 6.6 below the image on the left is a side view of the fan bank where the pyramidal cones can be seen through the acrylic sidewall. The right-side image is a picture taken from the inside of the tunnel looking directly at the fan bank. The fans are powered by a DC-power supply.
Figure 6.6: Fan bank with side view on left and into the fan view on the right

The test section is simply the model-stand discussed in section 2.1 Model and Testing Stand. It consists of two acrylic sidewalls with spacer posts to set the width to that which is desired and an acrylic top cover plate. The completed sidewalls with the posts for the narrow model can be seen below in Figure 6.7. The diffusion section is comprised of two acrylic sheets for tunnel side walls that are mounted to hinges where the walls meet the fan bank so that the diffusion angle can be changed to match up with the different test-section widths. There is also a large acrylic sheet that covers the diffusion section and acts as the upper diffusion section wall. In between the test section and the diffusion section a “fillet” piece was added to help smooth the transition of the flow from the straight test section to the divergent diffusion section. These fillet pieces were made by heating and bending two pieces of acrylic plate until the approximate fillet radius was achieved. The fillets pieces can also be seen below in Figure 6.7 connected to the test section side walls.
With the test section and fan bank constructed along with having all the parts for the diffuser section cut out, the inlets needed to be constructed. This was done by first tracing out the contraction curves onto boards for the base of the inlets. Next the contraction curves for all three inlets were cut into boards for the side walls of the inlet. The inlet section of the curve was extended about 2.5 inches to allow for a groove to be milled for insertion of honeycomb shaped flow strainers. The base board and contraction curves for the wide inlet can be seen in Figure 6.8 below.
Next the boards with the contraction curves cut into them were mounted on sidewall boards which can be seen below Figure 6.9. Next the curves were covered in flashing and secured via pop-rivets into the contraction curve boards which can be seen below in Figure 6.10.

![Figure 6.9: Contraction section boards mounted to side wallboards](image)

![Figure 6.10: Wide inlet with flashing fastened to the contraction curves](image)
Next the rivets were covered with Bondo and sanded to provide a smooth surface for air to flow over. Then two sheets of half inch thick the honeycomb flow straightener which can be seen below in were sandwiched between two pieces of screen and placed in the milled grooves in the baseplate and contraction curves.

![Honeycomb flow straightener](image1)

**Figure 6.11: Honeycomb flow straightener**

Next, PVC pipe was cut in half longways and then cut in 45° on the ends to from smooth halfpipe inlets around the intake of the inlet section. The halfpipe section for the wide tunnel can be seen below with the fan bank drying after painting.

![Halfpipe inlet and fan bank drying after being painted](image2)

**Figure 6.12: Halfpipe inlet and fan bank drying after being painted**
Lastly the PVC halfpipe was mounted onto the front of the inlets and a piece of acrylic was cut to serve as the top for each. The completed wide inlet can be seen below in Figure 6.13. All three completed inlets can be seen below in Figure 6.14

![Completed wide inlet](image1)

**Figure 6.13: Completed wide inlet**

![All three inlets](image2)

**Figure 6.14: All three inlets**

With all three inlets, the fan bank, and the test section constructed all that was left to do was mount the hinged sidewalls onto the fan bank and mount everything to the tunnel baseboard. The wind tunnel setup can be seen below in
Dimensions of the completed wind tunnel can be seen below in the data for each section.

**Contraction Inlets**

All three inlets have approximately the same height of 7.25 inches

**Narrow contraction section**

Inlet width (7.25 in)

Exit dimensions match model width - (0.89 in)

Contraction length - (3.6 in) *not including inlet and straighteners

**Medium Contraction section**

Inlet width - (10.25 in)

Exit dimensions match model width - (1.27 in)

Contraction Length - (5 in) *not including inlet and straighteners

**Wide contraction section**

Inlet width - (19.75 in)

Exit dimensions match model width - (2.45 in)

Contraction length - (10 in) *not including inlet and straighteners
Test Section

Length - (9 in)

Width - (variable and dependent on width of model and the contraction section)

Height - (~7.5 in) *the acrylic walls are 7 inches tall plus the seal at the bottom and the top which are each about ¼ in thick

Diffuser

Length - (~27.5 in long without the fillet curvature transition & ~32inches long with) * not including length of fan chamber which is 6in long including the thickness of the fans.

Width at inlet prior to gentle curvature to transition into diffuser - (variable but equal to TS width)

Width at exit to fans - (7.5 in)

Height - (~7.5 in)

Screen geometry (cell width and wire diameter)

Screen cells are square

Screen layered on both sides of the straighteners

Screen cells are 0.06 in wide (calculated by measuring the width of 10 cells which came out to be 0.5995 in)

Straightener geometry (cell shape, width, and length)

Two sheets each with a width or individual thickness of 0.5 in (or cell length of 1in)

Cells are hexagonal

Cells have a width of 1/8 in

Drive system specs (how many and what power motors)

Four Nidec 12 V 77 CFM @ .605 A computer fans

The fan bank is about 7.25 in x 7.25 in on the inside of the tunnel and about 6in long
Qualification Testing

Particle Image Velocimetry was used for the qualification testing of the wind tunnel for all three configurations (i.e., all three inlets and corresponding test section widths) the metrics of Turbulence Intensity (TI) inside the control volume, the flow uniformity leading into the entire data capture field, and the flow straightness reported as mean flow angle and max flow angle detected in the sample area near the inlet to the control volume. Figure 6.16, Figure 6.18, and Figure 6.20, below show the quiver plots of the baseline testing for the wide, square, and narrow tunnel configurations respectively. In the quiver plots the large black box depicts the bounds of the control volume, the location where the TI is calculated. The smaller black box inside the larger one is the sample area for determining the mean free stream velocity for Reynolds number calculations and determining the mean flow angle and max flow angle detected within the sample area. Lastly the long black thin black rectangle on the right-hand side of the plot depicts the location of the data sampled for calculating flow uniformity. Figure 6.17, Figure 6.19, and Figure 6.21 depict the turbulent kinetic energy maps for the entire investigation region for the wide, square, and narrow tunnel configurations respectively. In the turbulent kinetic energy maps the blue represents low tke and the lighter blue to green, the more tke present. Table 6.1 below shows the qualification testing results from all three tunnel configurations for the three different model aspect ratios. It may be noted that the TI for the narrow tunnel is quite high for a typical wind tunnel and is likely due to the narrow width of the test section along with the disturbance created from the milled pockets into the side walls of the test section for insertion of the model baseplate. The laser plane sits about four of the milled pocket depths away from the pocket surface for the narrow configuration whereas for the square configuration the laser plane is about seven pocket depths away and for the wide its about 12-13 pocket depths from the test section wall.

<table>
<thead>
<tr>
<th></th>
<th>TI (%)</th>
<th>$U_{\text{mean}}$</th>
<th>Max % from $U_{\text{mean}}$</th>
<th>Mean Angle (deg)</th>
<th>Max Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>0.7</td>
<td>4.59</td>
<td>2.5</td>
<td>-0.31</td>
<td>-0.51</td>
</tr>
<tr>
<td>Square</td>
<td>2.2</td>
<td>4.58</td>
<td>2.4</td>
<td>-0.11</td>
<td>-0.59</td>
</tr>
<tr>
<td>Narrow</td>
<td>19.4</td>
<td>4.68</td>
<td>2.8</td>
<td>0.19</td>
<td>0.48</td>
</tr>
</tbody>
</table>
Figure 6.16: Wide tunnel configuration baseline qualification testing

Figure 6.17: Wide tunnel configuration turbulent kinetic energy map
Figure 6.18: Square tunnel configuration baseline qualification testing

Figure 6.19: Square tunnel configuration turbulent kinetic energy map
Figure 6.20: Narrow tunnel configuration baseline qualification testing

Figure 6.21: Narrow tunnel configuration turbulent kinetic energy map
Appendix B: MATLAB® Codes

Modal Analysis Code

clc
clear all
close all

file1=['C:\Users\Joseph\Desktop\PhD work\good modal data\NewFile1.csv'];
file2=['C:\Users\Joseph\Desktop\PhD work\good modal data\NewFile2.csv'];
file3=['C:\Users\Joseph\Desktop\PhD work\good modal data\NewFile3.csv'];
m1=csvread(file1,10000,1,[10000 1 120001 1]);
m2=csvread(file2,10000,1,[10000 1 120001 1]);
m3=csvread(file3,10000,1,[10000 1 120001 1]);
increment=csvread(file1,1,3,[1 3 1 3]);
len=increment*110001;

%time & Sampling frequency
t=[0:increment:len]; %time vector of full signal
SampFreq=1/(t(2)-t(1)); %calculates sampling frequency
SampPeriod=1/SampFreq;
fprintf('The base sampling frequency is %i Hz',SampFreq)
t=t*1000; %converts to msec
SigL=length(t);

%Distance 1
Dis1=m1(:,1);
Dis1=Dis1+.31;
Dis1=30+Dis1*(50/10); %converted distance
Disnorm1=Dis1/max(abs(Dis1)); %normalized distance
detDis1=detrend(Dis1); %detrends signal to remove FFT spike at signal mean
fourDis1=fft(detDis1); %calculates FFT of distance
P2ofDis1 = abs(fourDis1/SigL);
P1ofDis1 = P2ofDis1(1:SigL/2+1);
P1ofDis1(1:end-1) = 2*P1ofDis1(1:end-1);
fofDis1 = SampFreq*(0:(SigL/2))/SigL;

%Distance 2
Dis2=m2(:,1);
Dis2=30+Dis2*(50/10); %converted distance
Disnorm2=Dis2/max(abs(Dis2)); %normalized distance
detDis2=detrend(Dis2); %detrends signal to remove FFT spike at signal mean
fourDis2=fft(detDis2); %calculates FFT of distance
P2ofDis2 = abs(fourDis2/SigL);
P1ofDis2 = P2ofDis2(1:SigL/2+1);
P1ofDis2(1:end-1) = 2*P1ofDis2(1:end-1);
fofDis2 = SampFreq*(0:(SigL/2))/SigL;

