ACTIVE CONTROL OF MASSIVELY SEPARATED HIGH-SPEED/BASE FLOWS WITH ELECTRIC ARC PLASMA ACTUATORS

BY
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DISSERTATION
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ABSTRACT

The current project was undertaken to evaluate the effects of electric arc plasma actuators on high-speed separated flows. Two underlying goals motivated these experiments. The first goal was to provide a flow control technique that will result in enhanced flight performance for supersonic vehicles by altering the near-wake characteristics. The second goal was to gain a broader and more sophisticated understanding of these complex, supersonic, massively-separated, compressible, and turbulent flow fields. The attainment of the proposed objectives was facilitated through energy deposition from multiple electric-arc plasma discharges near the base corner separation point. The control authority of electric arc plasma actuators on a supersonic axisymmetric base flow was evaluated for several actuator geometries, frequencies, forcing modes, duty cycles/on-times, and currents.

Initially, an electric arc plasma actuator power supply and control system were constructed to generate the arcs. Experiments were performed to evaluate the operational characteristics, electromagnetic emission, and fluidic effect of the actuators in quiescent ambient air. The maximum velocity induced by the arc when formed in a 5 mm x 1.6 mm x 2 mm deep cavity was about 40 m/s. During breakdown, the electromagnetic emission exhibited a rise and fall in intensity over a period of about 340 ns. After breakdown, the emission stabilized to a near-constant distribution. It was also observed that the plasma formed into two different modes: “high-voltage” and “low-voltage”. It is believed that the plasma may be switching between an arc discharge and a glow discharge for these different modes. The two types of plasma do not appear to cause substantial differences on the induced fluidic effects of the actuator. In general, the characterization study provided a greater fundamental understanding of the operation of the actuators, as well as data for computational model comparison.

Preliminary investigations of actuator geometry in the supersonic base flow determined that inclined cavity and normal cavity actuators positioned on the base near the base edge could produce significant disturbances in the shear layer. The disturbances were able to be tracked in time with phase-locked schlieren imaging and particle image velocimetry (PIV). The final set of flow control experiments were therefore performed with an eight-actuator base using the inclined cavity actuator geometry. The actuators were able to cause moderate influences on the axisymmetric shear layer velocity profile and base pressure. The most substantial changes to the shear layer and base pressure were noted for the highest current and duty cycle tests. At 1 A and 20% duty cycle, the base pressure was reduced by 3.5%. Similar changes were noted for all modes and a range of frequencies from about 10-30 kHz. Increases in duty cycle between 4% and 20% caused a nearly linear decrease in base pressure.

Analysis of the shear layer velocity profiles acquired through PIV show a local thickening of the shear layer in the region of the disturbances caused by the actuator. A slight increase in thickness was also observed away from the disturbance. Disturbances were able to be tracked at all frequencies and translated along the shear layer at a convective velocity of 430 ± 20 m/s. A fairly clear trend of increasing velocity disturbance amplitude correlating to increasing base pressure changes was noted. Moreover, the ability of the disturbances to stay well organized further down the shear layer also appears to be a significant factor in the actuators’ effect on base pressure. Consistent with these observations, it appears that increased duty cycle causes increased shear layer disturbance amplitudes.
The use of PIV has enabled substantial insight to be gained into the effects of the actuators on the ensemble-averaged flow field and on the variability of the instantaneous flow field with and without control. A sensitive bimodal recirculation region behavior was found in the no-control flow field that the plasma actuators could force. The flow field and turbulence statistics in each mode were substantially different. Through analysis of past no-control base pressure measurements, it is believed that the bimodal behavior fluctuates at a characteristic frequency between 0.4 and 0.5 Hz \([\text{St}_{10} = \delta(5x10^{-5})]\). The flat time-averaged base pressure distribution is due to the superposition of a normally non-flat instantaneous base pressure distribution. Also, the standard deviation of the base pressure measurements is reduced when in one recirculation region mode as compared to when it is fluctuating between recirculation region modes.
I would like to dedicate the effort put forth into my dissertation to my wife and daughter, as they were my guiding light and motivation through all of the challenges I faced. While I may have started this goal for personal reasons, I finished for much more than that, and the birth of my first child/daughter changed the reasons and fervency with which I was determined to persevere. I hope you hold on to the wonderment for the world around you like you have now, Skyla. I see it in your eyes every day. Life is a gift. Find your own way to unwrap it! To my wife, Karen, thank you for seeing me through this. I know I haven’t always had the time to show you, so I’ll tell you now. You are loved. I know I wasn’t always the easiest to deal with, but your patience and flexibility through this process is something I am grateful for. I also appreciate all of the support and understanding from my family, friends, and colleagues. To my father, thank you for never stopping to strive to give us the best you could. To my mother, thank you for making us your passion in life. Both of your strong, yet gentle, guidance is what has left me with this enthusiasm for all that life holds and a good example of how to share that wonder with my own little ones.

I would like to thank my advisors, Greg Elliott and Craig Dutton, for their assistance through this learning process and their effort (and sometimes the restraint thereof) in developing me into the leader I strive to become. Thank you to Greg Milner, Kent Elam, Mark Clawson and to my dissertation committee: Professor Greg Elliott, Professor Craig Dutton, Professor Joanna Austin, and Professor Ken Christensen for their expertise, assistance, and peer review in completing this project. Thank you to the Department of Defense, the Office of Naval Research, and the NDSEG program personnel for allowing me to pursue this challenge through their financial support. We are all better for your dedication to science and engineering. Thank you to ViêtNow and the VFW Post 1461 for their generous financial support. Additionally, I would like to thank my colleagues, Dr. Mo Samimy and Dr. Jin-Hwa Kim at The Ohio State University, for their discussions, input, and assistance regarding this work. Thank you to Dr. Daniel Bodony, Mahesh Natarajan, and Chris Ostoich for providing both the computational data for computing the thermophoretic influences and for the discussion and assistance with manipulating and analyzing the data.

Of course, I would be remiss if I didn’t acknowledge my compadres throughout this sometimes exciting, sometimes challenging, and sometimes frustrating effort. Thank you to my lab-mates, Todd Reedy, Tommy Herges, Eli Lazar, Becca Ostman, Nachiket Kale, Wilbur Chang, Brad Sanders, Blake Johnson, Ruben Hortensius, Angelo Herrera, Chris Ostoich, Brian Woodard, Andres Ortiz, Owen Kingstedt, Andy Swantek, Bill Flaherty, Manu Sharma, and Andrew Knisley (and to the many others that I didn’t name) for your expertise, guidance, assistance, time, companionship, sense of humor, conversation, and most importantly, friendship. More than anything, you are what made my experience here so enjoyable, and I am better for having known you. Extra special thanks goes out to Todd Reedy for his shared effort in attaining this goal, for his collaboration, and for the many late nights working together and reviewing papers together. We persevered! Hang in there. The light is near for you, too. Thank you for the time and effort invested from our undergraduate assistants, Jordan Holquist, Pat Gore, Cesar Alvarez, and Robyn MacDonald. I know you often times deferred homework to help me make progress. Thank you. Hopefully, you found it valuable, rewarding, and learned a thing or two along the way. To all of my “spotters”, for the many
times I trusted you with my life, thank you for never letting me down. My attention to detail and your safety never wavered either.

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The author would also like to thank AFOSR with Dr. John Schmisseur as program monitor (FA9550-04-1-0425) for supporting the companion research (Appendix A). Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of AFOSR. With regard to this work, I would like to thank my colleagues Todd Reedy, Rodney Bowersox, and Ravi Srinivasan for their discussions, input, and assistance.
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<tr>
<td>&quot;</td>
<td>inches</td>
</tr>
<tr>
<td>°</td>
<td>degree</td>
</tr>
<tr>
<td>°F</td>
<td>degrees Fahrenheit</td>
</tr>
<tr>
<td>A</td>
<td>axisymmetric</td>
</tr>
<tr>
<td>A, mA</td>
<td>Amp, milliamp</td>
</tr>
<tr>
<td>Al</td>
<td>aluminum</td>
</tr>
<tr>
<td>BEJ</td>
<td>base-extension junction</td>
</tr>
<tr>
<td>BN</td>
<td>boron nitride</td>
</tr>
<tr>
<td>CCD</td>
<td>charge-coupled device</td>
</tr>
<tr>
<td>DAQ</td>
<td>data acquisition</td>
</tr>
<tr>
<td>DC</td>
<td>direct current</td>
</tr>
<tr>
<td>DF</td>
<td>double flapping</td>
</tr>
<tr>
<td>DH</td>
<td>double helical</td>
</tr>
<tr>
<td>DNS</td>
<td>direct numerical simulation</td>
</tr>
<tr>
<td>EMI</td>
<td>electo-magnetic interference</td>
</tr>
<tr>
<td>ESSL</td>
<td>early stages of the shear layer</td>
</tr>
<tr>
<td>F</td>
<td>flapping</td>
</tr>
<tr>
<td>FFT</td>
<td>fast Fourier transform</td>
</tr>
<tr>
<td>FSM</td>
<td>flow simulation methodology</td>
</tr>
<tr>
<td>GSa</td>
<td>gigasamples</td>
</tr>
<tr>
<td>H</td>
<td>helical</td>
</tr>
<tr>
<td>HV</td>
<td>high-voltage</td>
</tr>
<tr>
<td>Hz, kHz, MHz</td>
<td>Hertz, kilohertz, megahertz</td>
</tr>
<tr>
<td>ICCD</td>
<td>intensified charge-coupled device</td>
</tr>
<tr>
<td>in</td>
<td>inches</td>
</tr>
<tr>
<td>J, mJ</td>
<td>Joule, millijoule</td>
</tr>
<tr>
<td>K</td>
<td>Kelvin</td>
</tr>
<tr>
<td>kg, g</td>
<td>kilogram, gram</td>
</tr>
<tr>
<td>LAFPA</td>
<td>localized arc filament plasma actuator</td>
</tr>
<tr>
<td>lb</td>
<td>pounds</td>
</tr>
<tr>
<td>LDV</td>
<td>laser Doppler velocimetry</td>
</tr>
<tr>
<td>LES</td>
<td>large eddy simulation</td>
</tr>
<tr>
<td>LV</td>
<td>low-voltage</td>
</tr>
<tr>
<td>m, cm, mm, km</td>
<td>meter, centimeter, millimeter, kilometer</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>MOSFET</td>
<td>metal-oxide-semiconductor field-effect transistor</td>
</tr>
<tr>
<td>NACA</td>
<td>National Advisory Committee for Aeronautics</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>neodymium-doped yttrium aluminum garnet</td>
</tr>
<tr>
<td>Pa, kPa, MPa</td>
<td>Pascal, kilopascal, megapascal</td>
</tr>
<tr>
<td>PCB</td>
<td>printed circuit board</td>
</tr>
<tr>
<td>PID</td>
<td>proportional-integral-derivative</td>
</tr>
<tr>
<td>PIV</td>
<td>particle image velocimetry</td>
</tr>
<tr>
<td>PLIF</td>
<td>planar laser-induced fluorescence</td>
</tr>
<tr>
<td>PPJ</td>
<td>pulsed plasma jet</td>
</tr>
<tr>
<td>PRMS</td>
<td>planar Rayleigh/Mie scattering</td>
</tr>
<tr>
<td>PSD</td>
<td>pressure-sensitive paint</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds-averaged Navier-Stokes</td>
</tr>
<tr>
<td>RMS</td>
<td>root-mean-square</td>
</tr>
<tr>
<td>RR</td>
<td>recirculation region</td>
</tr>
<tr>
<td>RMS</td>
<td>root-mean-square</td>
</tr>
<tr>
<td>SLR</td>
<td>single lens reflective</td>
</tr>
<tr>
<td>S, ms, μs, ns</td>
<td>seconds, milliseconds, microseconds, nanoseconds</td>
</tr>
<tr>
<td>SLR</td>
<td>single lens reflective</td>
</tr>
<tr>
<td>V, kV</td>
<td>Volt, kilovolt</td>
</tr>
<tr>
<td>VI</td>
<td>virtual instrument</td>
</tr>
<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
</tr>
<tr>
<td>Ω, kΩ</td>
<td>Ohm, kiloohm</td>
</tr>
<tr>
<td>W, kW</td>
<td>Watts, kilowatts</td>
</tr>
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### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$A_k$</td>
<td>representative area for tap $k$, where $k = 1, 2, \text{ or } 3$</td>
</tr>
<tr>
<td>$A_T$</td>
<td>total base area ($= 31.7 \text{ cm}^2 \text { or } 4.91 \text{ in}^2$)</td>
</tr>
<tr>
<td>$C_f$</td>
<td>skin friction coefficient</td>
</tr>
<tr>
<td>$C_p$</td>
<td>base pressure coefficient</td>
</tr>
<tr>
<td>$d_p$</td>
<td>particle diameter</td>
</tr>
<tr>
<td>$F_{th}$</td>
<td>thermophoretic force</td>
</tr>
<tr>
<td>$P_{1}, P_{2}, P_{3}$</td>
<td>base pressure at (1) inner, (2) middle, or (3) outer tap location</td>
</tr>
<tr>
<td>$P_{b}, P_{AW}$</td>
<td>base pressure, area-weighted base pressure</td>
</tr>
<tr>
<td>$P_{cett}$</td>
<td>open jet test section cell pressure</td>
</tr>
<tr>
<td>$P_{nozzle}$</td>
<td>nozzle exit pressure</td>
</tr>
<tr>
<td>$P$, $P_\infty$</td>
<td>total/stagnation pressure, freestream static pressure</td>
</tr>
<tr>
<td>$r_{k_{\max}}, r_{k_{\min}}$</td>
<td>maximum/minimum representative radius for tap $k$, where $k = 1, 2, \text{ or } 3$</td>
</tr>
<tr>
<td>$u_\tau$</td>
<td>friction velocity</td>
</tr>
<tr>
<td>$V_{th}$</td>
<td>thermophoretic velocity</td>
</tr>
<tr>
<td>$\delta^*$</td>
<td>boundary layer displacement thickness</td>
</tr>
<tr>
<td>$\sigma_{u}, \sigma_{v}$</td>
<td>standard deviation (RMS deviation) of velocity</td>
</tr>
<tr>
<td>$\sigma_{xx}, \sigma_{yy}$</td>
<td>Reynolds normal stresses</td>
</tr>
<tr>
<td>$\sigma_{xy}$</td>
<td>Reynolds shear stress</td>
</tr>
<tr>
<td>$| |$</td>
<td>magnitude (of velocity or turbulence intensity, for example)</td>
</tr>
<tr>
<td>$\langle \rangle$</td>
<td>ensemble-average (of velocity, for example)</td>
</tr>
<tr>
<td>$\nabla$</td>
<td>del vector operator</td>
</tr>
<tr>
<td>$D$</td>
<td>base diameter</td>
</tr>
<tr>
<td>$f$</td>
<td>frequency</td>
</tr>
<tr>
<td>$H$</td>
<td>shape factor ($= \delta^*/\theta$)</td>
</tr>
<tr>
<td>$I$</td>
<td>pixel intensity</td>
</tr>
<tr>
<td>$I_U$</td>
<td>streamwise (axial) turbulence intensity</td>
</tr>
<tr>
<td>$I_V$</td>
<td>transverse (radial) turbulence intensity</td>
</tr>
<tr>
<td>$i$</td>
<td>base pressure tap index (from inside out, $i = 1, 2, \text{ and } 3$)</td>
</tr>
<tr>
<td>$K$</td>
<td>turbulent kinetic energy (2D)</td>
</tr>
<tr>
<td>$k, m$</td>
<td>forcing mode</td>
</tr>
<tr>
<td>$Kn$</td>
<td>Knudsen number ($= \lambda/d_p$)</td>
</tr>
<tr>
<td>$M$</td>
<td>Mach number</td>
</tr>
<tr>
<td>$Q$</td>
<td>peak ratio</td>
</tr>
<tr>
<td>$R, R_o$</td>
<td>base radius</td>
</tr>
</tbody>
</table>
\( R, r \) radial coordinate