%Distance 3
Dis3=m3(:,1);
Dis3 = 30 + Dis3 * (50/10);\% converted distance
Disnorm3 = Dis3 / max(abs(Dis3));\% normalized distance
detDis3 = detrend(Dis3);\% detrends signal average to remove FFT spike at signal mean
fourDis3 = fft(detDis3);\% calculates FFT of distance

P2ofDis3 = abs(fourDis3 / SigL);
P1ofDis3 = P2ofDis3(1:SigL/2+1);
P1ofDis3(1:end-1) = 2 * P1ofDis3(1:end-1);
fofDis3 = SampFreq * (0:(SigL/2))/SigL;

max1 = fofDis1(find(P1ofDis1 == max(P1ofDis1)))\% finds frequency associated with max value of FFT
max2 = fofDis2(find(P1ofDis2 == max(P1ofDis2)))\% finds frequency associated with max value of FFT
max3 = fofDis3(find(P1ofDis3 == max(P1ofDis3)))\% finds frequency associated with max value of FFT

res1plus = fofDis1(find(P1ofDis1 == max(P1ofDis1))) -
fofDis1(find(P1ofDis1 == max(P1ofDis1)) + 1))
res1neg = fofDis1(find(P1ofDis1 == max(P1ofDis1))) -
fofDis1(find(P1ofDis1 == max(P1ofDis1)) - 1))

res2plus = fofDis2(find(P1ofDis2 == max(P1ofDis2))) -
fofDis2(find(P1ofDis2 == max(P1ofDis2)) + 1))
res2neg = fofDis2(find(P1ofDis2 == max(P1ofDis2))) -
fofDis2(find(P1ofDis2 == max(P1ofDis2)) - 1))

res3plus = fofDis3(find(P1ofDis3 == max(P1ofDis3))) -
fofDis3(find(P1ofDis3 == max(P1ofDis3)) + 1))
res3neg = fofDis3(find(P1ofDis3 == max(P1ofDis3))) -
fofDis3(find(P1ofDis3 == max(P1ofDis3)) - 1))

figure(1)
plot(t,Dis1,t,Dis2,t,Dis3);
grid on
grid minor
legend('Trial 1','Trial 2','Trial 3','northeast')
xlabel('t (msec)'); ylabel('distance from sensor (mm)')

figure(2)
plot(fofDis1,P1ofDis1,fofDis2,P1ofDis2,fofDis3,P1ofDis3)
legend('Trial 1','Trial 2','Trial 3','northeast')
xlabel('f (Hz)')
ylabel('|P1(f)|')
Oscilloscope DATA Analysis Code

clc
clear all
close all

for day=21:1:22
    day=22;
    for j=1:1:36

        file=['C:\Users\jdyge\OneDrive\Desktop\Jan',num2str(day),'\NewFile',num2str(j ),'.csv'];

        m=csvread(file,2,0,[2 0 299903 4]);
        increment=csvread(file,1,6,[1 6 1 6]);
        len=increment*299901;

        %picks length of pulse and pulse frequency based on data file name
        if j==1||j==2||j==3
            % Lpulse=.1158; %length of pulse in seconds
            Pulsefreq=7.5; %pulse frequency in Hz
        elseif j==13||j==14||j==15
            % Lpulse=.1158; %length of pulse in seconds
            Pulsefreq=8.64; %pulse frequency in Hz
        elseif j==25||j==26||j==27
            % Lpulse=.1158; %length of pulse in seconds
            Pulsefreq=8.18; %pulse frequency in Hz
        elseif j==4||j==5||j==6
            % Lpulse=.0772; %length of pulse in seconds
            Pulsefreq=11.25; %pulse frequency in Hz
        elseif j==16||j==17||j==18
            % Lpulse=.0772; %length of pulse in seconds
            Pulsefreq=12.95; %pulse frequency in Hz
        elseif j==28||j==29||j==30
            % Lpulse=.0772; %length of pulse in seconds to the
            % tenth
            Pulsefreq=12.27; %pulse frequency in Hz
        elseif j==7||j==8||j==9
            % Lpulse=.0579; %length of pulse in seconds to the
            % tenth
            Pulsefreq=15.00; %pulse frequency in Hz
        elseif j==19||j==20||j==21
            % Lpulse=.0579; %length of pulse in seconds to the
            % tenth
            Pulsefreq=17.27; %pulse frequency in Hz
        elseif j==31||j==32||j==33
            % Lpulse=.0579; %length of pulse in seconds to the
            % tenth
            Pulsefreq=16.36; %pulse frequency in Hz
        elseif j==10||j==11||j==12
            % Lpulse=.0463; %length of pulse in seconds to the
            % tenth
            Pulsefreq=18.75; %pulse frequency in Hz
        elseif j==22||j==23||j==24

    end
end
Lpulse = .0463; % length of pulse in seconds to the
tenth
Pulsefreq = 21.59; % pulse frequency in Hz

elseif j == 34 || j == 35 || j == 36
Lpulse = .0463; % length of pulse in seconds to the
tenth
Pulsefreq = 20.45; % pulse frequency in Hz
end

Lpulse = .0463; % length of pulse in seconds

% time & Sampling frequency
t = [0:increment:len]; % time vector of full signal
tpulse = [0:increment:Lpulse]; % time vector of a single pulse
SampFreq = 1 / (t(2) - t(1)); % calculates sampling frequency
SampPeriod = 1 / SampFreq; % calculates sampling period
t = t * 1000; % converts to msec
tpulse = tpulse * 1000; % converts to msec
SigL = length(t);

% Current
I = m(:,2);
I = 1000*I; % converts to milliamps
Ifilt = lowpass(I, 5000, SampFreq); % lowpass filter of current

% High Voltage Lead
V = m(:,3);
V = (V/1000); % converts to KiloVolts

% Monitor Capacitor Voltage
Vmon = m(:,4);
Vmon = lowpass(Vmon, 50000, SampFreq); % lowpass filter of monitoring voltage

windowSize = 13;
b = (1/windowSize) * ones(1, windowSize);
a = 1;
Vmonfilt = filter(b, a, Vmon);
Qmon = (.000000022) * Vmon;
Qmonfilt = (.000000022) * Vmonfilt;

% Optical Distance
sensordist = 67; % distance to sensor from flat plate in millimeters
Dis = m(:,5);
Dis = 30 + Dis * (50/10); % sensor relation from voltage to distance
height = sensordist - Dis; % converts distance from sensor to height from plate

windowSize = 29;
b = (1/windowSize) * ones(1, windowSize);
heightfilt = filter(b, a, height); % filters height
heightnorm = heightfilt / max(heightfilt); % normalized distance

% FFT of distance
detDis = detrend(Dis); % detrends signal to remove FFT spike at signal mean
fourDis = fft(detDis); % calculates FFT of distance
P2ofDis = abs(fourDis / SigL);
P1ofDis = P2ofDis(1:SigL/2+1);
PlofDis(1:end-1) = 2*PlofDis(1:end-1);
fofDis = SampFreq*(0:(SigL/2))/SigL;
Plotaxiscale=max(PlofDis)+.1;

%Power
P=I.*V;%power in watts
Pfilt=Ifilt.*V;%filtered power in watts

% The following two sections of if-elseif-else statements are for
% calculating the Vrms and Irms of a section of a pulse-on phase
if day==21
    if j==5
        start=150000-round(Lpulse/(3*increment));
pulseindex=start+round(Lpulse/(3*increment));
        Irms(j)=rms(Ifilt(start:pulseindex));
        Vrms(j)=rms(V(start:pulseindex));
    elseif j==12
        start=.2694/increment;
pulseindex=start+round(Lpulse/(3*increment));
        Irms(j)=rms(Ifilt(start:pulseindex));
        Vrms(j)=rms(V(start:pulseindex));
    elseif j==13 || j==14
        start=.2724/increment;
pulseindex=start+round(Lpulse/(3*increment));
        Irms(j)=rms(Ifilt(start:pulseindex));
        Vrms(j)=rms(V(start:pulseindex));
    elseif j==35
        start=.2784/increment;
pulseindex=start+round(Lpulse/(3*increment));
        Irms(j)=rms(Ifilt(start:pulseindex));
        Vrms(j)=rms(V(start:pulseindex));
    else
        pulseindex=150000+round(Lpulse/(3*increment));
        Irms(j)=rms(Ifilt(150000:pulseindex));
        Vrms(j)=rms(V(150000:pulseindex));
    end
end
if day==22
    if j==5
        start=150000-round(Lpulse/(3*increment));
pulseindex=start+round(Lpulse/(3*increment));
        Irms(j)=rms(Ifilt(start:pulseindex));
        Vrms(j)=rms(V(start:pulseindex));
    elseif j==6
        start=.2564/increment;
pulseindex=start+round(Lpulse/(3*increment));
        Irms(j)=rms(Ifilt(start:pulseindex));
        Vrms(j)=rms(V(start:pulseindex));
    elseif j==8
        start=.2784/increment;
pulseindex=start+round(Lpulse/(3*increment));
        Irms(j)=rms(Ifilt(start:pulseindex));
Vrms(j) = rms(V(start:pulseindex));

else
    pulseindex = 150000 + round(Lpulse/(3*increment));
    Irms(j) = rms(Ifilt(150000:pulseindex));
    Vrms(j) = rms(V(150000:pulseindex));
end
end

% this part calculates the power based off of area of lissajous
% diagram and filtered power based off of filtered area of lissajous
% diagram based on filtered monitoring capacitor voltage

Numcycles = (round(len/.001) - 1); % calculates #AC cycles - 1 that occur
during sample length

for cyc = 1:1:Numcycles
    ind = find(t >= (((cyc - 1)*1) + t(1)) & (t <= ((cyc)*1)));
    V2 = V(ind);
    Qmon2 = Qmon(ind);
    Qmonfilt2 = Qmonfilt(ind);

    % area inside Lissajous curve
    [k, Area] = boundary(V2*1000, Qmon2, .5);
    [kfilt, Afilt] = boundary(V2*1000, Qmonfilt2, .5);
    Pmon(cyc) = Area*1000*2*3.1415;
    Pmonfilt(cyc) = Afilt*1000*2*3.1415;
end

Pmonmean(j) = mean(Pmon);
Pmonfiltmean(j) = mean(Pmonfilt);

% plots
figure(1)
subplot(4,1,1)
plot(t,V);
axis([0 max(t) -10 10])
grid on
grid minor
xlabel('t (msec)'); ylabel('V (kV)');

subplot(4,1,2)
plot(t,I,t,Ifilt);
axis([0 max(t) -25 25])
grid on
grid minor
xlabel('t (msec)'); ylabel('I (mA)');

subplot(4,1,3)
plot(t,P,t,Pfilt);
axis([0 max(t) -120 120])
grid on
grid minor
xlabel('t (msec)'); ylabel('P (w)');
subplot(4,1,4)  
yyaxis left  
plot(t,Vmon);  
axis([0 max(t) -2.5 2.5])  
yyaxis right  
plot(t,heightfilt)  
grid on  
grids minor  
xlabel('t (msec)');yyaxis left; ylabel('Vm (V)');yyaxis right;  
ylabel('Height (mm)')  
saveas(figure(1),[C:\Users\jdyge\OneDrive\Desktop\good oscope data\Trial ',num2str(j),'\Jan',num2str(day),' Electrical Data.fig']);  
saveas(figure(1),[C:\Users\jdyge\OneDrive\Desktop\good oscope data\Trial ',num2str(j),'\Jan',num2str(day),' Electrical Data.jpg']);  
figure(2)  
plot(V,Qmon,V,Qmonfilt);  
axis([-12 12 -4e-7 4e-7])  
grids on  
grids minor  
xlabel('V (kV)'); ylabel('Q (C)');  
saveas(figure(2),[C:\Users\jdyge\OneDrive\Desktop\good oscope data\Trial ',num2str(j),'\Jan',num2str(day),' Lissajous.fig']);  
saveas(figure(2),[C:\Users\jdyge\OneDrive\Desktop\good oscope data\Trial ',num2str(j),'\Jan',num2str(day),' Lissajous.jpg']);  
figure(3)  
plot(fofDis,P1ofDis)  
xline(Pulsefreq);  
axis([0 30 0 Plotaxiscale])  
grids on  
grids minor  
xlabel('f (Hz)'); ylabel('|P1(f)|')  
saveas(figure(3),[C:\Users\jdyge\OneDrive\Desktop\good oscope data\Trial ',num2str(j),'\Jan',num2str(day),' FFT.fig']);  
saveas(figure(3),[C:\Users\jdyge\OneDrive\Desktop\good oscope data\Trial ',num2str(j),'\Jan',num2str(day),' FFT.jpg']);  
end  
end
High Speed Video Analysis Code

clc
clear all
close all

for day = 21:1:22
    for Trial = 1:1:36

    \% video tag identifier

    if day==21
        D=1;
        if Trial==1;         tag=1579628969;
        elseif Trial==2;     tag=1579629249;
        elseif Trial==3;     tag=1579629501;
        elseif Trial==4;     tag=1579629711;
        elseif Trial==5;     tag=1579629897;
        elseif Trial==6;     tag=1579630106;
        elseif Trial==7;     tag=1579630345;
        elseif Trial==8;     tag=1579630571;
        elseif Trial==9;     tag=1579630746;
        elseif Trial==10;    tag=1579630955;
        elseif Trial==11;    tag=1579631184;
        elseif Trial==12;    tag=1579631373;
        elseif Trial==13;    tag=1579631905;
        elseif Trial==14;    tag=1579632109;
        elseif Trial==15;    tag=1579632354;
        elseif Trial==16;    tag=1579632557;
        elseif Trial==17;    tag=1579632777;
        elseif Trial==18;    tag=1579632954;
        elseif Trial==19;    tag=1579633411;
        elseif Trial==20;    tag=1579633592;
        elseif Trial==21;    tag=1579633779;
        elseif Trial==22;    tag=1579633958;
        elseif Trial==23;    tag=1579634198;
        elseif Trial==24;    tag=1579634438;
        elseif Trial==25;    tag=1579634840;
        elseif Trial==26;    tag=1579635041;
        elseif Trial==27;    tag=1579635224;
        elseif Trial==28;    tag=1579635408;
        elseif Trial==29;    tag=1579635628;
        elseif Trial==30;    tag=1579635818;
        elseif Trial==31;    tag=1579636005;
        elseif Trial==32;    tag=1579636426;
        elseif Trial==33;    tag=1579636720;
        elseif Trial==34;    tag=1579636922;
        elseif Trial==35;    tag=1579637100;
        elseif Trial==36;    tag=1579637460;
        end
    elseif day==22

end
D=2;
if Trial==1;         tag=1579710504;
elseif Trial==2;     tag=1579710784;
elseif Trial==3;     tag=1579711046;
elseif Trial==4;     tag=1579711213;
elseif Trial==5;     tag=1579711477;
elseif Trial==6;     tag=1579711663;
elseif Trial==7;     tag=1579711901;
elseif Trial==8;     tag=1579712110;
elseif Trial==9;     tag=1579712343;
elseif Trial==10;    tag=1579712521;
elseif Trial==11;    tag=1579712787;
elseif Trial==12;    tag=1579712978;
elseif Trial==13;    tag=1579713359;
elseif Trial==14;    tag=1579713574;
elseif Trial==15;    tag=1579714044;
elseif Trial==16;    tag=1579714233;
elseif Trial==17;    tag=1579714420;
elseif Trial==18;    tag=1579714608;
elseif Trial==19;    tag=1579714821;
elseif Trial==20;    tag=1579715010;
elseif Trial==21;    tag=1579715183;
elseif Trial==22;    tag=1579715363;
elseif Trial==23;    tag=1579715546;
elseif Trial==24;    tag=1579715731;
elseif Trial==25;    tag=1579720533;
elseif Trial==26;    tag=1579720855;
elseif Trial==27;    tag=1579721032;
elseif Trial==28;    tag=1579721233;
elseif Trial==29;    tag=1579721411;
elseif Trial==30;    tag=1579721619;
elseif Trial==31;    tag=1579721826;
elseif Trial==32;    tag=1579722037;
elseif Trial==33;    tag=1579722224;
elseif Trial==34;    tag=1579722443;
elseif Trial==35;    tag=1579722647;
elseif Trial==36;    tag=1579722821;
end
end

file=['C:\Users\jdyge\OneDrive\Desktop\Jan',num2str(day),'\Video\slomo_',num2str(tag),'.mov'];
vid=VideoReader(file);
mov=read(vid);

numframes = size(mov, 4);% calculates number of frames in movie
frameW = size(mov, 2);% calculates width of frames in movie
frameH = size(mov, 1);% calculates height of frames in movie
pixelfactor=1.25/(sqrt((200^2)+(90^2))));% Linear length of 1 pixel in inches
framerate=1000; % framerate

% this part of the code converts the video into black and white based on pixel intensity and the cut off threshold
for k = numframes:-1:1
```matlab
    g(:, :, k)=im2bw(mov(:, :, :, k),.01);
    if Trial==10 && day==22
        g(1:18,1:33,k)=0; %masks out reflection in top corner
    end

    bottom=124; %pixel location of the dielectric surface (where the electrode lays flat)

    for k = 1:1:numframes %cycles through each video frame
      pos=1;
      edgefound=0;
      for j= 1:1:300 %cycles through each image from left to right to find the tip of the CED stops at 300 because thats where the CED stops
        height=0;
        underCE=0;
        i=bottom;
        while underCE==0
            if i==1 %if i has made it to the top without finding the CED then
                %2 possible outcomes the edge hasnt been found or there is CED pixels that are blackened out and set the CED height equal to the height to left.
                if edgefound==0 %edge hasnt been found thus not under CED
                    height=0;
                    underCE=1;
                else %edge was found so pixel is missing and edges estimated as the height of the position to the left.
                    H(pos)=H(pos-1);
                    pos=pos+1;
                    underCE=1;
                end
            else
                if g(i, j, k)==0
                    height=height+1;
                    i=i-1;
                else
                    underCE=1;
                    H(pos)=height;
                    pos=pos+1;
                    edgefound=1;
                    if pos==2
                        y(k)=j;
                        end
                    end
                end
            end
        end
    end
```
end
Volume(k)=(pixelfactor^2)*sum(H);
Exitarea(k)=pixelfactor*H(1);
end

VAratio=Volume./Exitarea; %calculates the volume/exit area ratio
K=[1:1:numframes]; %makes a frame vector
 t=K/framerate; %converts frame vector to time vector

stroke(D,Trial)=(max(Exitarea)-min(Exitarea))/max(Exitarea);
stroke2(D,Trial)=(max(Exitarea)-min(Exitarea))./75;

%this part calculates the velocity of the tip
voftip(1)=0;
voftip(2)=0;
voftip(numframes)=0;
voftip(numframes-1)=0;
for d=3:1:numframes-2
    voftip(d)=((sqrt(((Exitarea(d+2)-Exitarea(d-2))^2)+((pixelfactor*(y(d+2)-y(d-2)))^2)))/(4/1000));
end
voftipsmooth=smooth(voftip,5);

if day==21
    index=1;
else
    index=2;
end
meanVel(index,Trial)=mean(voftipsmooth);

% exit area (tip height) plot
figure (1)
subplot(4,1,1)
plot(t,Exitarea)
xlabel('time (s)')
ylabel('Height(in)')
axis([0 max(t) 0 .85])

% volume (cross sectional area) plot
subplot(4,1,2)
plot(t,Volume)
xlabel('time (s)')
ylabel('Area(in^2)')
axis([0 max(t) 0 .5])

% volume/area (VAratio) plot
subplot(4,1,3)
plot(t,VAratio)
xlabel('time (s)')
ylabel('Area/Height(in)')
axis([0 max(t) 0 .75])