\( Re, Re_\infty, Re_D \) Reynolds number, freestream Re, Re based on base diameter

\( St_D \) Strouhal number based on diameter

\( St_r \) Strouhal number based on recirculation length

\( St_\theta \) Strouhal number based on approach boundary layer momentum thickness

\( T \) period

\( T, T_0, T_\infty \) temperature, total temperature, freestream temperature

\( U \) streamwise (axial) velocity component

\( u \) streamwise (axial) velocity fluctuation

\( V \) transverse (radial) velocity component

\( v \) transverse (radial) velocity fluctuation

\( X, x \) streamwise/horizontal coordinate

\( Y, y \) transverse coordinate

\( \gamma \) specific heat ratio

\( \delta \) boundary layer thickness

\( \delta_{99\%} \) boundary layer thickness (99%)

\( \theta \) boundary layer momentum thickness or flow turning angle

\( \lambda \) mean free path

\( \mu, \mu_g \) dynamic viscosity, gas dynamic viscosity

\( \Pi \) wake strength parameter

\( \rho, \rho_g \) density, gas density

\( V, V_\infty, V_{\text{inf}} \) velocity, freestream velocity

**Superscripts**

\( ^\circ \) degree

**Subscripts**

\( \infty \) freestream condition

\( _\circ \) total or stagnation condition
CHAPTER 1 - BACKGROUND AND MOTIVATION

1.1 Introduction

Research into the control of compressible, separated, turbulent base flows is valuable towards improving understanding of the dominant flow features and interactions that play important roles in many practical high-speed, separated flow applications. Base flows are common features of most missiles and projectiles and share similar features with many other important aerospace, defense, and transportation-related systems, such as gas turbine engines, helicopter blades, and more. Control of the base flow field and manipulation of the base pressure is worthy of a sustained research effort as the base flow field plays a considerable role in determining the flight capabilities of projectiles and missiles. Indeed, it has been shown that the lower pressure on the aft section of the body can contribute between 35-50% of the total drag for these vehicles. For example, the base drag for the Space Shuttle was determined to be roughly half of the net orbiter drag during re-entry. Specifically, efforts toward the experimental control of base flows, and with other flows that contain similar flow features, is essential because many important flow parameters are still frequently predicted inaccurately with typical computational methods.

The experimental results obtained herein will be useful for comparison and validation in the coming years as computational techniques and their associated predictions improve. The mixing and turbulent structures introduced in the near-wake of blunt-based bodies can also play a significant role in modifying the plume and wake temperatures and radiation characteristics. They can affect the propulsive jet and external combustion in the vicinity of the base, leading to manipulation of infrared signatures. Therefore, experimental research furthering understanding of base flows and their control is of significant practical importance to both the experimental and computational fluid dynamics community as well as to defense and commercial interests.

1.2 Base Flow Fluid Dynamics

1.2.1 Base Flow Physics

Supersonic base flows are turbulent, compressible, and contain significant regions of separated flow. For that reason, they are challenging to predict and understand both from an experimental and computational perspective. However, it is also these factors that motivate the majority of the interest in these particular flows, as their difficulty stimulates a desire to understand them better. For example, base flows are very useful test cases for improving turbulence modeling as they possess nearly all of the fundamental problems that are encountered in modeling turbulent flows with strong viscous interactions. Furthermore, grasping these flow phenomena, whether through experiment or simulation, contributes to the fluid dynamics community’s general knowledge of one of the most difficult areas that still eludes a thorough understanding.

Figure 1 shows the organization of a time-averaged supersonic base flow for a cylindrical bluff-based body at zero angle-of-attack. The supersonic freestream and boundary layer separate from the rear edge of the cylindrical afterbody. The separation of the flow from the edge of the base produces a centered expansion process, or Prandtl-Meyer expansion fan, that accelerates and turns the flow towards the rear stagnation point. The turbulent mixing
between the lower-speed recirculation region and the high-speed outer inviscid flow drives a free shear layer. The shear layer develops, not from the boundary layer, but rather grows independently from the base corner. As the flow moves towards the rear stagnation point, it realigns with the freestream direction by recompression shocks that create a high-pressure region near convergence. Some of the lower speed shear layer fluid cannot traverse through this high-pressure region and is turned back towards the base, in essence, completing the formation of and driving the recirculation region. In a time-averaged sense, the point in space along the centerline that divides the upstream-moving from downstream-moving fluid is known as the reattachment (or rear stagnation) point. The forward stagnation point is nominally located at the intersection of the reverse streamline along the axis of symmetry and the central point of the base surface. Downstream of reattachment, the wake accelerates back to supersonic conditions.

In an instantaneous sense, however, the base flow’s shear layer, recirculation region, and wake are primarily comprised of large scale turbulent structures. The turbulent structures of the afterbody boundary layer are “frozen” as they pass through the centered expansion, changing very little in size, shape, and orientation as they convect downstream. Further downstream, the natural instabilities of the shear layer lead to the formation of additional large-scale structures. Observations have indicated that eddy shocklets, or shocks, form from the large-scale structures’ disturbance of the supersonic freestream. The average number of structures about the shear layer circumference decreases as the shear layer passes through the recompression waves, owing to the stabilizing influence of lateral streamline convergence present in axisymmetric geometries. It has also been shown that the base flow can experience significant flapping and convolution of the shear layer and trailing wake in a manner that is akin to a Kármán vortex street.

![Figure 1. Schematic of mean near-wake flowfield for a blunt cylindrical afterbody.](image)

The entrainment caused by the shear layer is a primary driver behind the reduced pressure on the base. Essentially, the reduced base pressure is created by the removal of fluid from the recirculation region by turbulent mixing present in the shear layer. Thus, the instability of the free shear layer is a driving force behind determining the base pressure as it promotes the formation of turbulent structures that entrain mass into the wake. As a result of this, a primary focus of this study is related to influencing these shear layer instabilities. Additionally, the angle of freestream/shear layer convergence is also directly correlated to the base pressure. A longer recirculation region
generally is linked to a higher base pressure. Therefore, the strength of the centered expansion from the base edge may also play a role in determining the base pressure.

Somewhat unexpectedly, the shear layer is compressible, and the recirculation region is not as low-speed as once envisioned.\textsuperscript{15,16} The shear layer typically has a convective Mach number greater than unity\textsuperscript{17} and is therefore highly compressible, while the recirculation region generally contains Mach numbers as high as 0.5.\textsuperscript{8} Therefore, part of the added challenge of fully understanding a supersonic base flow is that the flow on the inner edge of the shear layer is actually a dynamic, turbulent, and subsonic recirculating flow and is not stagnant.

1.2.2 Experimental Base Flow Characterization Studies

Lamb and Oberkampf\textsuperscript{18} and Dutton et al.\textsuperscript{12} have provided valuable reviews of the experimental research conducted on base flows through the mid-1990’s. They highlight that the primary techniques used in early work (since the mid-1950’s) were mean surface-pressure measurements, schlieren and shadowgraph flow visualizations, and some mean velocity data obtained with intrusive probes.\textsuperscript{19-22} For example, Demetriades\textsuperscript{23,24} investigated a Mach 3.0 wake with a pair of hot-wire probes to determine the space-time correlation between the measurements. He found that the eddy convection speed appeared equal to the mean flow speed within the accuracy of the measurement and that the eddy shape was inclined to the wake. He also noted that the aerodynamic interference of the two-probe system was significant but able to be corrected for. Gaviglio et al.\textsuperscript{25} also studied a supersonic wake in detail with a hot-wire anemometer in the late 1970’s. The authors noted the strong influences of compressibility and anisotropy. Increased compressibility was found to increase the production of turbulent kinetic energy in the presence of an adverse pressure gradient. However, in regions of expansion, negative production is observed through a decrease in turbulence. A detailed description of the flow was provided by measurements acquired in the approach flow, shear layer, and developing wake, but the recirculation region was avoided due to concerns about probe interference effects. Similarly, the wake behind a circular cylinder was probed with a pitot-static probe by Neale et al.\textsuperscript{26}, but they again avoided the recirculation region. The authors were able to determine that at Mach 3 the rear stagnation point is approximately three base radii downstream of the base. The centerline Mach number then became supersonic again just one base diameter downstream of the rear stagnation point.

In the last two decades, however, non-intrusive laser-based optical diagnostics techniques, such as laser Doppler velocimetry (LDV), particle image velocimetry (PIV), planar Rayleigh/Mie scattering (PRMS), pressure-sensitive paint (PSP), and planar laser-induced fluorescence (PLIF), have shed significant light on the statistical and structural features as well as dynamics of the recirculation region.\textsuperscript{27-29} Specifically, full-field mean and turbulence data, including the recirculation region, have been acquired for axisymmetric subsonic,\textsuperscript{30} transonic,\textsuperscript{31,32} and supersonic\textsuperscript{8,33} flow fields. Two-dimensional supersonic base flows with power-on have also been evaluated using LDV by Heltsley et al.\textsuperscript{31} Avidor et al.\textsuperscript{34} investigated the wake of a Mach 2.5 axisymmetric base flow out to 160 base diameters downstream using LDV. The facility they used was a specially-designed, modified Ludwieg tube that could produce about 30 ms of flow about a 6.4 mm (1/4”) diameter cylindrical sting that extended from upstream of the nozzle. Reijasse and Délay\textsuperscript{35} even used LDV to study the base region of a 0.01-scale model of the ARIANE 5 European launcher. A Mach 4 flow was developed around a central sting similar to the previously mentioned
configuration used by Avidor et al. The central sting served as a model of the central booster. The lateral boosters were mounted on opposite sides of the central sting and the power-on state was simulated with high-pressure air at a stagnation temperature of 400 K. The Mach number and nozzle pressure ratios were selected to reproduce flight at an altitude of 30 km. A strong backflow towards the spaces between the three nozzles was observed that could cause high heat loads from the convection of heated exhaust gases back towards the nozzle side walls during atmospheric flight.

While some base flow PIV data have since been published in the last decade, they generally include limitations imposed by model supports, poor recirculation region seeding, light reflections/glare, and/or the experiments have been performed on a different geometric configuration than is currently being investigated. An early publication by Scarano and van Oudheusden28 for a two-dimensional base flow configuration was able to resolve the downstream shear layer, rear stagnation point, and wake, but was unable to provide data closer than 10 mm ($X/R\sim1$) to the base as a result of glare. The glare and poor seeding density in the recirculation region led to a small signal-to-noise ratio. The investigation utilized TiO$_2$ for seed particles. The article also provided a detailed analysis of the particles’ flow tracking ability by evaluating their response through an oblique shock wave. The particle response time was estimated to be below 1 μs with a Stokes number less than 0.2 just downstream of separation. The Stokes number drops below 0.05 downstream of reattachment. The associated RMS slip velocity was quoted at 2.5% and 0.7% of the local velocity for the higher and lower Stokes number estimates, respectively.

Subsequent work on the same geometry by the same investigators was able to resolve the region close to the base by devising an innovative downstream laser illumination technique.36 The laser sheet was brought in normal to the base by a mirror that was positioned in the tunnel downstream of the base. The full-field instantaneous realizations were analyzed with proper orthogonal decomposition (POD) for various Mach numbers to evaluate the effect of compressibility on the base flow geometry. Increased compressibility acted to reduce the flapping behavior of the wake, and altered the global behavior to one of axial pulsations. With increased compressibility, the maximum levels of the turbulent fluctuations were decreased significantly. The location of maximum streamwise turbulence intensity and Reynolds shear stress were located near the rear stagnation point and did not move significantly with changes in compressibility. However, the radial turbulence intensity did move upstream for increasing compressibility.

Van Oudheusden and Scarano37 also investigated a base-flow-plume configuration at Mach 2 and 3 with a slightly under-expanded jet in the core of the base flow exhausting at Mach 4. The cylindrical model was supported by a relatively large model support that also contained the air supply tubing for the jet. Both the outer flow and inner jet flow were again seeded with TiO$_2$. Difficulty was experienced with seeding the recirculation regions between the centered expansion at the base edge and the jet exhaust nozzle, and asymmetries were encountered that were likely caused by the model support. A normal shock also formed in the Mach 2 PIV results downstream of the base that was observed to affect the symmetry of the data. Still, assessment of the side opposite the support yielded valuable information on the velocity field, turbulence intensities, and Reynolds shear stress. For instance, the maximum value of turbulence intensity magnitude (root-sum-square of the two component turbulence intensities) in the outer shear layer was quoted to reach about 22%.
Bitter et al.\textsuperscript{38} reported on their experiments with axisymmetric base flows. Unfortunately, the seeding quality was poor. Several filtering techniques were employed, including a conditional filtering process that only selected the most well-seeded images for processing. Additionally, the downstream model support altered the boundary conditions enough to result in an open wake. In this condition, the outer ambient conditions can affect the recirculation region behavior as entirely supersonic flow is not achieved again downstream of the base.