% velocity of tip plot
subplot(4,1,4)
plot(t, voftip, t, voftipsmooth)
xlabel('time (s)')
ylabel('Velocity(in/s)')
axis([0 max(t) 0 30])

saveas(figure(1), ['C:\Users\jdyge\OneDrive\Desktop\good video data\trial', num2str(Trial), '\HS-Video Jan', num2str(day), ' Data.fig']);
saveas(figure(1), ['C:\Users\jdyge\OneDrive\Desktop\good video data\trial', num2str(Trial), '\HS-Video Jan', num2str(day), ' Data.jpg']);

    end
end
PIV DATA Analysis Code

clc
clear all
close all

rho=1.13; %air density
columns=158;
rows=76;

for model=1:1:3 %cycles through all 3 models
    if model==1
        AR="wide";
    elseif model==2
        AR="square";
    else
        AR="narrow";
    end

    % executes graphing, momentum, energy and tke for tunnel clean
    % and model off
    for baseline=1:1:2
        if baseline==1
            bslAvg="CleanAvg";
            bsl="Clean";
        elseif baseline==2
            bslAvg="ModelOffAvg";
            bsl="ModelOff";
        end

        filepath=fullfile('C:\Users\jdyge\OneDrive\Desktop\PIV data\',AR,'\',bslAvg,'\',"B00001.dat");
        file = importdata(filepath); %import average vector field for tunnel clean
        PIVavg=file.data;

        % set each column of the PIV file into x,y,u,v vectors
        X=PIVavg(:,1);
        Y=PIVavg(:,2);
        U=PIVavg(:,3);
        V=PIVavg(:,4);

        % reshape the vectors into matrices (Note: columns is number of rows in PIV data
        % that got turned into columns)
        X=(reshape(X,columns,[]))';
        Y=(reshape(Y,columns,[]))';
        U=(reshape(U,columns,[]))';
        V=(reshape(V,columns,[]))';

        % Flowfield plots for average vector field
        startx=X(1:3:rows,columns);
starty=Y(1:3:rows,(columns-1)); %startx and starty together tell the streamline function to start on the right hand side of the plot and "flow" towards the exit. the 6 tells it to start at every 6th data point

figure(1)
quiver(X,Y,U,V);
streamline(X,Y,U,V,startx,starty)
xlabel('X-axis (mm)')
ylabel('Y-axis (mm)')

figure(2)
quiver(X(1:6:end),Y(1:6:end),U(1:6:end),V(1:6:end),2);
rectangle('Position',[X(1,57) Y(64) 83 34])
xlabel('X-axis (mm)')
ylabel('Y-axis (mm)')

figure(3)
z=sqrt(U.^2+V.^2);
contourf(X,Y,z)
c=colorbar;
c.Label.String = 'velocity (m/s)';
xlabel('X-axis (mm)')
ylabel('Y-axis (mm)')

% Conservation of Mass, Momentum, and Energy

inlet=141; % column location of inlet to CV
outlet=58; % column location of outlet to CV
base=64; % row location of base of CV
top=30; % row location of top of CV

dyInlet=(Y(base:-1:top,inlet))/1000;
dyOutlet=(Y(base:-1:top,outlet))/1000;
dxTop=(X(top,outlet:inlet))/1000;

UInlet=U(base:-1:top,inlet);
VInlet=V(base:-1:top,inlet);

UTop=U(top,outlet:inlet);
VTop=V(top,outlet:inlet);

UOutlet=U(base:-1:top,outlet);
VOutlet=V(base:-1:top,outlet);

% conservation of mass
MassfluxInlet=rho*trapz(dyInlet,(UInlet));
MassfluxOutlet=rho*trapz(dyOutlet,(UOutlet));
MassfluxTop=rho*trapz(dxTop,(VTop));
TunnelbaselineMassFlux(model,baseline)=MassfluxInlet-MassfluxOutlet+MassfluxTop;

% momentum
XMomfluxInlet=rho*trapz(dyInlet,(UInlet.*UInlet));
XMomfluxOutlet=rho*trapz(dyOutlet,(UOutlet.*UOutlet));
XMomfluxTop=rho*trapz(dxTop,(VTop.*VTop));
TunnelbaselineXMomFlux(model,baseline)=XMomfluxInlet-XMomfluxOutlet+XMomfluxTop;

% Momentum
YMomfluxInlet=rho*trapz(dyInlet,(VInlet.*UInlet));
YMomfluxOutlet=rho*trapz(dyOutlet,(VOutlet.*UOutlet));
YMomfluxTop=rho*trapz(dxTop,(VTop.*VTop));
TunnelbaselineYMomFlux(model,baseline)= YMomfluxInlet-YMomfluxOutlet+YMomfluxTop;

% Energy
EinIntegrand=(UInlet.^2+VInlet.^2).*UInlet;
EoutIntegrand=(UOutlet.^2+VOutlet.^2).*UOutlet;
EtopIntegrand=(UTop.^2+VTop.^2).*VTop;
EfluxInlet=.5*rho*trapz(dyInlet,EinIntegrand);
EfluxOutlet=.5*rho*trapz(dyOutlet,EoutIntegrand);
EfluxTop=.5*rho*trapz(dxTop,EtopIntegrand);
TunnelbaselineEnergyFlux(model,baseline)=EfluxInlet-EfluxOutlet+EfluxTop;

% Turbulent Kinetic Energy
uPrimeSquared=zeros(rows,columns,100);
vPrimeSquared=zeros(rows,columns,100);

for imageset=1:1:100 % cycles through 100 instantaneous images

    if imageset<10
        fileID=sprintf('B0000%d.dat',imageset);
    elseif imageset<100
        fileID=sprintf('B000%d.dat',imageset);
    else
        fileID=sprintf('B00%d.dat',imageset);
    end

    filepath=fullfile('C:\Users\jdyge\OneDrive\Desktop\PIV data\AR\bsl',fileID);
    file = importdata(filepath);
    PIVinstant=file.data;

    % set each column of the PIV file into x,y,u,v vectors
    x=PIVinstant(:,1);
y=PIVinstant(:,2);
u=PIVinstant(:,3);
v=PIVinstant(:,4);

    % reshape the vectors into matrices (Note: columns is number of rows in PIV data
    x=(reshape(x,columns,[]))';
y=(reshape(y,columns,[]))';
u=(reshape(u,columns,[]))';
v=(reshape(v,columns,[]))';
uPrime=U-u;
\[ uPrimeSquared = uPrime^2 \]

vPrime=V-v;
\[ vPrimeSquared = vPrime^2 \]

end %end for instantaneous image cycling

uMeanwindow=mean(uPrimeSquared,3);
vMeanwindow=mean(vPrimeSquared,3);

\[ tkeM = 0.5 \times (uMeanwindow + vMeanwindow) \]

figure(4)
surface(X,Y,tkeMAP)
xlabel('X-axis (mm)')
ylabel('Y-axis (mm)')

turb=sqrt(tkeMAP);
%turbulence intensity

\[ ti = turb./(z) \]

TIdim1=mean(ti(top:60,(outlet+4):(inlet-4)));
TI(model,baseline)=mean(TIdim1);

figsavepath=fullfile('C:','Users','jdyge','OneDrive','Desktop','PIV data','AR','bslAvg','Quiver.fig');
jpgsavepath=fullfile('C:','Users','jdyge','OneDrive','Desktop','PIV data','AR','bslAvg','Quiver.jpg');
saveas(figure(1),figsavepath);
saveas(figure(1),jpgsavepath);

figsavepath=fullfile('C:','Users','jdyge','OneDrive','Desktop','PIV data','AR','bslAvg','ReducedQuiver.fig');
jpgsavepath=fullfile('C:','Users','jdyge','OneDrive','Desktop','PIV data','AR','bslAvg','ReducedQuiver.jpg');
saveas(figure(2),figsavepath);
saveas(figure(2),jpgsavepath);

figsavepath=fullfile('C:','Users','jdyge','OneDrive','Desktop','PIV data','AR','bslAvg','Velocity Contour.fig');
jpgsavepath=fullfile('C:','Users','jdyge','OneDrive','Desktop','PIV data','AR','bslAvg','Velocity Contour.jpg');
saveas(figure(3),figsavepath);
saveas(figure(3),jpgsavepath);

figsavepath=fullfile('C:','Users','jdyge','OneDrive','Desktop','PIV data','AR','bslAvg','tkeMAP.fig');
jpgsavepath=fullfile('C:','Users','jdyge','OneDrive','Desktop','PIV data','AR','bslAvg','tkeMAP.jpg');
saveas(figure(4),figsavepath);
saveas(figure(4),jpgsavepath);

close all
clearvars tkeMAP uMeanwindow vMeanwindow X x y Y u V v z uPrimeSquared
vPrimeSquared ti turb TIdim1

end % end for baseline cycling
%end for clean tunnel analysis

for tunnelstatus=1:1:2 % for cycling through tunnel on/off setting
    if tunnelstatus==1
tunnel="TunnelOn";
    elseif tunnelstatus==2
        tunnel="TunnelOff";
    end

    for position=1:1:11 % cycles through all positions of the flap cycle
        positionvec(position)=position;
        filenameAvg=sprintf('position%davg',position);
        filepath=fullfile('C:\','Users','jdyge','OneDrive','Desktop','PIV
data\AR','\',tunnel,'\',filenameAvg,'\','B00001.dat'));
        file = importdata(filepath); % import average vector field
        PIVavg=file.data;

        % set each column of the PIV file into x,y,u,v vectors
        X=PIVavg(:,1);
        Y=PIVavg(:,2);
        U=PIVavg(:,3);
        V=PIVavg(:,4);

        % reshape the vectors into matrices (Note: 347 is number of rows in PIV data
        % that got turned into columns)
        X=(reshape(X,columns,[]))';
        Y=(reshape(Y,columns,[]))';
        U=(reshape(U,columns,[]))';
        V=(reshape(V,columns,[]))';

        % Flowfield plots for average vector field
        startx=X(1:3:rows,(columns-1));
        starty=Y(1:3:rows,(columns-1)); % startx and starty together tell the
        streamline function to start on the right hand side of the plot and "flow"
        towards the exit. The 6 tells it to start at every 6th data point

        figure(1)
quiver(X,Y,U,V);
        streamline(X,Y,U,V,startx,starty)
        xlabel('X-axis (mm)')
        ylabel('Y-axis (mm)')
quiver(X(1:6:end),Y(1:6:end),U(1:6:end),V(1:6:end),2);
rectangle('Position',[X(1,75) Y(25) 10 10])
rectangle('Position',[X(1,50) Y(62) 10 10])
xlabel('X-axis (mm)')
ylabel('Y-axis (mm)')
figure(3)
z=sqrt(U.^2+V.^2);
contourf(X,Y,z)
c=colorbar;
c.Label.String = 'velocity (m/s)';
xlabel('X-axis (mm)')
ylabel('Y-axis (mm)')

%induced velocity analysis, Finding velocity in windows

Vwindow1inlet=85;
Vwindow1outlet=75;
Vwindow1base=25;
Vwindow1top=15;

Vwindow2inlet=60;
Vwindow2outlet=50;
Vwindow2base=62;
Vwindow2top=52;

avgVelWindow1(position)=mean(mean(z(Vwindow1top:Vwindow1base,Vwindow1inlet:Vwindow1outlet)));
MaxVelWindow1(position)=max(max(z(Vwindow1top:Vwindow1base,Vwindow1inlet:Vwindow1outlet)));

avgVelWindow2(position)=mean(mean(z(Vwindow2top:Vwindow2base,Vwindow2inlet:Vwindow2outlet)));
MaxVelWindow2(position)=max(max(z(Vwindow2top:Vwindow2base,Vwindow2inlet:Vwindow2outlet)));

%Conservation of Mass, Momentum and Energy

inlet=141; %column location of inlet to CV
outlet=58; %column location of inlet to CV
base=64; %row location of base of CV
top=30; %row location of top of CV

dyInlet=(Y(base-1:top,inlet))/1000;
dyOutlet=(Y(base-1:top,outlet))/1000;
dxTop=(X(top,outlet-inlet))/1000;

UInlet=U(base-1:top,inlet);
VINlet=V(base-1:top,inlet);

UTop=U(top,outlet-inlet);
VTop=V(top,outlet-inlet);
UOutlet=U(base:-1:top,outlet);
VOutlet=V(base:-1:top,outlet);

% conservation of mass
MassfluxInlet(position)=rho*trapz(dyInlet,(UInlet));
MassfluxOutlet(position)=rho*trapz(dyOutlet,(UOutlet));
MassfluxTop(position)=rho*trapz(dxTop,(VTop));
Massflux(position)=MassfluxInlet(position)-MassfluxOutlet(position)+MassfluxTop(position);

%Xmomentum
XMomfluxInlet(position)=rho*trapz(dyInlet,(UInlet.*UInlet));
XMomfluxOutlet(position)=rho*trapz(dyOutlet,(UOutlet.*UOutlet));
XMomfluxTop(position)=rho*trapz(dxTop,(UTop.*VTop));
XMomflux(position)=XMomfluxInlet(position)-XMomfluxOutlet(position)+XMomfluxTop(position);

%Ymomentum
YMomfluxInlet(position)=rho*trapz(dyInlet,(VInlet.*UInlet));
YMomfluxOutlet(position)=rho*trapz(dyOutlet,(VOutlet.*UOutlet));
YMomfluxTop(position)=rho*trapz(dxTop,(UTop.*VTop));
YMomflux(position)=YMomfluxInlet(position)-YMomfluxOutlet(position)+YMomfluxTop(position);

% Energy
EinIntegrand=(UInlet.^2+VInlet.^2).*UInlet;
EoutIntegrand=(UOutlet.^2+VOutlet.^2).*UOutlet;
EtopIntegrand=(UTop.^2+VTop.^2).*VTop;

EfluxInlet(position)=.5*rho*trapz(dyInlet,EinIntegrand);
EfluxOutlet(position)=.5*rho*trapz(dyOutlet,EoutIntegrand);
EfluxTop(position)=.5*rho*trapz(dxTop,EtopIntegrand);
EnergyFlux(position)=EfluxInlet(position)-EfluxOutlet(position)+EfluxTop(position);

% Turbulent Kinetic Energy
uPrimeSquared=zeros(rows,columns,100);
vPrimeSquared=zeros(rows,columns,100);

for imageset=1:1:100 % cycles through 100 instantaneous images

    filename=sprintf('position%d',position);
    if imageset<10
        fileID=sprintf('B0000%d.dat',imageset);
    elseif imageset<100
        fileID=sprintf('B000%d.dat',imageset);
    else
        fileID=sprintf('B00%d.dat',imageset);
    end
filepath = fullfile('C:\', 'Users\', 'jdyge\', 'OneDrive\', 'Desktop\', 'PIV data\', 'AR', '\', 'tunnel', '\', 'filename', '\', 'fileID');
file = importdata(filepath);
PIVInstant = file.data;

% set each column of the PIV file into x, y, u, v vectors
x = PIVInstant(:, 1);
y = PIVInstant(:, 2);
u = PIVInstant(:, 3);
v = PIVInstant(:, 4);

% reshape the vectors into matrices (Note: columns is number of rows in PIV data)
% that got turned into columns)
x = (reshape(x, columns, []))';
y = (reshape(y, columns, []))';
u = (reshape(u, columns, []))';
v = (reshape(v, columns, []))';

uPrime = U - u;
uPrimeSquared(1:rows, 1:columns, imageset) = uPrime.^2;

vPrime = V - v;
vPrimeSquared(1:rows, 1:columns, imageset) = vPrime.^2;

end % end for instantaneous image cycling

uMeanwindow = mean(uPrimeSquared, 3);
vMeanwindow = mean(vPrimeSquared, 3);
tkeMAP = 0.5*(uMeanwindow + vMeanwindow);

figure(4)
surface(X, Y, tkeMAP)
xlabel('X-axis (mm)')
ylabel('Y-axis (mm)')

TKEwindow1(position) = mean(mean(tkeMAP(Vwindow1top:Vwindow1base, Vwindow1outlet : Vwindow1inlet)));

TKEwindow2(position) = mean(mean(tkeMAP(Vwindow2top:Vwindow2base, Vwindow2outlet : Vwindow2inlet)));

figsavepath = fullfile('C:\', 'Users\', 'jdyge\', 'OneDrive\', 'Desktop\', 'PIV data\', 'AR', '\', 'tunnel', '\', 'filenameAvg', '\', 'Quiver.fig');
jpgsavepath = fullfile('C:\', 'Users\', 'jdyge\', 'OneDrive\', 'Desktop\', 'PIV data\', 'AR', '\', 'tunnel', '\', 'filenameAvg', '\', 'Quiver.jpg');
saveas(figure(1), figsavepath);
saveas(figure(1), jpgsavepath);
figsavepath = fullfile('C:\Users\jdyge\OneDrive\Desktop\PIV data\AR', '\', 'tunnel', '\', 'filenameAvg', '\', 'ReducedQuiver.fig');
jpgsavepath = fullfile('C:\Users\jdyge\OneDrive\Desktop\PIV data\AR', '\', 'tunnel', '\', 'filenameAvg', '\', 'ReducedQuiver.jpg');
saveas(figure(2), figsavepath);
saveas(figure(2), jpgsavepath);

figsavepath = fullfile('C:\Users\jdyge\OneDrive\Desktop\PIV data\AR', '\', 'tunnel', '\', 'filenameAvg', '\', 'Velocity Contour.fig');
jpgsavepath = fullfile('C:\Users\jdyge\OneDrive\Desktop\PIV data\AR', '\', 'tunnel', '\', 'filenameAvg', '\', 'Velocity Contour.jpg');
saveas(figure(3), figsavepath);
saveas(figure(3), jpgsavepath);

figsavepath = fullfile('C:\Users\jdyge\OneDrive\Desktop\PIV data\AR', '\', 'tunnel', '\', 'filenameAvg', '\', 'tkeMAP.fig');
jpgsavepath = fullfile('C:\Users\jdyge\OneDrive\Desktop\PIV data\AR', '\', 'tunnel', '\', 'filenameAvg', '\', 'tkeMAP.jpg');
saveas(figure(4), figsavepath);
saveas(figure(4), jpgsavepath);

close all

clearvars tkeMAP uMeanwindow vMeanwindow X y U v z uPrimeSquared vPrimeSquared

end %end for position cycling

MassFluxflap(model, tunnelstatus) = mean(MassFlux);
Xmomflap(model, tunnelstatus) = mean(XMomFlux);
Ymomflap(model, tunnelstatus) = mean(YMomFlux);
Eflap(model, tunnelstatus) = mean(EnergyFlux);