Extensive research has been completed over the last 20 or so years by Dutton and colleagues that has shed significant light on the fluid dynamics of supersonic base flows. The research has all been completed in the same University of Illinois facility as is used for the present wind tunnel experiments, and so deserves some additional elaboration on the significant findings. It is a specially designed base flow facility that uniformly accelerates the flow over an upstream sting, eliminating the interference and boundary-condition modification of the downstream support used in most past and current work. The nominal freestream Mach number was designed to be 2.5. Herrin and Dutton\textsuperscript{8} also noted that the peak values of turbulent kinetic energy and axial-radial shear stress as measured by LDV were located in the subsonic portion of the shear layer upstream of the rear stagnation point, which is in contrast to the observations of past researchers for solid-surface compressible shear layer reattachment.\textsuperscript{39,40} For rearward-facing steps, the maximum value of these turbulent quantities was located downstream of reattachment. It was theorized that this is caused by the fundamental differences between pliable and solid-wall boundary reattachment.

\subsection*{1.2.3 Experimental Base Flow Control Studies}

Several modifications to the standard cylindrical bluff-base geometry were also made in order to investigate the influence of passive\textsuperscript{41-44} and active\textsuperscript{45,46} control methodologies on the sensitive base region. One such modification was to boattail the afterbody.\textsuperscript{41} The boatailed afterbody had a 5 deg., 0.5 caliber (\(x/D = 0.5\)) taper, and was found to make a substantial improvement to the base pressure by reducing the net drag by 21\%\textsuperscript{47}. The boatailed configuration also dropped the peak value of turbulent kinetic energy by 18\% and the mean shear layer growth rate by 20\% relative to the cylindrical base. The reduced turbulence likely decreased mass entrainment from the recirculation region, which ultimately led to the increase in base pressure. The more gradual expansion and slight boundary layer recovery process that occurs on the boattail may also contribute to the reduced base drag coefficient. Research by Pastoor et al.\textsuperscript{48} supports the hypothesis of decreased turbulence ultimately leading to increased base pressure by further suggesting that techniques that reduce base pressure fluctuations, in general, may also cause a mean base pressure increase. Additional modifications to the geometry of the base have been studied, such as the addition of a base cavity.\textsuperscript{49} At subsonic speeds, it was found that the base cavity geometry implemented on a 2-D flat plate base model resulted in a 10-14\% increase in the base pressure coefficient. The base pressure increase was theorized to be due to the displacement of the low pressure vortices away from the base surface.

The addition of triangular-shaped tabs and an axisymmetric ring upstream of the boundary layer separation point have also been experimented with in the University of Illinois facility.\textsuperscript{42,50} The addition of 0.3 and 0.5 mm thick tabs to the afterbody just before separation was found to decrease the base pressure by 2.5\% relative to the cylindrical base.\textsuperscript{51} It was noticed that streamwise vorticity produced by the tabs penetrated through the base corner
expansion, increasing mixing and base drag. Conversely, an axisymmetric ring tab was found to increase the base pressure by up to 5.0%. Interestingly, the triangular-shaped tabs, which decreased base pressure, were observed to increase normalized base pressure RMS measurements at all radial locations investigated and reduce the peak PSD frequency of the base pressure fluctuations at the outermost tap ($r/R_o=0.84$). Conversely, the strip tab did exactly the opposite (increased base pressure, decreased radially-acquired normalized base pressure RMS measurements, and increased peak PSD frequency at the outermost tap). The disturbances also appear to have a spatially uniform influence on the base pressure as the cross correlation between base pressure fluctuations acquired at various circumferential and radial locations exhibit a zero time delay.

The addition of streamwise slot cavities to a supersonic projectile at Mach 1.36 and 1.83 was tested for changes to the surface pressure distribution. While the changes to the base drag were modest, a slight reduction was noted for 0.5 mm cavities. However, an increase in drag was noted for a 2 mm slot width.

Passive control of the recirculation region using splitter plates that divided the base into halves, thirds, and quarters has also been completed recently. The area-averaged base drag coefficient either did not change or increased slightly (up to 4%) depending of the splitter plate configuration. Even though the area-weighted average base drag coefficient was not modified substantially, the introduction of the splitter plates did alter the radial and spectral distribution of the base pressure. The normally flat base pressure distribution exhibited monotonically increasing radial variation with increasing number of divisions of the recirculation region. A substantial base pressure peak formed at the center of the base, which is contrary to the normally observed slight increase in base pressure at the edge of the base for the no-control case.

In addition to passive studies, some attempts at open-loop active control have been made as well. One such example is known as base bleed in which mass is injected through the base into the recirculation region. The non-dimensional injection parameter, $I$, used to quantify the amount of fluid injected into the base area, is defined as the bleed mass flow rate normalized by the product of the base area and the freestream mass flux. Optimum values for the bleed rate have been reported to result in a 10 to 90% increase in base pressure. For the University of Illinois experiments, an optimum value of $I$ was found to be 0.0148, which was consistent with past measurements. An increase in base pressure of 24% relative to the cylindrical base and 4% relative to the boattailed afterbody was reported. It was found that at low values of the injection parameter the mean base pressure coefficient slope with respect to $I$ was positive, implying increased base pressure and reduced base drag for increasing values of $I$. For bleed rates above the optimum value of $I$, the mean base pressure coefficient drops rapidly to values that constitute a decrease in base pressure even relative to the no-control cylindrical base scenario. LDV measurements at the optimum value of $I$ suggest that the maximum base pressure increase is realized when the bleed rate is just great enough to eliminate any rearward mean velocity along the sting centerline.

Another example of open-loop active control that has displayed substantial control authority is base burning. In a facility similar to the University of Illinois facility at the Georgia Institute of Technology, research was carried out in the early 1980’s that investigated the effectiveness of base burning. The axisymmetric sting and afterbody were supported from upstream, and a uniform Mach 3 flow was developed along the sting using a converging-diverging nozzle. The hydrogen fuel was diluted with $N_2$, He, and $CO_2$ to simulate practical values of
the injectant total heating values. Both base burning alone and base burning with pre-burning were evaluated. The majority of the base drag, or about 90%, was eliminated with both techniques, although base burning with pre-burning outperformed base burning alone by about 10% on average for different hydrogen mass fractions.

1.2.4 Numerical Base Flow Studies

In the last decade, substantial progress has been made to the state-of-the-art of numerical simulations for base flows. Yet, many features of the flow remain challenging to capture numerically. It is especially difficult to simulate the flow due to the large regions of separation, mixed supersonic/subsonic regions, and its large range of spatial scales as a result of the large Reynolds numbers (Re). Reynolds-averaged Navier-Stokes (RANS) simulations usually struggle to compute the base pressure and other flow features correctly because of their inability to capture the large-scale structure dynamics in the separated shear layer in a time-accurate manner. Large-eddy simulations (LES) and direct numerical simulations (DNS) at full experimental Reynolds number are generally still too computationally intensive for current computational resources, although some do exist at full-scale experimental Reynolds numbers. As a result, various hybrid schemes are oftentimes used if the full-scale experimental Reynolds number is to be examined, or a reduced Reynolds number is selected if a non-hybrid (e.g., DNS) scheme is used.

In the simulations of Kawai and Fujii, an LES/RANS hybrid methodology is selected that uses RANS for wall-bounded regions and LES for detached regions. The base pressure is predicted reasonably well, and the resolved energy spectrum has a slope on a log-log scale that approximates Kolmogorov’s -5/3 law. It captures shear layer roll-up and the mushroom-shaped patterns noted in end-view shear layer visualizations by Bourdon and Dutton at an estimated 250 times reduction in computational cost compared to pure LES and monotone integrated large-eddy simulations (MILES) for computation of the same sized domain.

Work by Sandberg et al. and Sivasubramanian et al. used reduced, transitional Reynolds numbers based on base diameter (ReD) between 30,000 and 100,000, i.e., between 1.5-2 orders of magnitude lower than the experimental values. As a result of the reduced Reynolds number, the base pressure, mean reattachment point, location of maximum reverse velocity, and ratio of the maximum reverse velocity to freestream velocity were not able to be compared directly to experiment for validation, but the end view of the wake did exhibit a similar mushroom-like pattern as was found in experiment. Therefore, it is conjectured that similar instability mechanisms may be active in the higher Reynolds number flow of the experiments. Additionally, the location of maximum turbulent kinetic energy shifts upstream of the mean reattachment point for higher numerical Reynolds numbers, which is consistent with the experiments.

In another DNS study by the same group, the authors explored the effect of reduced computational domains by partitioning the base flow azimuthally (e.g., half-cylinder, quarter-cylinder, etc.). This allowed the evaluation of the effect of eliminating lower-order, highly unstable azimuthal wave numbers, or modes, in the shear layer. A mode (k or m), as schematically visualized in Figure 2, can be represented in physical space as the number of waveforms that fit circumferentially around the base perimeter (e.g, fluctuations of k = 2 represent the oscillation of two full waveforms spaced along the circumference). Fluctuations of the axisymmetric mode (k = 0) cause
spatially uniform variation about the circular shear layer. Each distinct mode can fluctuate with a range of spectral amplitudes. The authors noted the lower-order azimuthal instability modes $k = 2$ and 4 (as shown on the left in Figure 2) were the most dominant and caused the most substantial changes to the flow and pressure field upon their removal. Unfortunately, these reduced domain DNS simulations were only compared to a fully axisymmetric, RANS simulation that showed a large base pressure peak near the center of the base, which is both typical of RANS simulations and inconsistent with experiments. Therefore, while elimination of modes $k = 2$ and 4 did cause an increase in base pressure relative to the half-cylinder case, the fully axisymmetric RANS solution always showed the largest average pressure coefficient for all Reynolds numbers attempted. Therefore, a direct and meaningful comparison to the fully axisymmetric case was not able to be made for this study.

![Figure 2. Schematic of wake patterns generated by various azimuthal modes.](image)

Deck and colleagues\textsuperscript{62 - 65} have also been involved in a sustained effort to simulate base flows and their control for several geometries. For a base flow with a smaller diameter cylindrical rear-body extension at a high subsonic Mach number (~0.7), the antisymmetric ($m=1$, helical) mode was found to be absolutely unstable near the base-extension junction (BEJ), while other modes ($m = 0$ and $m \geq 2$) remained of a convective nature.\textsuperscript{62} Recent simulations attempted to exploit this revelation by employing steady blowing actuators in the sensitive base region.\textsuperscript{63} Control was implemented in two distinct locations for comparison. The flow was found to be more receptive near the BEJ than the early stages of the shear layer (ESSL), a likely consequence of the absolute instability. Two fundamental frequencies associated with $St_r$ (Strouhal number based on recirculation length) of 0.08 and 0.20 were noted in the no-control case.\textsuperscript{64} The lower frequency oscillations represent the transverse motion of the recirculation region, or shear layer flapping, while the higher frequency fluctuations represent movement of the rear stagnation point in the form of axial pulsations. The direct comparability of a subsonic base flow with a base extension to a supersonic base flow without a base extension may be limited, but the studies highlight important fundamental fluid physics elements that the various base flow configurations have in common, which can assist in developing effective control techniques in general.

Simon et al.\textsuperscript{65} performed an LES/RANS hybrid method (zonal-detached eddy simulation) on an axisymmetric base flow geometry similar to that used at the University of Illinois at a similar Mach number and Reynolds number. Their simulations helped illuminate several prominent features of the flow, including the presence of two primary low-frequency oscillations in the recirculation region. The lowest, at a Strouhal number based on base diameter ($St_D$) of approximately 0.05, was too low to be caused by large-scale structures and was
attributed to a global flow behavior caused by the pulsation of the rear stagnation point. This was rationalized from the high level of coherence that was detected between pressure sensors located at the center of the base and at the rear stagnation point. The other low-frequency oscillation, at \( St_D = 0.13 \), was observed to be caused by a “global motion of the whole reverse velocity axis around its mean position.” In other words, the reverse flow was found to slowly undulate around the axis of symmetry. The authors also noted that this would be consistent with the displacement of the instantaneous recirculation core centroid position as reported by Bourdon et al.\(^{14} \) Consistent with experiments\(^8 \), Simon et al.\(^{65} \) observed the presence of eddy shocklets and a Reynolds shear stress that peaked at the onset of compression reacting to the extra strain rate of the adverse pressure gradient. The location of peak Reynolds shear stress was noted to contrast with expectations for subsonic flows. Eddy convection is also slowed in the shear layer/wake due to the adverse pressure gradient produced by the recompression waves, which is also consistent with experiments.\(^{66} \)

Some steady-flow control simulations of boattailing, base bleed, and afterbody tabs have been completed and compared to experimental studies in the University of Illinois facility. Flow Simulation Methodology (FSM) simulations of base bleed at Mach 2.46 and \( Re_D = 100,000 \) concluded that a slightly lower (as compared to the experiments) bleed rate (or injection parameter) of \( I = 0.0113 \) was optimum for increasing the base pressure.\(^{67} \) It increased the base pressure approximately 27% over the no-control case, which compares reasonably well with experiment. The lower injection parameter was attributed to the lower Re of the simulations, which was theorized to result in decreased entrainment. It was noted that in the simulations adding an equivalent amount of mass as was removed by entrainment led to the optimum injection parameter, which is consistent with Chapman-Korst theory.\(^{15,16} \) The no-control/ baseline base pressure coefficient and recirculation length were significantly different than the experimental no-control values, however, which may also contribute to the differences noticed in the optimal injection parameter.

Interestingly, the base pressure coefficient and recirculation length computed in LES base-bleed simulations by Fureby et al.\(^{54} \) showed a high level of qualitative and quantitative agreement to experiment. Relative to experiment, the simulations produced a similar centerline axial velocity distribution for both the no-control and control cases. The computed base pressure profiles were relatively flat and agreed reasonably well with experiment. However, the computation over predicted the base pressure consistently by about 5%. This was attributed to a few possible differences between simulation and experiment, such as a thinner approach boundary layer thickness. The optimum bleed rate of the cases examined was equivalent to experimental observations. With an optimum bleed rate, the base pressure was raised due to a displacement of the forward stagnation point and a reduction in size and intensity of the recirculation region. Decreased turbulence intensities near the forward stagnation point were also observed. Generally speaking, they noted that the maximum base pressure occurs when freestream flow turning is minimized, and that, therefore, peak base pressures are reached when entrainment of freestream air into the wake is minimized.

The vast majority of these flow control simulations use steady actuation for simplicity, but some work on time-varying control inputs does exist.\(^{60} \) Sivasubramanian et al. simulated an axisymmetric periodic perturbation by the addition of a time-varying input of radial momentum just upstream of separation. For \( Re_D = 10^5 \) (1.5 orders of
magnitude less than experiments), four frequencies were studied ranging from \( St_D = 0.83 \) to \( 5.0 \). The lowest frequency was selected because it corresponds with the most unstable streamwise wavelength for the axisymmetric mode at \( Re_D = 30,000 \). However, this shifted to higher frequencies for higher \( Re_D \), which motivated the additional studies at higher \( St_D \). The results suggest that the lowest forcing frequency actually decreases the base pressure as might be expected since it corresponded to an instability of the flow. However, the base pressure increases monotonically for increasing frequency. The highest forcing frequency actually raised the average base pressure in the simulation by 5% over the unforced case. The authors note that this result is consistent with the experimental results using an axisymmetric trip (strip tab or ring), but clearly, there is a different physical mechanism at work for each respective result, as the experimental results were for a steady influence, while the numerical results were for a time-varying disturbance and showed both positive and negative changes for different forcing frequencies.