VelWindow1Avg(model, tunnelstatus) = mean(avgVelWindow1);
VelWindow1Max(model, tunnelstatus) = mean(MaxVelWindow1);
VelWindow2Avg(model, tunnelstatus) = mean(avgVelWindow2);
VelWindow2Max(model, tunnelstatus) = mean(MaxVelWindow2);

if tunnelstatus == 1
ARVelWindow1meansTunnelon(model, :) = avgVelWindow1;
ARVelWindow2meansTunnelon(model, :) = avgVelWindow2;
else
ARVelWindow1meansTunneloff(model, :) = avgVelWindow1;
ARVelWindow2meansTunneloff(model, :) = avgVelWindow2;
end

figure(5)
subplot(4,1,1)
plot(positionvec, MassFlux, positionvec, MassfluxInlet, positionvec, MassfluxOutlet, positionvec, MassfluxTop)
xlabel('position in flap')
ylabel('Mass Flux')
legend({'MassFlux', 'MassInlet', 'MassOutlet', 'MassTop'}, 'Location', 'eastoutside')

subplot(4,1,2)
plot(positionvec, XMomFlux, positionvec, XMomfluxInlet, positionvec, XMomfluxOutlet, positionvec, XMomfluxTop)
xlabel('position in flap')
ylabel('Momentum X')
legend({'XMomFlux', 'XMomInlet', 'XMomOutlet', 'XMomTop'}, 'Location', 'eastoutside')

subplot(4,1,3)
plot(positionvec, YMomFlux, positionvec, YMomfluxInlet, positionvec, YMomfluxOutlet, positionvec, YMomfluxTop)
xlabel('position in flap')
ylabel('Momentum Y')
legend({'YMomFlux', 'YMomInlet', 'YMomOutlet', 'YMomTop'}, 'Location', 'eastoutside')

subplot(4,1,4)
plot(positionvec, EnergyFlux, positionvec, EfluxInlet, positionvec, EfluxOutlet, positionvec, EfluxTop)
xlabel('position in flap')
ylabel('Energy Flux')
legend({'EnergyFlux', 'EfluxInlet', 'EfluxOutlet', 'EfluxTop'}, 'Location', 'eastoutside')

figure(6)
plot(positionvec, avgVelWindow1, positionvec, avgVelWindow2)
xlabel('position in flap')
ylabel('Avg Velocity in Window 1 and 2 (m/s)')
legend('Window1', 'Window2')

figure(7)
plot(positionvec, TKEwindow1, positionvec, TKEwindow2)
xlabel('position in flap')
ylabel('Avg tke in Window 1 and 2 (J/kg)')
legend('Window1', 'Window2')

figsavepath=fullfile('C:\', 'Users\', 'jdyge\', 'OneDrive\', 'Desktop\', 'PIV data\', AR, '\', 'tunnel\', '\', 'flux vs flap position.fig');
jpgsavepath=fullfile('C:\', 'Users\', 'jdyge\', 'OneDrive\', 'Desktop\', 'PIV data\', AR, '\', 'tunnel\', '\', 'flux vs flap position.jpg');
saveas(figure(5), figsavepath);
saveas(figure(5), jpgsavepath);

figsavepath=fullfile('C:\', 'Users\', 'jdyge\', 'OneDrive\', 'Desktop\', 'PIV data\', AR, '\', 'tunnel\', '\', 'WindowVelocities.fig');
jpgsavepath=fullfile('C:\', 'Users\', 'jdyge\', 'OneDrive\', 'Desktop\', 'PIV data\', AR, '\', 'tunnel\', '\', 'WindowVelocities.jpg');
saveas(figure(6), figsavepath);
saveas(figure(6), jpgsavepath);

figsavepath=fullfile('C:\', 'Users\', 'jdyge\', 'OneDrive\', 'Desktop\', 'PIV data\', AR, '\', 'tunnel\', '\', 'WindowTKE.fig');
jpgsavepath=fullfile('C:\', 'Users\', 'jdyge\', 'OneDrive\', 'Desktop\', 'PIV data\', AR, '\', 'tunnel\', '\', 'WindowTKE.jpg');
saveas(figure(7),figsavepath);
saveas(figure(7),jpgsavepath);

    end %end for tunnelon/off cycling
close all

end %end for model cycling aka end of code

figure(8)
plot(positionvec,ARVelWindow2meansTunnelon(1,:),positionvec,ARVelWindow2meansTunnelon(2,:),positionvec,ARVelWindow2meansTunnelon(3,:))
xlabel('position in flap')
ylabel('Avg Velocity in Window 2 (m/s)')
legend('Wide','Square','Narrow')

figsavepath=fullfile('C:\','Users','jdyge','OneDrive','Desktop','PIV data','ARvelwindows2Tunnelon.fig');
jpgsavepath=fullfile('C:\','Users','jdyge','OneDrive','Desktop','PIV data','ARvelwindows2Tunnelon.jpg');
saveas(figure(8),figsavepath);
saveas(figure(8),jpgsavepath);

figure(9)
plot(positionvec,ARVelWindow2meansTunneloff(1,:),positionvec,ARVelWindow2meansTunneloff(2,:),positionvec,ARVelWindow2meansTunneloff(3,:))
xlabel('position in flap')
ylabel('Avg Velocity in Window 2 (m/s)')
legend('Wide','Square','Narrow')

figsavepath=fullfile('C:\','Users','jdyge','OneDrive','Desktop','PIV data','ARvelwindows2Tunneloff.fig');
jpgsavepath=fullfile('C:\','Users','jdyge','OneDrive','Desktop','PIV data','ARvelwindows2Tunneloff.jpg');
saveas(figure(9),figsavepath);
saveas(figure(9),jpgsavepath);

figure(10)
plot(positionvec,ARVelWindow1meansTunneloff(1,:),positionvec,ARVelWindow1meansTunneloff(2,:),positionvec,ARVelWindow1meansTunneloff(3,:))
xlabel('position in flap')
ylabel('Avg Velocity in Window 1 (m/s)')
legend('Wide','Square','Narrow')

figsavepath=fullfile('C:\','Users','jdyge','OneDrive','Desktop','PIV data','ARvelwindows1Tunneloff.fig');
jpgsavepath=fullfile('C:\','Users','jdyge','OneDrive','Desktop','PIV data','ARvelwindows1Tunneloff.jpg');
saveas(figure(10),figsavepath);
saveas(figure(10),jpgsavepath);
Appendix C: Wind Tunnel Blockage Analysis

The blockage of a wind tunnel is an important metric to consider while performing experimental work in a wind tunnel and can be defined as Equation 6.2

\[ \%BL = 100 \times \frac{A_{model}}{A_{TS}} = 100 \times \frac{W_{model} \times H_{model}}{W_{TS} \times H_{TS}} \]  

Equation 6.2

We know that the width of the model is nominally the width of test section on the inside. This reduces the blockage calculation greatly to just what can be seen in Equation 6.3

\[ \%BL = 100 \times \frac{H_{model}}{H_{TS}} \]  

Equation 6.3

Filling in the nominal numbers from the design of the tunnel and CEDs results in the design blockage seen below in

\[ \%BL = 100 \times \frac{H_{model}}{H_{TS}} = 100 \times \frac{.75\text{in}}{7.5\text{in}} = 10\% \]  

Equation 6.4

Now for the actual blockage, and later the uncertainty in the blockage, the measured widths of the test section and electrodes must be used. It should also be noted that although the baseplates frontal width is equivalent to the test section width, the electrodes width is slightly less. This requires a modification equation to Equation 6.2 to account for the model’s frontal area being comprised of the frontal area of the baseplate and electrode which results in Equation 6.12.

\[ \%BL_{\text{wide}} = 100 \times \frac{(W_{\text{electrode}} \times H_{\text{electrode}}) + (W_{TS} \times H_{\text{plate}})}{W_{TS} \times H_{TS}} \]  

Equation 6.5

and filling in the measured values for each model and the test sections results in the following for each configuration give the results seen Equation 6.13 through Equation 6.15.
\[
\%BL_{\text{wide}} = 100 \times \frac{\left(\frac{3}{8}\text{in} \times \frac{7}{16}\text{in}\right) + \left(\frac{31}{64}\text{in} \times \frac{3}{8}\text{in}\right)}{\frac{31}{64}\text{in} \times 7\frac{7}{16}\text{in}} = 10.7\%
\]

Equation 6.6

\[
\%BL_{\text{square}} = 100 \times \frac{\left(\frac{13}{64}\text{in} \times \frac{7}{16}\text{in}\right) + \left(\frac{41}{64}\text{in} \times \frac{3}{8}\text{in}\right)}{\frac{41}{64}\text{in} \times 7\frac{7}{16}\text{in}} = 9.4\%
\]

Equation 6.7

\[
\%BL_{\text{narrow}} = 100 \times \frac{\left(\frac{51}{64}\text{in} \times \frac{3}{8}\text{in}\right) + \left(\frac{57}{64}\text{in} \times \frac{3}{8}\text{in}\right)}{\frac{57}{64}\text{in} \times 7\frac{7}{16}\text{in}} = 9.6\%
\]

Equation 6.8
Appendix D: Uncertainty Analysis

Uncertainty analysis was conducted using the method of addition in quadrature, a commonly employed method for propagating the uncertainties in measurements to the final calculated result. If we let any measured quantity be represented by $a$ with a measurement uncertainty of $\delta a$, then $u(a)$ defined by Equation 6.9 is the relative uncertainty.

$$ u(a) = \frac{\delta a}{a} $$

Equation 6.9

There are three main rules that allow for the application of addition in quadrature to propagate the uncertainty associated with the measured quantity $a$ with measurement uncertainty of $\delta a$, to the final calculated result. If we introduce another measurement represented by $b$ with a measurement uncertainty of $\delta b$, and a final calculated result of $Z$ with an unknown uncertainty of $\delta Z$, which we desire, we can summarize the three rules as follows in Equation 6.10, Equation 6.11, and Equation 6.12.

For addition and subtraction $Z = a \pm b$

$$ \delta Z = \sqrt{(\delta a)^2 + (\delta b)^2} $$

Equation 6.10

For multiplication and division $Z = a \times b \quad Z = \frac{a}{b}$

$$ \delta Z = Z \sqrt{\left(\frac{\delta a}{a}\right)^2 + \left(\frac{\delta b}{b}\right)^2} $$

Equation 6.11

For powers of type $Z = a^n$

$$ \delta Z = Z \left( |n| \frac{\delta a}{|a|} \right) $$

Equation 6.12
With these three rules and order of operations the uncertainty equations in the following subsections can be easily derived.

**Uncertainty for Blockage**

To calculate the uncertainty in the blockage we need the uncertainty in the test section area and the uncertainty in the frontal area of the model which is a summation of the frontal area of the base plate and the frontal area of the compliant electrode. First the uncertainty of the frontal area of the three test section configurations can be found.

\[ A_{TS} = W_{TS}H_{TS} \]

\[ \delta A_{TS} = A_{TS} \sqrt{\left(\frac{\delta W_{TS}}{W_{TS}}\right)^2 + \left(\frac{\delta H_{TS}}{H_{TS}}\right)^2} \]

\[ \delta A_{TS\text{-wide}} = 18.48in^2 \sqrt{\left(\frac{1}{128in}\right)^2 + \left(\frac{1}{2in}\right)^2} \approx .06in^2 \]

\[ \delta A_{TS\text{-square}} = 12.20in^2 \sqrt{\left(\frac{1}{128in}\right)^2 + \left(\frac{1}{7\frac{7}{16}in}\right)^2} \approx .06in^2 \]

\[ \delta A_{TS\text{-narrow}} = 6.62in^2 \sqrt{\left(\frac{1}{128in}\right)^2 + \left(\frac{1}{7\frac{7}{16}in}\right)^2} \approx .06in^2 \]

The uncertainty in the frontal area of the electrodes can be calculated using addition in quadrature as shown in Equation 6.19 where \( W_{electrode} \) is the width of the electrode, \( H_{electrode} \) is the height of the tip of the electrode, and \( A_{electrode} \) is the frontal area of the electrode as calculated by Equation 6.18. Equation 6.20
through Equation 6.22 show the actual uncertainty calculation for the electrodes frontal area of the three models.

\[ A_{\text{electrode}} = W_{\text{electrode}}H_{\text{electrode}} \]  
Equation 6.18

\[ \delta A_{\text{electrode}} = A_{\text{electrode}} \sqrt{\left(\frac{\delta W_{\text{electrode}}}{W_{\text{electrode}}}\right)^2 + \left(\frac{\delta H_{\text{electrode}}}{H_{\text{electrode}}}\right)^2} \]  
Equation 6.19

\[ \delta A_{\text{electrode-wide}} = 1.04in^2 \sqrt{\left(\frac{1}{\frac{128}{2.8}in}\right)^2 + \left(\frac{1}{\frac{64}{16}in}\right)^2} \approx .04in^2 \]  
Equation 6.20

\[ \delta A_{\text{electrode-square}} = .53in^2 \sqrt{\left(\frac{1}{\frac{128}{13.64}in}\right)^2 + \left(\frac{1}{\frac{64}{7}in}\right)^2} \approx .02in^2 \]  
Equation 6.21

\[ \delta A_{\text{electrode-narrow}} = .30in^2 \sqrt{\left(\frac{1}{\frac{128}{51}in}\right)^2 + \left(\frac{1}{\frac{3}{8}in}\right)^2} \approx .01in^2 \]  
Equation 6.22

Since the base of the model spans the width of the test section the uncertainty in the frontal area of the model base plate uses the test section width, \( W_{TS} \), and test section width uncertainty, \( \delta W_{TS} \). With the uncertainty in the thickness of base plate, \( \delta H_{\text{base}} \), known to be \((1/64)\) of an inch, the uncertainty in the entire frontal area of the base, \( \delta A_{\text{base}} \), can be calculated using Equation 6.24. Equation 6.25 through Equation 6.27 show the calculation of the uncertainty in the frontal area of all three models.

\[ A_{\text{base}} = W_{TS}H_{\text{base}} \]  
Equation 6.23

\[ \delta A_{\text{base}} = A_{\text{base}} \sqrt{\left(\frac{\delta W_{TS}}{W_{TS}}\right)^2 + \left(\frac{\delta H_{\text{base}}}{H_{\text{base}}}\right)^2} \]  
Equation 6.24
\[
\delta A_{\text{base-wide}} = .89in^2 \sqrt{\left(\frac{128}{31}\right)^2 + \left(\frac{164}{64}\right)^2} \cong .04in^2
\]
Equation 6.25

\[
\delta A_{\text{base-square}} = .45in^2 \sqrt{\left(\frac{128}{41}\right)^2 + \left(\frac{164}{64}\right)^2} \cong .02in^2
\]
Equation 6.26

\[
\delta A_{\text{base-narrow}} = .30in^2 \sqrt{\left(\frac{128}{57}\right)^2 + \left(\frac{164}{64}\right)^2} \cong .01in^2
\]
Equation 6.27

With the uncertainty in the electrode frontal area and the base plate frontal area uncertainty, combining them gives the total frontal area uncertainty for the model setup. Equation 6.28 shows the equation used to combine the uncertainties and Equation 6.29 through Equation 6.31 show the calculation carried out.

\[
\delta A_{\text{model}} = \sqrt{(\delta A_{\text{base}})^2 + (\delta A_{\text{electrode}})^2}
\]
Equation 6.28

\[
\delta A_{\text{model-wide}} = \sqrt{(.04in^2)^2 + (.04in^2)^2} \cong .06in^2
\]
Equation 6.29

\[
\delta A_{\text{model-square}} = \sqrt{(.02in^2)^2 + (.02in^2)^2} \cong .03in^2
\]
Equation 6.30

\[
\delta A_{\text{model-narrow}} = \sqrt{(.01in^2)^2 + (.01in^2)^2} \cong .01in^2
\]
Equation 6.31
With the uncertainty in the frontal area of the whole model known and with the uncertainty in the test section known the uncertainty in the blockage can be calculated via Equation 6.33 and Equation 6.34 through Equation 6.36 show the calculation.

\[
\%BL = \frac{A_{model}}{A_{TS}}
\]

\[
\delta\%BL = \%BL \sqrt{\left(\frac{\delta A_{model}}{A_{model}}\right)^2 + \left(\frac{\delta A_{TS}}{A_{TS}}\right)^2}
\]

\[
\delta\%BL_{base-wide} = 10.7\% \sqrt{\left(\frac{.06\text{in}}{1.93\text{in}}\right)^2 + \left(\frac{.06\text{in}}{18.48\text{in}}\right)^2} \approx .3\%
\]

\[
\delta\%BL_{base-square} = 9.4\% \sqrt{\left(\frac{.03\text{in}}{.98\text{in}}\right)^2 + \left(\frac{.06\text{in}}{12.20\text{in}}\right)^2} \approx .3\%
\]

\[
\delta\%BL_{base-narrow} = 9.6\% \sqrt{\left(\frac{.01\text{in}}{.6\text{in}}\right)^2 + \left(\frac{.06\text{in}}{6.62\text{in}}\right)^2} \approx .2\%
\]

**Uncertainty in Constructed Driving Signals (Pulsing Ratio and Duty Cycle)**

The uncertainty in the constructed driving signals can be quantified by the uncertainty in the Frequency Ratio and the uncertainty in the duty cycle.
For the frequency ratio it’s difficult to propagate the uncertainty through the FFT so for a worst-case scenario half the value of the largest distance to the nearest bin for any trial of the modal frequency was used as the uncertainty in the modal frequency. The true uncertainty would be significantly lower. The uncertainty in the pulse frequency was calculated using the same addition in quadrature and knowing the uncertainty in the pulse period. The uncertainty for all signals were calculated but Equation 6.39 shows the example of the worst-case calculation.

\[ \delta R_f = 0.5 \sqrt{\left(\frac{\delta f_{\text{pulse}}}{f_{\text{pulse}}}\right)^2 + \left(\frac{\delta f_{\text{modal}}}{f_{\text{modal}}}\right)^2} \]

Equation 6.39

The duty cycle is the ratio of the on part of the signal to the on part of the signal. The signal is constructed in the signal generator by defining the AC frequency (or inversely the AC period), the number of full AC cycles to occur, and the pulse period. Equation 6.40 below shows how the duty cycle can be calculated from the discussed parameters. Applying the rules for calculating the uncertainty results in Equation 6.41. The uncertainty was calculated for all signals and the example provided in Equation 6.42 is the worst-case scenario for all signals. Most of the uncertainty comes from the cycle number being restricted to whole integers.

\[ \%DC = \frac{N_{\text{cycles}} \times P_{\text{AC}}}{P_{\text{pulse}}} \]

Equation 6.40
\[
\delta \% DC = \% DC \sqrt{\left(\frac{\delta N}{N}\right)^2 + \left(\frac{\delta P_{AC}}{P_{AC}}\right)^2 + \left(\frac{\delta P_{pulse}}{P_{pulse}}\right)^2}
\]

\[
\delta \% DC = 33.3\% \sqrt{\left(\frac{5}{15}\right)^2 + \left(\frac{0.000005 \text{ ms}}{1 \text{ ms}}\right)^2 + \left(\frac{0.0005 \text{ ms}}{46.323 \text{ ms}}\right)^2} = 1.1\%
\]

**Equation 6.41**

\[
\delta \% DC = 33.3\% \sqrt{\left(\frac{5}{15}\right)^2 + \left(\frac{0.000005 \text{ ms}}{1 \text{ ms}}\right)^2 + \left(\frac{0.0005 \text{ ms}}{46.323 \text{ ms}}\right)^2} = 1.1\%
\]

**Equation 6.42**

**Uncertainty in PIV**

Uncertainty in the PIV results were calculated using a recommended procedure developed by the International Towing Tank Conference and used by Dr. Griffin in his uncertainty analysis of PIV [47, 48]. Since the PIV system used for this work was the same as used in the work performed by Dr. Griffin, a similar approach was performed. Table 6.2 shows the principal dimensions of the PIV setup which are the inputs to the uncertainty analysis. The principal dimensions along with sensitivity factors for each possible source of error are used to calculate the uncertainty in time, position, and velocity. Table 6.3 shows the sources of error and the sensitivity factors. The results are added in quadrature as done in the uncertainty analyses in earlier sections to obtain the results. The results for the uncertainty in the velocity are 160 mm/s. It is important to note that this is for the tunnel-on setting.
### Table 6.2: Principal dimensions of PIV