In the same study, a simulation of steady forcing of modes \( k = 2, 4, 8, \) and \( 16 \) (for \( FSM/Re_D = 100,000 \)) and \( k = 4, 8, \) and \( 16 \) (for \( DNS/Re_D = 30,000 \)), also by the addition of radial momentum just before separation, was compared to the experimental passive control results from Bourdon and Dutton\(^5\) using triangular tabs. It should be noted that the experiments were performed at a higher \( Re_D \) (~3.3x10\(^6\)). The results from the two studies exhibited some inconsistencies when comparing the mean base pressure changes. In the simulations, both positive and negative changes to the mean base pressure were predicted depending on the case being examined. For example, only modes \( k = 4 \) and \( 8 \) (and only for DNS at \( Re_D = 30,000 \)) of the tested cases produced significant positive changes in the base pressure (~5%). The rest of the cases either did not cause a substantial change or decreased the base pressure. However, in experiments, the addition of a varying number of triangular tabs, which likely caused a similar control force, was only seen to decrease the base pressure. Furthermore, the differences seen between different Reynolds numbers for different numerical schemes produce some uncertainty about whether the results from the highest numerical Reynolds number simulation can be extrapolated to make meaningful conclusions about the experimental Reynolds number flow.

A summary of different control methods and their influence on the base pressure is presented in Table 1 for both experimental and numerical studies.

### 1.3 Electric Arc Flow Control Science

#### 1.3.1 Flow Control Background

Flow control schemes can be classified as either passive or active with regard to their energy expenditure. Passive control methods require no auxiliary power or control loop\(^6\) and are therefore typically simple and economical. Vortex generators and spoilers are examples of devices that would be classified as passive flow control devices.\(^6\) A major drawback of passive control systems is that they generally can only be optimized for a single flow condition.\(^7\) Active control schemes generally have a power requirement, but can consequently be selectively applied. All active control methods require a control input that can either incorporate an input from a flow monitoring device (closed-loop) or not (open-loop). Open-loop control is, of course, simpler because the control systems are generally straightforward and no sensors are necessary. Closed-loop alternatives, on the other hand, are
the most complicated because of the need to measure and incorporate flow measurements into their reactive scheme. In many cases, the ability to detect the current state of a flow parameter assists in allowing the closed-loop control method to be more versatile and effective over a wider range of flow conditions and Mach numbers. For that reason, closed-loop active control is generally the most useful.

Table 1. Summary of selected base flow control results.

<table>
<thead>
<tr>
<th>Type</th>
<th>Method</th>
<th>Time Dependence</th>
<th>As Investigated by</th>
<th>Type of Study</th>
<th>Influence on Avg. Base Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>Boattail</td>
<td>steady</td>
<td>Herrin &amp; Dutton</td>
<td>Experimental</td>
<td>Positive, 21% net, 16% positive for base alone ($C_{p_{boattail}}$=-0.086, $C_{p_{cylinder}}$=-0.102)</td>
</tr>
<tr>
<td></td>
<td>Strip tab (Ring)</td>
<td>steady</td>
<td>Bourdon, Janssen &amp; Dutton</td>
<td>Experimental</td>
<td>Positive, up to 5% for optimum case (0.5 mm thick, 12 mm long, center of strip located at 18 mm upstream of separation). Optimum geometry decreases base pressure ~2% when positioned 0 mm upstream of separation</td>
</tr>
<tr>
<td></td>
<td>Triangular tabs</td>
<td>steady</td>
<td>Bourdon &amp; Dutton</td>
<td>Experimental</td>
<td>Negative, max. change of about 10% for 32 tabs (near monotonic decrease), thicker (0.5 mm) tabs decreased base pressure more rapidly</td>
</tr>
<tr>
<td></td>
<td>Radial momentum added at discrete locations prior to separation (like vortex generators or triangular tabs), modes 4, 8, &amp; 16 forced</td>
<td>steady</td>
<td>Sivasubramanian, Sandberg, von Terzi, &amp; Fasel</td>
<td>Numerical</td>
<td>Negative/positive; at $Re=100k$ for FSM, slightly positive for $k=2$, negative for higher modes; at $Re=30k$ for DNS, positive for $k=4$ &amp; 8, negative for $k=16$</td>
</tr>
<tr>
<td></td>
<td>Splitter plates</td>
<td>steady</td>
<td>Reedy, Elliott, &amp; Dutton</td>
<td>Experimental</td>
<td>Negative, up to 4% change, significant modification of the radial and spectral distributions</td>
</tr>
<tr>
<td>Active</td>
<td>Base Bleed</td>
<td>steady</td>
<td>Mathur &amp; Dutton</td>
<td>Experimental</td>
<td>Positive, ~24%, 3% more than boattail</td>
</tr>
<tr>
<td></td>
<td>Base Burn</td>
<td>steady</td>
<td>Strahle, Hubbartt, &amp; Walterick</td>
<td>Experimental</td>
<td>Positive, up to 90% at Mach 3</td>
</tr>
<tr>
<td></td>
<td>Radial momentum added axi-symmetrically prior to separation (like strip tab), mode 0, 4 different frequencies</td>
<td>time-dependent</td>
<td>Sivasubramanian, Sandberg, von Terzi, &amp; Fasel</td>
<td>Numerical</td>
<td>Negative/positive; at $Re=100k$ for FSM, negative for $St_D=0.83$, small/no change for $St_D=2$ &amp; 4, 5% positive for $St_D=5$; at $Re=30k$ for DNS, positive for $k=0$ ($St_D=0.83$)</td>
</tr>
</tbody>
</table>
Several possible active flow control techniques include acoustic excitation, continuous or pulsed suction, synthetic jets, and microelectromechanical systems (MEMS). In addition to these, recent interest has arisen for energy deposition as a high-speed flow control method. One such technique for depositing energy in a flow that has gained appeal is the use of plasma actuators. The potential benefits of studying plasmas as a means of flow control are extensive, ranging from increasing mixing to delaying flow separation. It has even been suggested by some researchers that plasmas could be used as virtual ramps for engine inlet control and as virtual flaps for vehicle attitude control if they can be efficiently produced.

There are many types of actuators that are contained within the plasma actuator genre, such as optically-induced discharges, Townsend discharges, glow discharges, which can include dielectric barrier discharges, and electric arcs, which include localized arc filament plasma actuators (LAFPAs) and SparkJets/pulsed plasma jets. The intended uses of plasma actuators are just as broad, including drag reduction, lift and moment enhancement, improved mixing, and modifications to shock structures. Mechanical control surfaces have traditionally been used in these applications, but they suffer from a list of potential drawbacks, such as limited time response, noise and vibration production, weight penalties, and higher manufacturing and operating costs. On the basis of potentially improving upon these limitations, research into plasma actuators for flow control is currently expanding. Plasma actuators can operate at high frequencies with a very short response time and can effect real-time control even for high-speed flows.

1.3.2 Electric Arc Plasma Physics

Despite the potential to benefit many aerodynamic applications, plasma actuators are still in an early stage of development even after several years of research because of the challenges involved in their application to actual engineering systems. On a system level, evaluation is difficult due to a large number of interdependencies between weight and volume constraints, power generation requirements, and the related flow field improvements. These interdependencies suggest that a detailed system study could be beneficial in allowing a more thorough understanding of the true potential of this actuator type on base flows. Understanding the potential performance benefits of these actuators for each specific flow type is an important component needed to complete such an analysis. To that end, the study presented herein was performed in order to determine the control authority of one type of plasma actuator, known as the electric arc, over a supersonic base flow.

The process that forms the arc is generally referred to as breakdown. During breakdown, the gas constituents become ionized and are dissociated from their respective electrons. The required voltage to break down a specific gas depends on the gas itself, the diameter of the molecule, the gas temperature and percent humidity, the electrode material, the electrode shape, and even the electrode surface finish. Estimates of the breakdown voltage $V_b$ for an idealized parallel-plate electrode configuration can be made through the empirically-determined Paschen’s law. The general equation for Paschen’s law is:

$$ V_b = \frac{B(pd)}{C + \ln(pd)} $$

(1)
where $p$ is the pressure, $d$ is the electrode separation, and $B$ and $C$ are empirically determined constants. For air, a $B$ value of 365 V/(cm*Torr) and $C$ value of 1.18 (when using cm and Torr for units) can be used, which results in the relation plotted in Figure 3. A reduction in the estimated breakdown voltage will occur if the electrodes’ temperature is elevated or if there are secondary sources of electrons. For gap separations of 1 and 2 mm at standard pressure (101 kPa), the breakdown voltage of air for parallel flat plates is approximately 5 kV and 8 kV, respectively. However, the wind tunnel nozzle exit pressure is representative of pressures at about 10,700 m (35,000 ft) above sea level. For the larger 2 mm gap, but at the lower pressure experienced in the supersonic wind tunnel facility, the breakdown voltage will be reduced to less than 2 kV (left edge of the curve in Figure 3). In other words, the breakdown requirements are significantly reduced for the wind tunnel environment.

![Paschen's curve for air relating arc breakdown voltage to the product of pressure and gap separation.](image)

Before arc formation, a glow discharge occurs due to the Townsend mechanism, for which an electric field causes an electron avalanche that is self sustained by freeing electrons from the metallic surface. An overvoltage occurs when the voltage across the gap increases faster than the ions can migrate to the cathode. As a result, a channel of positive ions created in the wake of the electron avalanche forms what is known as a streamer. Photon radiation causes additional avalanches nearby, and as the channel of positive ions grows, they will coalesce due to their own induced electric field, forming the streamer. The streamer grows rapidly to connect the two electrodes and passes the high current to eliminate the over-potential. The spark occurs over a small space due to the induced electric fields drawing the positive ions together. This mechanism is a form of instability of the glow discharge type of plasma that is more likely to occur when the gap or pressure is increased.
Upon breakdown of the dielectric, the DC arc discharge forms a non-equilibrium thermal discharge/plasma that is self-sustaining by thermionic emission (the hot metallic cathode emits electrons from the metal surface) and field electron emission (a strong electric field emits electrons from a cold cathode through tunneling) from the cathode. Ion bombardment leads to the high cathode temperatures that can cause increased oxide deposition and corrosion of the cathode. The arc discharge and glow discharge are two types of plasmas that are generally differentiated by their respective currents. At high enough currents, a glow discharge will transition to an arc discharge as the cathode becomes hot enough for thermionic emission to become significant. The arc, therefore, has larger currents and current densities than a glow discharge. The arc also has a lower voltage drop and acts over a smaller volume. For low to moderate currents in the arc discharge regime, the electric arc has an inverse relation between voltage and current so that once ignited the sustaining voltage will fall if the current is increased.

Furthermore, an arc plasma is generally composed of three separate components; there is the cathode layer, the positive column, and the anode layer. The three segments are represented schematically in Figure 4. The majority of the voltage drop occurs near the two electrodes with only a small drop associated with the positive column. The positive column cannot generally sustain a large potential because it is quasi-neutral, or has equal distributions of positive ions and electrons within it, and is, therefore, a conducting medium. Hence, it cannot support an electric field. The voltage drop near the electrodes occurs because the cathode and anode repel electrons and ions, respectively, resulting in either a positive or negative space charge and a subsequent electric field or voltage fall.

![Figure 4. Schematic of an electric arc discharge with the cathode (-) shown on the left and the anode (+) shown on the right. Positively-charged ions and negatively-charged electrons are represented with a plus sign (+) and ‘e’-, respectively.](image)

1.3.3 Electric Arc Flow Control

Within a given flow, the electric arc can produce temporally-varying disturbances with the added benefit of providing flow control with no moving parts. The disturbances are similar to that of a wedge, bump, or crossflow jet, but can be selectively applied based on flow regime or flight conditions. Previous research indicates that a significant component of the forcing is tied to the Joule and convective heating that occur primarily in the vicinity of the cathode. For example, Kimmel et al. studied surface plasma discharges on boundary layers at Mach 5. They
found that the local boundary layer thickness is increased from heating of the boundary layer. The heating effect distorts the surface pressure profile and can increase the local surface pressure by up to 10% immediately downstream of the cathode. This surface pressure modification can be used to augment lift on a supersonic flat plate, for example. Furthermore, a large cathode positioned near the leading edge of the flat plate caused the greatest change in lift. More information on the general uses of surface plasmas is available in a relatively recent plasma/high-speed flow control survey of both experimental and numerical research by Shang, et al. 

Adelgren et al. have shown that, by depositing energy from a high-frequency electric arc plasma, large-scale turbulent structures can be forced in the compressible shear layer of a supersonic (Mach 1.38) axisymmetric jet. The axisymmetric jet was forced for a range of $St_D$ between 0.16 to 0.56 (5.1 kHz to 18.0 kHz) and appeared to be most sensitive to $St_D$ values between 0.32 and 0.56. The 3A arcs were produced in 20 pulse bursts every 0.1 seconds (10 Hz) between 2% thoriated tungsten electrodes separated by 1 mm. Adelgren et al. indicated that, from comparison to laser energy deposition experiments, the energy of the arc (1 mJ per pulse) should be increased to produce a stronger effect.

Electric arcs for forcing the shear layer of compressible jets have also been employed by Samimy et al., Utkin et al., and Kim et al. using localized arc filament plasma actuators (LAFPAs) similar to that shown on the left in Figure 5. The studies reported that for high-subsonic and low-supersonic Mach numbers modulation (increase and decrease) of jet noise signatures, centerline Mach number, and normalized jet width was observed. The direction of change depended on the combination of forcing mode and frequency. The jet was most sensitive to the jet preferred $St_D$ ($\sim 0.3$) for all azimuthal modes except $m = 3$. For $m = 3$, the most effective $St_D$ was 0.09. The flapping mode resulted in the most entrainment, mixing, and jet spreading of all modes tested at the jet preferred $St_D$. These specific experimental investigations discharged the arc in a recessed cavity just upstream of the nozzle exit that, originally, was incorporated solely to prevent the plasma from “blowing-off” due to the local convective flow.