<table>
<thead>
<tr>
<th>Target Flow of Measurement</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Flow</td>
<td>2-D airflow</td>
</tr>
<tr>
<td>Measurement Facility</td>
<td>Eiffel Style Wind Tunnel</td>
</tr>
<tr>
<td>Measurement Area</td>
<td>153 mm x 73 mm</td>
</tr>
<tr>
<td>Uniform Flow Speed</td>
<td>4.6 m/s</td>
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<tr>
<td>Calibration</td>
<td></td>
</tr>
<tr>
<td>Distance of Reference Points</td>
<td>89 mm</td>
</tr>
<tr>
<td>Distance of Reference Image</td>
<td>1464 pixels</td>
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<tr>
<td>Magnification Factor</td>
<td>0.0609171</td>
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<tr>
<td>Flow Visualization</td>
<td></td>
</tr>
<tr>
<td>Tracer Particle</td>
<td>Olive oil</td>
</tr>
<tr>
<td>Average Diameter</td>
<td>0.001 mm</td>
</tr>
<tr>
<td>Standard Deviation of Diameter</td>
<td>0.0001 mm</td>
</tr>
<tr>
<td>Average Specific Gravity</td>
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<tr>
<td>Light Source</td>
<td>Double Pulse Nd:YAG laser</td>
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<tr>
<td>Thickness of Laser Sheet</td>
<td>1 mm</td>
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<tr>
<td>Time Interval</td>
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<td>Image Detection</td>
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<tr>
<td>Camera</td>
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</tr>
<tr>
<td>Spatial Resolution</td>
<td>4008 pixels x 2672 pixels</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>5 fps (2 images at 2.5 Hz)</td>
</tr>
<tr>
<td>Gray Scale Resolution</td>
<td>14 bit</td>
</tr>
<tr>
<td>Cell Size</td>
<td>9 x 9 µm²</td>
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<tr>
<td>Optical System</td>
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<tr>
<td>Distance from the Target</td>
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</tr>
<tr>
<td>Length of Focus</td>
<td>62 mm</td>
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<td>F Number of Lens</td>
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<td>Data Processing</td>
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<td>Pixel Unit Analysis</td>
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<td>Category</td>
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<td>------------------</td>
</tr>
<tr>
<td>α (mm/pix)</td>
<td>Calibration</td>
</tr>
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<td>ΔX (pix)</td>
<td>Acquisition</td>
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</tr>
<tr>
<td>Δt (s)</td>
<td>Acquisition</td>
</tr>
<tr>
<td>δu (mm/s)</td>
<td>Experiment</td>
</tr>
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**Summary**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Category</th>
<th>Error Source</th>
<th>Uncertainty-U(x) (units)</th>
<th>Sensitivity Factor-C (units)</th>
<th>CU(x)</th>
<th>Uc</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Magnification Factor</td>
<td>4.74E-04 mm/pix</td>
<td>7.55E+04 pix/s</td>
<td>3.58E+01</td>
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<tr>
<td>ΔX</td>
<td>Image Displacement</td>
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<td>7.67E+02</td>
<td>1.55E+02</td>
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<tr>
<td>Δt</td>
<td>Image Interval</td>
<td>1.00E-08 s/mm/s^2</td>
<td>5.75E+07</td>
<td>5.75E-01</td>
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<tr>
<td>δu</td>
<td>Experiment</td>
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<td>1.00E+00</td>
<td>1.10E+01</td>
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<tr>
<td><strong>Total Uncertainty (mm/s)</strong></td>
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Appendix E: Full Results of Electrical and Mechanical Behavior of CED Device Tests

Table 6.4: Test matrix

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<tr>
<th>Geometry</th>
<th>Frequency ratio</th>
<th>Duty Cycle</th>
<th>Driving signal file</th>
<th>Trial 1</th>
<th>Trial 2</th>
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<tr>
<td>wide</td>
<td>.5 Frequency ratio</td>
<td>33 duty cycle</td>
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<td>50 duty cycle</td>
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<td>33 duty cycle</td>
<td>SDG003</td>
<td></td>
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<tr>
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</tr>
<tr>
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<td>SDG006</td>
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<td>50 duty cycle</td>
<td>SDG007</td>
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<td>SDG028</td>
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<tr>
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<td>SDG029</td>
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<tr>
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<tr>
<td></td>
<td>1.25 Frequency ratio</td>
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<td>SDG034</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>1.25 Frequency ratio</td>
<td>66 duty cycle</td>
<td>SDG035</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For Figure 6.22 to Figure 6.165 the left hand side graph(s) are from day 1 of testing and the right hand side graph(s) are from day 2 of testing.
Figure 6.22: Electrical treatment 1
Figure 6.23: Lissajous treatment 1
Figure 6.24: FFT treatment 1
Figure 6.25: Video data treatment 1
Figure 6.26: Electrical data treatment 2
Figure 6.27: Lissajous treatment 2
Figure 6.28: FFT treatment 2
Figure 6.29: Video data treatment 2
Figure 6.30: Electrical data treatment 3
Figure 6.31: Lissajous treatment 3
Figure 6.32: FFT treatment 3
Figure 6.33: Video data treatment 3
Figure 6.34: Electrical data treatment 4
Figure 6.35: Lissajous treatment 4
Figure 6.36: FFT treatment 4
Figure 6.37: Video data treatment 4
Figure 6.38: Electrical data treatment 5
Figure 6.39: Lissajous treatment 5
Figure 6.40: FFT treatment 5
Figure 6.41: Video data treatment 5
Figure 6.42: Electrical data treatment 6
Figure 6.43 Lissajous treatment 6
Figure 6.44: FFT treatment 6
Figure 6.45: Video data treatment 6
Figure 6.46: Electrical data treatment 7
Figure 6.47: Lissajous treatment 7
Figure 6.48: FFT treatment 7
Figure 6.49: Video data treatment 7
Figure 6.50: Electrical data treatment 8
Figure 6.51: Lissajous treatment 8
Figure 6.52: FFT treatment 8
Figure 6.53: Video data treatment 8
Figure 6.54: Electrical data treatment 9
Figure 6.55: Lissajous treatment 9
Figure 6.56: FFT of treatment 9
Figure 6.57: Video data treatment 9
Figure 6.58: Electrical data treatment 10
Figure 6.59: Lissajous treatment 10
Figure 6.60: FFT treatment 10
Figure 6.61: Video data treatment 10
Figure 6.62: Electrical data treatment 11
Figure 6.63: Lissajous treatment 11
Figure 6.64: FFT treatment 11
Figure 6.65: Video data treatment 11
Figure 6.66: Electrical data treatment 12
Figure 6.67: Lissajous treatment 12
Figure 6.68: FFT treatment 12
Figure 6.69: Video data treatment 12
Figure 6.70: Electrical treatment 13
Figure 6.71: Lissajous treatment 13
Figure 6.72: FFT treatment 13
Figure 6.73: Video data treatment 13
Figure 6.74: Electrical data treatment 14
Figure 6.75: Lissajous treatment 14
Figure 6.76: FFT treatment 14
Figure 6.77: Video data treatment 14
Figure 6.78: Electrical data treatment 15
Figure 6.79: Lissajous treatment 15
Figure 6.80: FFT treatment 15
Figure 6.81: Video data treatment 15
Figure 6.82: Electrical data treatment 16
Figure 6.83: Lissajous treatment 16
Figure 6.84: FFT treatment 16

[Graphs showing frequency-domain analysis with peaks at specific frequencies]
Figure 6.85: Video data treatment 16
Figure 6.86: Electrical treatment 17
Figure 6.87: Lissajous 17
Figure 6.88: FFT treatment 17
Figure 6.89: Video data treatment 17
Figure 6.90: Electrical data treatment 18
Figure 6.91: Lissajous treatment 18
Figure 6.92: FFT treatment 18
Figure 6.93: Video data treatment 18
Figure 6.94: Electrical data treatment 19
Figure 6.95: Lissajous treatment 19
Figure 6.96: FFT treatment 19
Figure 6.97: Video data treatment 19
Figure 6.98: Electrical data treatment 20
Figure 6.99: Lissajous treatment 20
Figure 6.100: FFT treatment 20
Figure 6.101: Video data treatment 20
Figure 6.102: Electrical data treatment 21
Figure 6.103: Lissajous treatment 21
Figure 6.104: FFT treatment 21
Figure 6.105: Video data treatment 21
Figure 6.106: Electrical data treatment 22
Figure 6.107: Lissajous treatment 22
Figure 6.108: FFT treatment 22
Figure 6.109: Video data treatment 22
Figure 6.110: Electrical data treatment 23
Figure 6.111: Lissajous treatment 23
Figure 6.112: FFT treatment 23
Figure 6.113: Video data treatment 23
Figure 6.114: Electrical data treatment 24
Figure 6.115: Lissajous treatment 24
Figure 6.116: FFT treatment 24
Figure 6.117: Video data treatment 24
Figure 6.118: Electrical data treatment 25
Figure 6.119: Lissajous treatment 25
Figure 6.120: FFT treatment 25
Figure 6.121: Video data treatment 25
Figure 6.122: Electrical data treatment 26
Figure 6.123: Lissajous treatment 26
Figure 6.124: FFT treatment 26
Figure 6.125: Video data treatment 26
Figure 6.126: Electrical data treatment 27
Figure 6.127: Lissajous treatment 27
Figure 6.128: FFT treatment 27
Figure 6.129: Video data treatment 27
Figure 6.130: Electrical data treatment 28
Figure 6.131: Lissajous treatment 28
Figure 6.132: FFT treatment 28
Figure 6.133: Video data treatment 28
Figure 6.134: Electrical data treatment 29
Figure 6.135: Lissajous treatment 29
Figure 6.136: FFT treatment 29
Figure 6.137: Video data treatment 29
Figure 6.138: Electrical data treatment 30
Figure 6.139: Lissajous treatment 30
Figure 6.140: FFT treatment 30
Figure 6.141: Video data treatment 30
Figure 6.142: Electrical data treatment 31
Figure 6.143: Lissajous treatment 31
Figure 6.144: FFT treatment 31
Figure 6.145: Video data treatment 31
Figure 6.146: Electrical data treatment 32
Figure 6.147: Lissajous treatment 32
Figure 6.148: FFT treatment 32
Figure 6.149: Video data treatment 32
Figure 6.150: Electrical data treatment 33
Figure 6.151: Lissajous treatment 33
Figure 6.152 FFT treatment 33
Figure 6.153: Video data treatment 33
Figure 6.154: Electrical data treatment 34
Figure 6.155: Lissajous treatment 34
Figure 6.156: FFT treatment 34
Figure 6.157: Video data treatment 34
Figure 6.158: Electrical data treatment 35
Figure 6.159: Lissajous treatment 35
Figure 6.160: FFT treatment 35
Figure 6.161: Video data treatment 35
Figure 6.162: Electrical data treatment 36
Figure 6.163: Lissajous treatment 36
Figure 6.164: FFT treatment 36
Figure 6.165: Video data treatment 36