Interestingly, some numerical results suggest that the recessed cavity is an integral part of the forcing mechanism. Kleinman et al. reported that in their simulations the elimination of the thermal plasma source only marginally reduces the control authority of the actuator. They also reported that a narrower cavity increased the fluidic response. Both of these conclusions point to the zero-net-mass-flux synthetic jet produced by the plasma in the cavity as being the primary cause of the fluid dynamic influence.

Recently acquired experimental results obtained by Hahn et al. suggest the contrary. Hahn and his colleagues removed the recess used by earlier researchers and instead placed the actuators further downstream at the edge of the rearward-facing surface that forms the jet exhaust plane. In this way, the arcs were still removed from the direct influences of the convective fluid flow, but were not formed within a cavity as in past experiments. Even with this modification, the researchers noted similar structures in schlieren images, an equivalent reduction in noise signatures, and approximately equivalent changes (as measured by PIV) in centerline Mach number, normalized jet width, and centerline 2-D turbulent kinetic energy (TKE). The configurations investigated varied the forcing mode, Strouhal number/frequency, and electrode separation, and yet, the various measures of comparison remained in close agreement despite the removal of the cavity. The use of cavities should, therefore, be explored further in the present investigation to determine their significance in the actuation of supersonic base flows.
Hahn et al.\textsuperscript{93} also investigated the change in actuator performance on a Mach 0.9 jet for various duty cycles. Duty cycle is defined as the ratio of the plasma-on time to the total pulsing period. A reduced duty cycle was found to increase the performance of the actuators in terms of increased mixing. Specifically, the centerline Mach number decayed more rapidly when the arc was limited to the minimum duty cycle that still provided a complete and sustainable plasma formation. This result may suggest that the breakdown process causes the primary influence of the plasma actuator and possibly plays a more significant role in the electric arc actuator’s performance than the plasma itself. Hahn et al.\textsuperscript{93} proposed that reduced residual ionization and electrode heating from a lower duty cycle may explain the increased control authority. Reduced residual ionization and electrode heating will lead to a larger breakdown voltage that couples more energy directly into the flow at breakdown. Prior to breakdown, as the potential difference is increased between the electrodes, energy is stored capacitively between the electrodes in an electric field. At breakdown, the rapid drop in potential difference between the electrodes indicates the existence of a substantial energy transfer that forms the plasma through molecular ionization and produces heat, light, and sound. The rapid thermal energy input also contributes to the synthetic jet production, which may, as alluded to by these results, be a significant component of the overall control authority. Therefore, a larger breakdown voltage or voltage fall, as allowed for with shorter duty cycles, may provide more energy to the flow than that provided during the plasma-on stage. These sorts of actuator optimization studies are important for achieving maximum fluidic effect for the actuators.

![Figure 5. Example schematics of (left) a localized arc filament plasma actuator (LAFPA) and (right) a SparkJet or pulsed plasma jet.](image)

One additional type of plasma actuator that uses electric arcs for high-speed flow control is known as the SparkJet\textsuperscript{94-97}, plasma synthetic jet (PSJ)\textsuperscript{98,99}, or pulsed-plasma jet (PPJ)\textsuperscript{100-102}. As opposed to typical LAFPA configurations that form the arc either on a surface or in a shallow recession or groove, the PPJ forms the discharge in a cavity submerged beneath a surface as shown in the schematic on the right in Figure 5. The fluidic actuation is then caused by the formation of a zero-net-mass-flux synthetic jet out a small orifice in the surface. Several
characterization studies have been performed\textsuperscript{94-96,98,100,102}, but only limited results have been published on its implementation to and control over specific fluid flows.

The confined discharge in a PPJ configuration is less likely to “blow-off” and is, consequently, often times configured with three-electrodes. The three electrodes used are a ground electrode, a low-energy, high-voltage (HV) initiator electrode, and a high-energy, low-voltage (LV) electrode, typically attached to a capacitor in order to facilitate large energy inputs over a short pulse duration. The high-power discharge can result in significantly higher maximum exhaust velocities than typical LAFPA configurations (as much as an order of magnitude, depending on the plasma parameters). As a result of the small diameter orifice between the surface and the cavity, however, the influence is generally more localized and the rate of cavity cooling and refill is generally lower than for LAFPAs. At higher frequencies, the PPJ’s performance can degrade in the form of misfires and/or reduced momentum throughput as a result of the slower refill rate.\textsuperscript{100} Also, as a result of the higher energy input from the capacitors, increased electromagnetic interference (EMI) and pitting and corrosion of the electrodes are also typical\textsuperscript{102}, which may pose challenges for reliability if the actuators were mass produced and operated simultaneously and continuously.

Estimates of the maximum exhaust velocity for PPJs firing in quiescent air range from 250 m/s at 35 torr\textsuperscript{100} to 500 m/s at atmospheric pressure.\textsuperscript{102} Increased discharge current and capacitor capacitance appear to be the primary parameters that increase the maximum achievable exhaust velocity. Spectroscopic measurements suggest that 2-30\% of the electrical energy discharged between the electrodes is converted into heat energy within the cavity.\textsuperscript{100} The synthetic jet has been shown to increase the boundary layer thickness through the creation of counter-rotating vortex pairs at subsonic speeds\textsuperscript{103} and to stabilize the oscillations of a shock in front of a 24° compression ramp at supersonic speeds.\textsuperscript{101} The PPJ synthetic jet was seen to penetrate 1.5 boundary layer thicknesses into the supersonic crossflow with a jet-to-crossflow momentum flux ratio of about 0.6. Another study of the influence of the energy dissipation rate on the jet velocity found that, for a constant energy input per pulse, a more powerful jet could be produced by discharging the arc over a shorter duration.\textsuperscript{99} It was proposed that it would be beneficial to develop a pulsed discharge that could supply 1 mJ of energy over a few nanoseconds.

1.4 Present Experiments

The current project is undertaken to evaluate the effect of electric arc plasma actuators on high-speed separated flows. Two underlying goals motivate these experiments. The first goal is to provide a flow control technique that will result in enhanced flight performance for supersonic flight vehicles by altering the wake characteristics. In recent DNS work by Sandberg and Fasel\textsuperscript{58,59}, they noted that an increase in base pressure was caused by eliminating low-order azimuthal instability modes in the base shear layer. Therefore, the current experimental work aims to reproduce their disruption of the lower-order modes without causing other significant negative consequences. The second goal is to gain a broader and more sophisticated understanding of these complex, supersonic, massively-separated, compressible, and turbulent flow fields. To that end, the aim is to provide experimental results that will grant a greater fundamental comprehension of the primary fluid dynamic mechanisms at work in supersonic axisymmetric base flows.
The present objectives are fulfilled through energy deposition from multiple electric-arc plasma discharges near the base corner separation point. This open-loop active flow-control methodology will allow investigation of the influence of stimulating axisymmetric, anti-symmetric/helical, and lower-order azimuthal instability modes, which could alter the stability characteristics of the near wake. Modification of the wake stability characteristics could affect the base flow field, reattachment length, and, ultimately, base pressure. The lengthening of the reattachment region corresponds to an increase of the base pressure as it relates to decreased expansion fan strength, freestream flow turning, and mass entrainment from the recirculation region by the shear layer. A description of the electric arc plasma actuator setup recently constructed at the University of Illinois is also included within the focus of this research endeavor, as well as a characterization study of these actuators and their fluid dynamic and thermal effects on quiescent ambient air. The characterization study provides data for computational model comparison and validation that can lead to greater understanding of the fundamental fluidic effects of the actuator.

In the experiments conducted and described herein, closed-loop active control is not implemented, as this is outside the range of present-day capabilities. This is due to the increased complexity of closed-loop active control experiments and the lack of understanding of how the actuators should be driven for a given fluidic state. The open-loop active control scheme employed for the current base flow experiments is feasible with the current level of knowledge and understanding of the technique, and the understanding gained from these initial open-loop studies may help present opportunities for closed-loop control in the future.

State-of-the-art diagnostic techniques have been applied to provide quantitative measurements of the base flow with and without control. Flow field modification resulting from the active control scheme was evaluated through mean base pressure measurements, schlieren imaging, and PIV for both mean velocity and turbulence measurements. These results provide the ability to quantify the effectiveness of the flow-control methodology and give accurate and detailed data for comparisons with future computations and experimental data. Additionally, by adjusting the frequency and phase relationships of each actuator positioned around the circumference of the axisymmetric base, the influence of stimulating both axisymmetric, anti-symmetric, and lower-order azimuthal instability modes can be probed for varying frequencies in order to ascertain the combination that provides the greatest flow control authority.

It is an opportune time to evaluate the potential of this flow-control technique on a supersonic base flow, especially in the flexible and high-fidelity test bed discussed below. This is true for three reasons: (1) the prominent features of base flows have only recently been well illuminated due to recent progress with various interrogation techniques, such as schlieren, particle image velocimetry (PIV), planar laser scattering visualization and other laser-based techniques,27-29, (2) the recent and rapid development of sophisticated computational techniques that can shed light on the underlying physical phenomena of base flows and base drag,34-67, and (3) the current development and widespread proliferation of several novel types of plasma actuators and their potential to exhibit control over complex, high-speed fluid flows.73-91 The intended objectives of this initiative are also an extension of previous research on the influences of plasma actuators on the shear layer of axisymmetric jets,78,87-91,118-119 and they are conducted to determine if similar fluid dynamic interactions and mechanisms are present for the shear layer of base flows. To this end, evaluation of actuator geometries with and without cavities and of the effect of varying duty
cycles will be included in this manuscript for the sake of comparison to past numerical and experimental work and to motivate and guide future experiments.

Previously, PIV has been difficult to apply in massively separated, recirculating, supersonic base flow as the seeding technology did not provide adequate particle density to accommodate such measurements. Recent advances in seeder technology have only now made this technique possible for this facility. Additionally, several factors reduce the likelihood of the previously acquired base flow PIV data, discussed above, from accurately representing flight conditions, especially for an axisymmetric body with a simple bluff base. Thus, a PIV characterization of the velocity field downstream of the base without control will be presented for the first time for this facility. These data were acquired without model support in the supersonic flow region, making them even more unique and of importance to both the numerical and experimental fluid dynamics communities.

The PIV data presented herein build on past LDV data by Herrin et al.\(^8\), and also provide two noteworthy advances. First, the current PIV data provide instantaneous full-field realizations of the entire flow field (within the limitations of the laser sheet and camera view), whereas the LDV data were acquired on a point-by-point basis. Therefore, the LDV data did not provide simultaneous flow field data over the entire field of view, were acquired over several independent runs over many days, and both sides of the nominally axisymmetric flow were not probed due to the long experimental runs needed to acquire the data. Second, the PIV data provide higher spatial resolution measurements on average, and an evenly distributed and continuous resolution throughout the full field. The LDV measurements can provide higher spatial resolution locally (due to the small probe volume size), but increased resolution was generally reserved for only a few regions, like the shear layer just after separation. Important understanding of the instability and flapping mechanisms present in the full-field are illuminated by the PIV technique and are an important contribution to the state-of-the-art of this research, in addition to the direct benefit of the plasma-based active flow control work.

The organization of the remaining chapters of this document is as follows. Chapter 2 elaborates on the electric arc generating system, the experimental facilities, and the apparatus used in the quiescent and base flow studies. The interrogation techniques and the specific setups used in these investigations are discussed in detail. Chapter 3 presents results and discussion for preliminary plasma actuator characterization studies in quiescent ambient air. Chapter 4 follows with a presentation of the results of the primary flow control investigations using the electric arc plasma actuator to control the supersonic axisymmetric base flow. A detailed characterization of the no-control velocity field using PIV for an axisymmetric base flow without downstream model support is also included in this chapter. The associated uncertainties are estimated and the selected forcing frequencies and modes are tabulated and justified. The final chapter, Chapter 5, then summarizes the primary results and conclusions of the study. It also discusses the contributions from this work to the state-of-the-art of plasma-based flow control and provides suggestions for future progress.
CHAPTER 2 - EXPERIMENTAL FACILITIES AND INSTRUMENTATION

This chapter begins with a discussion of the plasma actuator power supply and electronics, voltage and current measurement techniques, and electro-magnetic interference (EMI) considerations. Then, the experimental design used in preliminary characterization research on the actuator outside of the tunnel is elaborated upon. The geometric configuration of the electric arc actuator, which was a normal cavity recessed into a piece of boron nitride, and the experimental setups used to probe the fluidic actuation of the arc in quiescent, ambient air are described in detail. The diagnostics included were emission imaging, schlieren imaging, and PIV. Next, the design and experimental conditions of the base flow facility are described. The flow facility was outfitted with a specially-designed afterbody that housed the electrodes, high-voltage wires, and pressure measurement lines. Therefore, the fabricated components used for the assemblies that were investigated in the wind tunnel are discussed, too. The early, four-actuator design evaluated different geometric configurations, and the second, eight-actuator design assessed the control authority of eight actuators equally-spaced circumferentially around the base using a single, preferred geometry. The selected geometry formed the discharge in an inclined cavity near the base edge and was designed to cause disturbances to the shear layer. Lastly, the schlieren and PIV diagnostic configurations used to probe the influences of the arcs on the flow are presented.

2.1 Plasma Actuator Power Supply and Control System

Pulsed plasmas created by electric arcs will be investigated for their active-control potential over the instability mechanisms in supersonic separated/base flows. The selected flow control actuator is a high-frequency arc created between two tungsten electrodes. Each arc is independently controlled using a system similar to that developed by Samimy et al.89 and described in detail by Utkin et al.90 for controlling high-speed jets. Research by Utkin et al.90 and Kim et al.91 on high-speed jets supported the use of electric arcs as potential flow control devices for supersonic base flows. Additionally, a preliminary boundary layer study in a Mach 4 facility was performed by the author that also supported the use of electric arcs in supersonic flows for control. The Mach 4 boundary layer study evaluated the plasma/boundary layer interaction of three different types of plasma actuators: a capacitively-coupled radio frequency (RF) discharge that pulses at a frequency of 13.56 MHz, a pulsed plasma from an arc discharge, and a laser-induced optical breakdown. The electric arc actuator was found to provide the best combination of effectiveness and practicality. Additional details on this preliminary study can be found in Appendix A.

Figure 6 shows a schematic of the plasma actuator electronics for eight actuators. The actual system, also shown in Figure 6, incorporates a Glassman High Voltage, Inc. 10 kV, 1-Amp DC power supply and uses eight liquid-cooled high-voltage Behlke MOSFET switches (HTS 101-03 HFS DLC IV) and corresponding electrode pairs so that each actuator can be independently controlled. Two high-power solid-body 15 kΩ ballast resistors from Power Film Systems, Inc. are placed in series on both sides of each switch to regulate the load on the power supply. Nominal system design includes four actuators per power supply so that each actuator can be supplied up to 0.25 A of current. Through additional testing with the resistors in parallel, it was determined that the power supply could
provide momentary duty-cycled currents above 1 A from its high-voltage capacitors so long as the time-averaged current draw over one complete cycle remained below 1 A. Therefore, additional 3.75 kΩ ballast resistors were acquired to drive all channels at 1 A. A supplementary ceramic capacitor (15kV, 1 nF, TDK Electronics FD-12AU) buffers the DC power supply.

An optically-isolated pulse generator with TTL outputs is used to control the high-voltage switches. The switches can operate at repetition rates up to 100 kHz, although they transition to and can only operate in burst mode for frequencies of about 40 kHz and above. The bursts are sustained for approximately 1-2 ms before the switches time out for about 1 ms. The optical isolator used in the switch control circuit is a device that decouples the physical electrical connection between the high-voltage (HV) switches and the low-voltage (LV) TTL outputs from the pulse generator, essentially safeguarding the operator from dangerous high-voltage spikes and crossovers. The optical isolator is incorporated into a printed circuit board (PCB) that also conditions the electrical signal and provides the required ground, 5 V, 15 V, and 85 V inputs to the switches. A schematic of the PCB layout is shown in Figure 7. The circuit is a modification by Nachiket Kale (UIUC graduate student) of the original design used by researchers at The Ohio State University. Additional detail on the circuit can be found in Kale’s upcoming dissertation. The TTL inputs on the PCB can also be triggered by a data acquisition board with analog outputs. Then, the plasma frequency, phase, and on-time can be controlled by a PC using software such as LabVIEW, for example.

When one of the HV switches opens, responding to a control input, the voltage ramps up at the tip of the high-voltage electrode until a high enough electric field is created to cause an electron avalanche. At this point, a conductive plasma forms and is sustained by a lower potential and a current flow. The pulsed plasma arc has a discharge time as short as 0.1 μs, but can be sustained for up to several hundreds of microseconds. The minimum discharge time used in practice in order to ensure complete formation of the plasma is 1 μs. For 100 kHz actuation, the duty cycle would be 10% in that case.

![Figure 6. Electric arc plasma actuator (left) schematic with base setup and (right) system photograph.](image)
Acquisition of specific current and voltage waveforms and confirmation of the appropriate signal delay times were made by a Pico Technology 4424 Picoscope, an Agilent Technologies N2771A 15 kV high-voltage probe, and a Pearson model number 4100 current probe. A Tektronix TDS 2024B oscilloscope (200 MHz, 2 GSa/s) was also used when higher temporal resolution was required (for laser delay time determination, for example). The Picoscope has 12-bit resolution, ±1% DC voltage accuracy, 20 MHz bandwidth, and 50 ppm (0.005%) time base accuracy. The Tektronix oscilloscope has 8-bit resolution, ±3% DC voltage accuracy, and the same 50 ppm time base accuracy as the Picoscope. The 1000:1 Agilent voltage probe and the current monitor have bandwidths of 50 MHz and 35 MHz, respectively. The sensitivity of the current monitor is 1 Volt/Ampere +1/-0% with a 0.09%/μs droop rate. This implies that over a 20 μs period of time the signal from a constant current source will drop 1.8%. The uncertainty in the electric measurements due to the electromagnetic interference (EMI) that is produced immediately after breakdown was not well characterized, and thus, measurements in this time window were not used for analysis until the signals stabilized.

Operational procedure and safety considerations for operating the high-voltage cart are outlined in Appendix B. Included are generally accepted best practices when working with any electrified circuits and protocol more specific to this particular system. EMI considerations are also discussed.

By individually controlling each arc, the phase between each excitation location can be varied. This allows for the exploration of forcing the base flow with different frequency and mode combinations. For example, the sensitivity of stimulating both lower-order azimuthal and axisymmetric modes can be examined. Another advantage of the pulsing methodology is that measurements can be synchronized and phase-averaged with respect to the forcing so that the influences of the control method can be better understood throughout the pulse cycle.
2.2 Quiescent Flow LAFPA Experimental Setup

Investigations of the arc operating in ambient, quiescent air were conducted in order to characterize the actuator’s performance outside of the wind tunnel environment. The induced fluid properties of a single LAFPA actuator were characterized using a simple normal cavity geometry milled 2 mm deep into a piece of boron nitride (BN). A half-section view of the normal cavity geometry is shown in Figure 8. On the surface, the cavity has a rectangular shape with slightly rounded edges. The surface dimensions are 5 mm x 1.6 mm. The closest point between the two electrodes is ~2 mm apart. The plasma itself is created between two 1 mm (.040") diameter, pin-type, pure tungsten electrodes typically used for arc welding. The electrodes angle slightly in towards each other as shown in Figure 8, and have truncated conical tips that are maintained at no more than 0.5 mm above the bottom of the cavity. The normal cavity geometry was selected for several reasons. Based on previous investigations with the LAFPA geometry88-91, the cavity configuration was used to reduce the possibility that high-speed flow could extinguish the arc. Additionally, the cavity geometry was incorporated to test the performance of the actuator as a synthetic jet, (i.e., zero-net-mass-flux jet).

All electric arc surface discharges, including those for the base flow apparatus discussed below, were formed from electrodes that are encased in a piece of BN. The Grade AX05 Combat BN was obtained from Saint-Gobain Ceramics and Plastics, Inc. BN was selected because of its high degree of machinability, dielectric strength, and high temperature capabilities. In certain inert environments, BN can withstand 2000°C. It also has high thermal conductivity (on the order of most metals), which may explain why the BN has been observed to have a stabilizing effect on the arc. Specifically, mounting the electrodes in the BN increased arc reliability by reducing the rate of charring accumulation on the electrodes relative to the arc being formed in open air.

The electric arc discharge’s performance in quiescent, ambient air was evaluated using several methods: voltage and current measurements (discussed above), intensified and un-intensified emission photography, instantaneous and conditionally-averaged Schlieren imaging, PIV, and spectroscopy. A detailed description of the schlieren imaging, emission imaging, and PIV setups used to investigate the electromagnetic radiation and fluidic characteristics of the LAFPAs is given below. The results of the emission spectroscopy are presented in works by DeBlauw, et al.105 and Sanders, et al.106

![Figure 8. Section view of cavity geometry, dimensions in mm; width is 1.6 mm.](image-url)
2.2.1 Schlieren Photography

Schlieren imaging was acquired using a typical z-type configuration as shown in Figure 9. The light source used was a Xenon Corp. M-437B Nanopulser with approximate spark duration of 20 ns. An iris was positioned directly in front of the spark to make the emitted light effectively a point source, which helps to make the image sharper. The light is collimated and sent through the test region by a 15.0 cm (5.91") diameter parabolic mirror with a focal length of 120 cm (47.2"). An identical mirror then focuses the light back to a point that is positioned halfway across a knife-edge. A New Focus model 9852 50-mm circular classic center-mount mirror is used to turn the light back away from the plasma before it reaches the knife-edge. A Cooke Corporation PCO.1600 camera and C-mounted Nikon Nikkor lens were used to capture the images and send them to a computer for storage and analysis. Timing was controlled by Quantum Composers 9514 and 9518 pulse generators. A Thorlabs APD110A avalanche photodiode was used to detect the initiation of visible emission from the plasma for triggering purposes. The visible emission initiation was used as the starting time for all images obtained with a delay time for the quiescent schlieren imaging experiments.

![Schematic of the “z-type” schlieren density-gradient imaging technique used for the quiescent LAFPA experiments.](image)

2.2.2 Emission Photography

Preliminary emission photographs of single arc discharges over the entire discharge period (20 μs) were obtained with a Cooke Corporation PCO.1600 camera and Nikon Nikkor lens. The intensity of the arc discharge emission photographs required the incorporation of a neutral density filter. Timing was controlled by Quantum Composers 9514 and 9518 signal generators. A Thorlabs DET210 photodiode was used to detect the initiation of visible emission from the plasma for triggering purposes. Simultaneous emission waveforms and pulse duration data were acquired by a Hamamatsu HC120-05 PMT detector and an Agilent Infiniium oscilloscope. Figure 10 shows a schematic of the emission photography acquisition method. The photodiode triggers the camera at a delay controlled by a signal generator. Then, the camera data are sent to the computer for storage.

Subsequently, intensified emission photographs were also acquired for several 20 ns intervals of a 20 μs pulse while the arc was operating at 1 kHz. Each photograph was acquired with and correlated to its voltage and current traces. Timing was again controlled by Quantum Composers 9514 and 9518 pulse generators. The plasma voltage drop at breakdown was detected by an Agilent Technologies N2771A 15 kV high-voltage probe and was used for triggering purposes in order to ensure appropriate delay times. The intensified emission photography was
acquired with a 512 x 512 pixel Roper Scientific Extended Blue PI-Max 2 intensified camera detector. Due to the high levels of electromagnetic noise produced by the plasma actuator system, the CCD was kept several meters away from the plasma. In order to obtain high-fidelity emission images, an atypical imaging setup was used. An 85 mm, 1:1.4D Nikon Nikkor AF lens was mounted backwards at a distance of approximately 25 mm away from the arc. The lens directed the scattered light from the emission into another lens affixed to the camera located 2.6 m away. A schematic of the emission imaging setup is shown in Figure 11(a). The lens attached to the intensified camera was a Nikon AF Nikkor 50 mm diameter, 70-300 mm focal length, 1:4-5.6G telephoto zoom lens. This allowed the 2 mm electric arc gap separation to be viewed from several meters away and still span over half of the detector width. The emission photographs were obtained with a spatial resolution of approximately 80 pixels/mm. The camera’s view was perpendicular to the boron nitride surface. The electrode gap was positioned horizontally, and the plane of the cavity surface was oriented vertically. All intensified emission photographs were acquired with a camera gain of 210 and an exposure time of 20 ns for the various delay times investigated.

Figure 10. Schematic of emission photography acquisition method.

2.2.3 Particle Image Velocimetry

To obtain quantitative planar velocity field data, two-component PIV velocity measurements of the plasma actuator mounted in a normal cavity were obtained for a quiescent ambient environment. Several parametric changes of discharge frequency, current, and on-time were explored. A schematic of the specialized optics configuration used for the quiescent experiments is shown in Figure 11(b). A similar optical configuration was used as for the intensified emission photography with the exception that only the backwards lens was used. The backwards lens was positioned roughly 5.7 cm away from the location of the laser sheet over the cavity. A lens attached to the camera was omitted, and the scattered laser light was focused directly to the camera CCD at a distance of approximately 53 cm. The resultant magnification was 1.85 μm per pixel or just over 540 pixels per mm. The image dimensions were square and had roughly 3.6 mm per edge. The field-of-view of the images was positioned with the bottom horizontal edge centered about the cavity and coincident with the cavity edge/BN surface.

The flow field was seeded with a mineral oil-based Concept Engineering Ltd. Smoke Systems ViCount 1300 Aerosol System that, according to the manufacturer, produces smoke oil particles 0.2-0.3 microns in diameter. The estimated maximum Stokes number in the induced flow was less than 0.2, implying high-fidelity tracking particles. The Stokes number, or ratio of particle relaxation time to characteristic flow time, was estimated
with a Stokes flow estimate of the particle relaxation time and a characteristic flow time estimate of 1 μs. The characteristic flow time was estimated from the shortest resolvable flow time scale taken to be the shortest laser delay separation time. The 1 μs characteristic flow time also corresponds to 1/20th the typical electric arc time. Moreover, if the characteristic flow time is multiplied by the maximum flow field velocity (discussed below, ~40 m/s), the equivalent length scale is about 1/40th the cavity width (0.04 mm). A summary of the uncertainty associated with the quiescent flow PIV is presented with the results and discussion in Chapter 3. The influence of thermophoresis on the particle dynamics is also investigated.

The particles were illuminated by a thin light sheet created by a dual-head New Wave Nd:YAG laser in conjunction with spherical and cylindrical lenses. The laser sheet plane was located perpendicular to the nominal path of the arc, half way between the two electrodes (see Figure 11(b)). The PIV laser was operated at a wavelength of 532 nm, with each pulse delivering approximately 95 mJ of energy. In order to achieve a median particle pixel displacement between 5 and 10 pixels, the time separation between the laser pulses was adjusted for each arc delay time in accordance with the local flow velocity. The time separation varied from between 1-10 μs. For each test case, 315 image pairs were acquired with a 2048 x 2048 pixel Cooke Corporation PCO.2000 CCD camera. The instantaneous velocity field realizations were correlated to their respective voltage and current measurements. The (0,0) reference point in the images was defined at the center of the cavity along the surface of the BN. The TTL initiation signal to the high-voltage switches was used as the starting time for all velocity fields obtained with a delay time. This was used instead of the plasma light emission, current ramp up, or voltage breakdown because the lasers required at least 100 microseconds to optically pump before the laser could be discharged through the Q-switch.

The resulting image pairs were processed by DaVis 8.0.5 software developed by LaVision GmbH. A 32-pixel-by-32-pixel interrogation window was used on the final (third) pass with 50% overlap of the interrogation regions. The resultant velocity vector array was square with 128 vectors in each direction. In total, 16384 vectors were computed per image pair. The PIV post-processing settings required a peak ratio (sometimes termed $Q$) of at least two to retain the given vector. A dual pass remove and replace filter was also used that would remove vectors if they differed more than 3 standard deviations from the mean value of the eight surrounding vectors and replace it with $2^{\text{nd}}, 3^{\text{rd}}, 4^{\text{th}},$ or $5^{\text{th}}$ peak options if they were within 3 standard deviations of the mean value of the neighboring vectors. However, no numerical interpolation was used. After post-processing, the scalar fields of the mean streamwise velocity, transverse velocity, and speed, RMS of the transverse and streamwise velocity, RMS magnitude, mean 2-D kinetic energy, 2-D turbulent kinetic energy, two normal stresses (square of the RMS), and Reynolds shear stress are computed and retained for analysis.

2.3 Base Flow Facility and Flow Properties

The base flow control experiments are performed in a specially-designed base flow facility. The tunnel is shown schematically in Figure 12 and is an axisymmetric, open-jet, supersonic, blowdown-type wind tunnel with a nominal Mach number and unit Reynolds number at the nozzle exit of 2.5 and $52 \times 10^6/\text{m}$, respectively. It has recently been renovated with the latest in facility pressure-control hardware and has been equipped with a new and
more efficient diffuser. The tunnel, with its upstream model support, or sting, has been designed to have the supersonic flow develop over a cylindrical body. The absence of downstream or side sting supports eliminates potential disturbances to the sensitive recirculation region that could alter the boundary conditions and prominent flow features of this separated flow. This critical feature differentiates this facility from the majority of other facilities and makes it of central importance for small-scale experimentation on base flows and their control.

![Figure 11. Top-view schematic (not to scale) of (a) the intensified imaging setup and (b) the PIV setup for the quiescent flow investigations.](image)

The air supply system delivers dried and compressed air at a rate and pressure of 34 m³/min and 1 MPa, respectively, to a 140 m³ tank farm. After passing through the stagnation chamber and a flow-conditioning module with screens and honeycombs, the air is accelerated by an annular converging-diverging de Laval nozzle to a nominal Mach number \(M_a\) of 2.5 and an exit diameter of 14.4 cm. The Mach number was actually measured to be 2.51 through pressure measurements and isentropic relations and 2.44 ± 1% with PIV measurements and adiabatic relations. The difference in the two results is likely accounted for by non-isentropic boundary layer losses, which act to reduce the effective expansion and associated Mach number. Using LDV, Herrin at al.⁸ reported the freestream Mach number and turbulence intensities to be 2.46 ± 1% and less than 1%, respectively, which is in reasonably good agreement to the recently acquired PIV results given the recent renovation, different stagnation conditions, and the nearly 20 year gap between the two data sets.

The supersonic flow develops over a hollow sting that is 63.5 mm in diameter and extends from outside the tunnel in the upstream direction (to allow for instrumentation access) to the exit plane of the nozzle. The stainless steel sting is held in place by a taper lock bolted to the upstream face of the stagnation chamber. After leaving the nozzle, the supersonic stream enters the 25.4 cm (10”) diameter by 30.5 cm (12”) long open-jet test section that has
three fused silica windows for optical access. A conical flow catcher and supersonic diffuser with both constant-area cylindrical and conically divergent subsections are used to decelerate the flow while minimizing the stagnation pressure losses. Finally, the supersonic jet’s noise intensity is reduced by a perforated duct and an exhaust muffler before exiting to the atmosphere out a vertical pipe with a rain cap.

Access points for continuous pressure monitoring include the stagnation chamber (temperature is also monitored), four static pressure taps equally spaced around the outer diameter of the nozzle exit, and four static pressure taps equally spaced circumferentially on the upstream wall in the test section. Pressure is also monitored axially along the afterbody (inner surface of the nozzle flow) and radially on the base surface as will be described in greater detail below. These and additional details on the design and recent refurbishment of the tunnel can be found in a work by Reedy et al.\textsuperscript{44}

![Figure 12. Schematic of axisymmetric wind tunnel, used with permission.\textsuperscript{44}](image)

In order to create matched-pressure conditions within the open jet test section, the stagnation pressure is modulated by a 6” Valtek Mark One pneumatic control valve with an integrated proportional-integral-derivative (PID) control algorithm. The algorithm attempts to equilibrate the average of the four nozzle exit pressure measurements with the outer test chamber pressure. By ensuring that the jet is “perfectly expanded” in this way, any potential interference waves emanating from the nozzle exit lip are eliminated. The necessary operating stagnation pressure to maintain matched-pressure conditions is between 393 to 400 kPa (57-58 psia) and changes slightly from day-to-day. The run pressure allows for a tunnel run time of approximately 100 seconds before recharging of the tank farm is necessary. Once the necessary stagnation pressure for a given day is established, the stagnation pressure can be maintained fairly consistently within ±2 kPa (±0.3 psi) of the specified value with manual run control. This level of consistency will result in a matched pressure differential (between the nozzle exit and the test chamber-separated region) of no more than ±0.7 kPa (±0.1 psi) at any instant in time (standard deviation of less than 345 Pa or 0.05 psid [pounds per square inch differential]). Preference was given to the nozzle being slightly under-expanded in order to prevent a weak shock from propagating through the sensitive base recirculation region.
Experimentation has determined that the recirculation region is less sensitive to a weak expansion fan than it is to a weak shock wave. The presence of a shock wave from an over-expanded jet not only shifts the stagnation point significantly downstream, but the rate of change in base pressure is more severe for an over-expanded jet than for an under-expanded jet. For example, tests indicate that the underexpanded jet condition with a 2 kPa (0.3 psia) pressure differential ($P_{\text{nozzle}} - P_{\text{cell}} = 2 \text{ kPa}$) will result in a base pressure ratio reduction of about 1.2% from matched conditions. Conversely, a similar pressure differential over-expanded jet condition ($P_{\text{nozzle}} - P_{\text{cell}} = -2 \text{ kPa}$) will result in 17.3% base pressure ratio increase relative to that of matched conditions. Therefore, a slight under-expansion was preferred compared to the alternative.

The mean base pressure ($P_b$) was measured at three distinct radial locations along a diagonal that bisects two of the actuators (i.e., 45-degree offset for four-actuator base, 22.5-degree offset for eight-actuator base). The diagonal was aligned so that it bisected the gap between the top actuator and the immediately adjacent actuator on the model when installed in the facility. The pressure was measured with 0.40 mm (1/64") diameter circular taps at radial locations of 9.53 mm (3/8"), 17.46 mm (11/16"), and 25.40 mm (1.0") [shown schematically in the Electric Arc Base Flow Afterbody section below, see Figure 15 discussed below, for example]. When non-dimensionalized by the base radius of 31.75 mm (1.25"), the three tap locations become 0.30, 0.55, and 0.80. Three 0.40 mm (1/64") diameter afterbody pressure taps also exist along the brass afterbody to measure the freestream static pressure along the sting just before separation (also shown below). The three taps are located 20.64 mm (0.813"), 31.75 mm (1.250"), and 42.86 mm (1.688") upstream of the base plane, or in non-dimensional form, the taps are located at 0.33, 0.50, and 0.68 base diameters upstream of the centered expansion. The pressure is then transferred by plastic tubing through the hollow sting to a Pressure Systems Inc. (now Measurement Systems Inc.) pressure scanner (Netscanner Model 98RK and modules Model 9816). The tubing has a frequency response of roughly 5 Hz. The Netscanner also monitored the four nozzle (outer freestream) exit static pressures and one test chamber pressure from four circumferentially-spaced pressure taps that were joined together in a manifold.

The average base pressure ratio, formed between the base pressure ($P_b$) and the freestream static pressure ($P_o$), is nominally 0.55. This typical base pressure ratio implies that a reduction in pressure of approximately 45% occurs between the freestream and the base surface. In theory, the freestream static pressure would be the same at the afterbody and nozzle exit pressure taps, but in actuality, these numbers deviated slightly. So in practice, the freestream static pressure was taken to be the mean of the average nozzle and afterbody pressures.

Another commonly used non-dimensional parameter to represent the base pressure is the base pressure coefficient, defined as:

$$c_{p_{\text{base}}} = \frac{2[(P_b/P_o) - 1]}{\gamma M_o^2}$$

(2)

where $\gamma$ is the specific heat ratio. The nominal base pressure coefficient was measured to be -0.102 with a 4% variation across the base surface. Higher pressures are generally found at larger radii.

Herrin et al. have previously reported that the rear stagnation point was located at approximately 2.65 base radii ($R$) downstream of the base for this facility. They also reported that the maximum reverse velocity was about
27% of the freestream velocity and occurred at \( X/R \approx 1.5 \), or at 0.57\( L_r \) as measured from the base, where \( L_r \) is the recirculation region length.

The stagnation temperature was maintained at 295 K ± 6 K over all of the final flow control data sets (designated the “8 actuator” experiments below). The majority of the variation and standard deviation in the stagnation temperature arises from the day-to-day variation in ambient temperature. The uncertainty of the temperature measurement technique itself is listed at 2.2 K, which does not change the estimated uncertainty of ±6 K to the given significant figures. Over the course of a given run, the standard deviation in temperature is generally less than 0.6 K, and the standard deviation in the average stagnation chamber temperature over all of the runs in a given day is generally less than 1.0 K. However, stagnation chamber temperature variations from day-to-day have been observed from 282-302 K (48°- 84° F). This measured stagnation temperature variation can result in a 2-3% variation in the freestream velocity as measured by PIV. So for the most accurate comparisons, control-off PIV vector data were acquired each day that new control-on PIV data were acquired.

A summary of relevant flow parameters is presented in Table 2. Given the typical run conditions of the facility, the supersonic freestream conditions for pressure, temperature, and density are below atmospheric. Estimates of the freestream pressure, temperature, and density, assuming an isentropic expansion from a typical run pressure and temperature to Mach 2.5, are 22.8 kPa (3.3 psia), 133 K, and 0.60 kg/m³. By measuring the flow expansion angle \( \theta \) induced by the centered expansion process from velocimetry data (~12°), estimates of the resultant flow conditions in the supersonic stream immediately downstream of the centered expansion process can also be made. When further assuming an isentropic expansion fan, the pressure, temperature, and density in this region are 9.7 kPa (1.4 psia), 104 K, and 0.32 kg/m³. Therefore, the pressure in the supersonic region outside of the turbulent shear layer is even lower than the typically measured base pressure of 12.8 kPa (1.85 psia).

### Table 2. Important wind tunnel flow parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Estimated Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_\infty )</td>
<td>2.44</td>
<td>0.02</td>
</tr>
<tr>
<td>( P_\infty ), kPa</td>
<td>400</td>
<td>2</td>
</tr>
<tr>
<td>( P_o ), kPa</td>
<td>23.4</td>
<td>1</td>
</tr>
<tr>
<td>( T_\infty ), K</td>
<td>295</td>
<td>6</td>
</tr>
<tr>
<td>( T_o ), K</td>
<td>135</td>
<td>3</td>
</tr>
<tr>
<td>( Re_o ), ( 10^6 ) m⁻¹</td>
<td>56.4</td>
<td>2</td>
</tr>
</tbody>
</table>

The downstream static pressure measurements and the stagnation pressure measurements were acquired by 0-103 kPa and 0-690 kPa differential pressure transducers, respectively, each with ±0.05% full-scale accuracy. Since the differential pressure transducers were all referenced to atmospheric pressure, absolute pressures were obtained by adding the atmospheric pressure as measured by a Pressure Systems Inc. Model 9034 pressure calibrator to each of the differential measurements. The Model 9034 pressure calibrator is capable of measuring 0-310 kPa within 0.01% of full-scale.
Also, tank, stagnation, nozzle, and cell pressures, as well as stagnation temperature, are all monitored independently of the PSI rack by a pressure and temperature instrument rack that was built in-house. A schematic of the imaging, pressure, and temperature acquisition system as well as the pneumatic valve control signal output is shown in Figure 13. The measurements are displayed by meters on the rack and are also digitized by a National Instruments USB-6009 14-bit DAQ board and transferred via USB to a computer for use in a LabVIEW virtual instrument (VI). The VI front panel is shown in Figure 14. A National Instruments 9265 0-20 mA analog output module with 16-bit resolution coupled with the previously mentioned LabVIEW PID controller can be used to automatically control the wind tunnel stagnation pressure using the pneumatic control valve. Typically, matched pressure can be maintained to within a standard deviation of about ±690 Pa (±0.1 psid), which is slightly less precise than what is attainable with the manual control option. The majority of runs for these experiments were performed with manual control due to the observed susceptibility of the LabVIEW control algorithm to the plasma EMI. Of the measurements acquired by the instrumentation rack and digitized for use in the LabVIEW VI, only the stagnation chamber temperature is saved for future analysis. The recorded values for the stagnation, nozzle, and cell pressures are obtained from the PSI pressure scanner. The tank pressure is not recorded for use with future data analysis.

![Figure 13. Sensor and instrumentation schematic for the base flow facility showing acquisition of imaging, pressure, and temperature data and output of pneumatic control valve signal.](image)

Several safety checks are incorporated into the design of the tunnel, some of which were motivated by a recent failure of an all-BN base plate during a tunnel run. Investigation into the cause of the failure revealed that the DAQ board failed to initialize correctly. As a result, a stagnation pressure representative of atmospheric pressure was continually fed back into the PID control algorithm even as the stagnation pressure increased. The large errant differential pressure between the set point and the “measured” stagnation pressure resulted in the pneumatic valve continually opening rapidly until it was completely open and the full tank pressure of 827 kPa (120 psia) was released into the stagnation chamber. As a result of this finding, a check was implemented in the LabVIEW VI that sent an output signal of 5 V from the DAQ board. The signal was wired back into a spare input on the same DAQ board. After initialization, the VI checks that the DAQ is reading the correct output voltage before the pneumatic
valve can be opened or controlled. The middle of the three dark green indicators next to the “ACQUIRE” button (top-center) in Figure 14 illuminates once the check has been completed. Additional changes to the LabVIEW control VI were also implemented, including check boxes (two red switches located just above the “ACQUIRE” button in Figure 14) representing the downstream gates, which the operator has to click to the appropriate configuration for every run in order for the tunnel’s pneumatic valve to operate.

An emergency wind tunnel shutdown switch is installed on the instrumentation box. The pneumatic valve also has several overrides incorporated into its control using relays on the back of the meters of the instrumentation rack. These prevent the stagnation pressure from rising above 483 kPa (70 psia) or the cell pressure from rising above 138 kPa (20 psia). Two coupled relays were incorporated into the control mechanisms for the base flow facility and the neighboring supersonic wind tunnel since both are supplied with compressed air from the same tank farm. As the two tunnels also share the same exhaust, a solid “blank” plate and a machined “open” plate were changed out at the downstream portion of the wind tunnels in order to prevent air from traveling back up through the tunnel currently not in use. A key was affixed to the “open” plate, and the relays were configured such that each tunnel’s pneumatic valve could only be opened if the key was inserted into the relay mechanism. Neither tunnel would run if either both keys were inserted into the mechanisms at the same time or if neither key was inserted. This was accomplished by wiring the 4-20 mA pneumatic control valve wire for each tunnel into the “normally open” switch of one mechanism and to the “normally closed” switch of the other mechanism. The insertion of one key would close both switches for one tunnel, but open both switches for the other tunnel. In essence, the relays function as an interlock.

![Figure 14. LabVIEW VI front panel for tunnel control and data acquisition.](image)

### 2.4 Electric Arc Base Flow Afterbody

The downstream end of the wind tunnel sting is threaded so that an interchangeable afterbody and base can be affixed to it, allowing experimentation with various types of base flow apparatuses. This permits experiments with both standard/non-standard base assemblies as well as passive and active flow control schemes. The internal
portion of the sting can house lines for pressure measurements or base bleed/jets, high-voltage wires, threaded rods for the retention of the base plate, or other components required for the current experiments. The connection between the sting and afterbody is designed to be airtight. Each afterbody is designed and machined uniquely for each specific experiment and may include such elements as a boattail, pressure taps, air jets / bleed ports, electrode holes, and/or cavities to name a few options.

For the investigation at hand, two different base flow afterbody arrangements with electric arc plasma actuators were studied. A preliminary electrode configuration study (with four actuators) preceded the main experimental work (with eight actuators). The preliminary study evaluated various electrode surface discharge arrangements. Four different surface discharge configurations were spaced equally around the edge of the base in order to evaluate the effectiveness of each actuator independently. From the four-actuator study, a single actuator geometry was selected and replicated eight times over to produce an eight-actuator base plate with a common actuator geometry. The eight-actuator base plate was the final testing arrangement used for the plasma actuator flow control experiments. Schematics of the two assembled models are shown in Figure 15.

For this set of experiments, the base apparatus that attached to the sting was composed of two separate assemblies known as the afterbody and base plate. The arrangement of the sting relative to the nozzle is shown schematically in Figure 16. A zoomed-in view of both the afterbody and base plate is shown assembled in Figure 17. Two-dimensional drawings with dimensions of all the components are included in Appendix C. The afterbody assembly has a threaded connection with an o-ring groove in order to make a sealed connection to the sting (see Figure 17). It also has machined into it three afterbody pressure taps (not shown), “ground“ electrode holes, and an internal retaining ring slot that was designed to hold the ground electrodes in firm contact to the brass afterbody for both positioning and electrical reasons (also shown in Figure 17).

Figure 15. (left) Four-actuator and (right) eight-actuator base assemblies used for the actuator geometry study and the final flow control studies, respectively.
Figure 16. Schematic of the sting, afterbody, and base plate assembled and mounted in the base flow facility.

Figure 17. Schematic of afterbody and base plate assemblies, showing sting (at left), brass afterbody (in gold), and the aluminum base plate with boron nitride inserts (at right).

The second assembly, known as the base plate, is primarily made from aerospace-grade aluminum 7075, but also has slots for the addition of BN inserts for insulative purposes. The BN inserts contain the internal paths for the HV and ground electrodes and the appropriate plasma actuator surface geometry. The aluminum base plate
includes three base pressure taps (see Figure 15) and a threaded rod retention mechanism that extended to the other end of the sting. The threaded rod was fastened to a cap on the external portion of the sting to lock the base in place. Removal of the base could be accomplished by loosening the fastener from the external cap and then pulling the base plate away from the brass afterbody and ground electrodes.

The “Z-shaped” BN inserts, shown in Figure 18, have two support dowels between the aluminum (Al) and BN pieces. A very tight fit was maintained between the two different materials, and all BN-to-Al interfaces were sealed with vacuum grease. The inclined, high-voltage electrode hole was sealed with silicone sealant on the inside of the boron nitride base plate. Besides eliminating leaks, its function was to maintain the electrodes at the correct location and proximity to the ground electrodes, prevent them from getting pulled into the low-pressure facility, and provide a dielectric barrier between the exposed high-voltage tungsten electrode and the grounded aluminum base. Before this dielectric barrier was used, occasional internal arcing would leave telltale charring on the inside of the base.

The HV wire extends through the center of the sting, and the HV electrode angles slightly out from the center toward the edge of the BN base (see top-right of Figure 17) in order to achieve approximately 2-millimeter proximity between the closest points of the electrodes’ surface. The “ground” electrodes extend normal to the base surface and are grounded together into the brass afterbody that serves a double purpose as a conductor. The electrodes were made from 1 mm diameter, 2% ceriated tungsten welding rods for the base flow experiments for easier starting and less charring than the pure tungsten electrodes used in the quiescent experiments.

Originally, the base plate did not use aluminum and was made entirely from BN. The all-BN base plate failed structurally, which prompted the re-design incorporating high-strength aluminum. Additionally, several blow-outs of the side wall of the all BN base plate occurred because the ground electrode was positioned too close to the edge of the base. The later Al/BN designs increased the wall thickness of that edge from 0.5 mm (0.20”) to 1.0 mm (0.40”), which decreased the frequency and severity of future incidents. The first Al/BN design (four-actuator base plate) was validated with a single BN insert before it was expanded to all four actuator geometries. Once validated for a single actuator, the insert concept was reproduced for the three other actuator geometries. Then, the new assembly was tested to ensure safe, reliable operation and an air-tight seal of the various pieces.

For the four-actuator actuator geometry study, the four electrode arrangements under consideration are designated “chamfered”, “flush”, “normal cavity”, and “inclined cavity” and are shown, respectively, clockwise from top-left in Figure 19 and in the top-right image of Figure 18. The bottom-left image in Figure 18 shows the actual base installed in the wind tunnel. Clockwise from the top in this latter image is the “inclined cavity”, “flush”, “normal cavity”, and “chamfered” geometries. The “cavity” configurations are designed to eject heated gas into the base region by creating an arc within a cavity that is either inclined towards the base edge or normal to the base surface. The other two configurations are designed to evaluate the effect of surface discharges with surface-flush electrodes. The “flush” geometry simply has the electrodes come flush to the base surface. The “chamfer” design has a small bevel along the base edge that extends 4 mm along the base circumference. The electrodes then are mounted surface flush to this beveled edge.
Figure 18. (top-left) BN inserts with dowels and (top-right) the four geometries machined into the boron nitride inserts that are used in the electric arc base flow assembly. The four configurations shown, clockwise from top-left, are “chamfered”, “flush”, “normal cavity”, and “inclined cavity”. (bottom-left) Four-actuator base assembly showing the four different geometries; clockwise from the top, is “inclined cavity”, “flush”, “normal cavity”, and “chamfer”. (bottom-right) Photo of additional fifth geometry known as “afterbody normal cavity” mounted on the bottom of the afterbody.

A fifth cavity geometry was proposed and implemented in-situ subsequent to testing the original four designs. The “normal cavity” geometry was modified to produce this alternate design. It is called the “afterbody normal cavity” and consisted of a normal cavity that ejected heated ionized gas into the supersonic stream just upstream (~2-3 mm) of the base corner along the afterbody. A photograph of the design mounted on the bottom of
the afterbody is shown in the bottom-right corner of Figure 18. The fifth design was implemented to evaluate the effectiveness of disturbing the supersonic stream and boundary layer upstream of the base-corner expansion fan and to more closely mimic the type of actuation used in recent numerical studies. However, it was not certain that the disturbances so generated would fully penetrate the strong dilatation process of the expansion fan to influence the base region.

![Figure 19. Two-dimensional drawings of the various actuator configurations machined into the boron nitride inserts that are used in the electric arc base flow assembly. The four configurations shown, clockwise from top-left, are “chamfered”, “flush”, “normal cavity”, and “inclined cavity”.](image)

Each actuator geometry was then tested and evaluated independently by comparing the flow features with “plasma on” and “plasma off”. Comparison was made through schlieren imaging and PIV (setups discussed below). The outcome of the comparison study on the different geometries will be presented in the results and discussion section.

Subsequent to the electrode configuration study, a single-actuator configuration (“inclined cavity”) was selected based on the results of the configuration study and replicated on a new base plate to eight equally-spaced locations circumferentially around the edge of the base. Images of its design, construction, and final fully-assembled form are shown in Figure 20. The base plate was investigated in the supersonic base flow facility with the ability to control the number of active actuators, actuator frequency, and phase of actuation (i.e., in-phase, out-
of-phase, or particular discharge mode: flapping mode, helical mode, double helical mode, etc.). The increased number of actuators caused some additional proximity issues as stray arcing was noted to occur on the inside of the afterbody between the HV electrode and the retaining ring or aluminum base. However, experimentation with various dielectric sealants was able to remedy these issues. Silicone sealant was ultimately settled upon for use on the inside of the afterbody.

Figure 20. (top-left) Eight-actuator base disassembled, (top-right) Al base plate for the eight actuator study, (bottom-left) assembly of eight actuator base plate showing eight HV wires, threaded retention rod and coupling with locking nut, ground electrodes, base pressure lines, and base plate o-ring, (middle-right) the assembly of the afterbody showing the three afterbody pressure taps internally, three base pressure lines, retaining ring, threaded retention rod, and ground electrodes, and (bottom-right) fully-assembled eight-actuator base assembly installed in base flow facility.
2.5 Base Flow Instrumentation and Diagnostics

The electric arc discharge’s influence on a supersonic base flow was evaluated using four specific measurement techniques: voltage and current measurements (discussed above), pressure measurements (also discussed above), instantaneous and conditionally-averaged Schlieren imaging, and PIV. A detailed description of the schlieren and PIV setups used to investigate the control authority of the LAFPAs is given below. The TTL initiation signal to the high-voltage switches was used as the starting time for all delay times. With the reduced operating pressure environment, the breakdown occurred much faster and with a higher consistency than at ambient conditions. Therefore, it was not deemed necessary to time the measurements from breakdown in order to achieve accurate, phase-locked imagery.

Feasibility studies were performed on several techniques that ultimately were not able to be performed. These include surface oil flow visualization, pressure-sensitive paint (PSP), particle Rayleigh/Mie scattering, and high-speed pressure transducer measurements. Surface oil flow visualizations were not made due to potential contamination concerns with the actuators. High-speed pressure measurements obtained with piezoresistive (Kulite-type) pressure transducers were not acquired due to the limitations imposed by the plasma EMI. Both traditional and high-speed PSP were not acquired with the plasma on because of the challenges imposed by the light emission of the plasma actuators. Traditional PSP was acquired on the Al/BN base without active actuators in order to center the sting before acquiring data. Side- and end-view Mie scattering imaging was also attempted. The traditional seed fluid, ethanol, was deemed unsafe for use in the facility with the presence of active electric arcs (due to combustion concerns), and the PIV seeding proved too large and disperse to acquire meaningful flow visualization images. Additional investigations with the technique were abandoned due to the uncertainty and cost of trying other seed particles and given the modest merit of this qualitative technique over and above the already-obtained PIV full-field velocity data.

2.5.1 Schlieren Photography

Schlieren imaging was acquired using a typical z-type configuration as shown in Figure 21. Schlieren was performed on the base flow to evaluate the fluidic effect of the actuators. The light source was a Xenon Corp. M-437B Nanopulser with approximate spark duration of 20 ns. An iris is positioned directly in front of the spark to make the emitted light effectively a point source. The light is then collimated and sent through the test region by a 20.3 cm (8”) diameter parabolic mirror with a focal length of 1.6 m (63”). An identical mirror then focuses the light back to a point that is positioned halfway across a knife-edge. A flat mirror is used to turn the light towards the camera before it reaches the knife-edge. A Cooke Corporation PCO.2000 camera and C-mounted Nikon Nikkor lens were used to capture the images and send them to a computer for storage and analysis. Timing was controlled by Quantum Composers 9514 and 9518 pulse generators.
Figure 21. Schematic of the “z-type” schlieren density-gradient imaging technique for the base flow experiments.

2.5.2 Particle Image Velocimetry

Two-component planar velocity measurements were obtained for the supersonic base flow field with active plasma actuators. A schematic of the base flow PIV setup is shown in Figure 22. Several fields-of-view were investigated, including those that focused on the recirculation region, wake, and approach boundary layer. The location of all setups are referenced to a (0,0) point located at the center of the base. The positive abscissa is directed axially downstream, while the ordinate is directed radially upward. For all data sets acquired, instantaneous velocity field realizations were correlated to their respective voltage and current measurements. The flow field was seeded with a mineral oil-based Concept Engineering Ltd. Smoke Systems ViCount 1300 Aerosol System with an after-market extended nozzle modification that allows seed injection into high-pressure environments. The fog generator produces smoke oil particles reported by the manufacturer to be about 0.2-0.3 microns in diameter. The estimated maximum Stokes number in this turbulent, compressible flow was on the order of 0.02 implying high-fidelity tracking particles given the flow structures present. The Stokes number, or ratio of particle relaxation time to characteristic flow time, was estimated with a Stokes flow estimate of the particle relaxation time and a shear layer “eddy rollover time” estimate of the characteristic flow time. A summary of the uncertainty associated with the base flow PIV is presented with the results and discussion in Chapter 4. The full analysis is described in detail in Appendix D.
Figure 22. Base flow PIV schematic.

The particles were illuminated by a thin light sheet (~0.2 mm) that traversed the vertical diameter of the base (i.e., bisected the base into two vertically-symmetric semi-circles). The light sheet was created by a dual-head New Wave Nd:YAG laser in conjunction with spherical and cylindrical lenses. The PIV laser was operated at a wavelength of 532 nm, with each pulse delivering approximately 180 mJ of energy. The time separation between the laser pulses was held constant at 2.0 µs for all cases except for the boundary layer investigations. The time separation between laser pulses for the boundary layer investigations was 0.5 µs because of the decreased field-of-view. The CCD camera was a 2048 x 2048 pixel Cooke Corporation PCO.2000 camera. An 85 mm, 1:1.4D Nikon Nikkor AF lens was mounted to the camera in order to acquire images at a magnification of 46.2 µm per pixel (21.6 pixels per mm) from a focal distance of roughly 27 cm away from the laser sheet plane. 203 and 170 image pairs per test case were acquired for the eight-actuator and four-actuator experiments, respectively. 1,000 to 1,500 image pairs were acquired, processed, and conditionally filtered for the no-control and boundary layer acquisitions. The large number of image pairs was acquired for these benchmark test cases to reduce the uncertainty associated with the turbulence and Reynolds stress statistics. Conditional filtering by visual inspection was necessary to eliminate some instantaneous vector fields that had obviously erroneous data (from pixel saturation and non-uniform particle seeding) so as not to affect the velocity field statistics.

The resulting image pairs were processed by DaVis 8.1.0 software developed by LaVision GmbH. The final pass used 16x16 pixel interrogation regions with 50% overlap. The starting interrogation region size was 64x64 pixels. The first two resolution steps (64x64 and 32x32 pixels) were processed with 8 passes with a square weighting function. The last step was processed with 2 passes with an adaptive PIV technique and Lanczos reconstruction. The 64x64 pixel initial interrogation window size and higher number of passes was found to be
beneficial in resolving the strong transverse gradients in the initial shear layer. Using larger interrogation region sizes (128x128 pixels) caused a significant increase in erroneous vectors across the initial shear layer.

The PIV post-processing settings required a peak correlation ratio (sometimes termed Q) of at least two. A dual pass remove and replace filter was also used that would remove vectors if they differed more than 3 standard deviations from the mean value of the eight surrounding vectors and replace it with 2nd, 3rd, 4th, or 5th peak options if they were within 3 standard deviations of the mean value of the neighboring vectors. However, no numerical interpolation was used. The maximum streamwise and transverse velocities were set to ±700 m/s and 350 m/s, respectively. Finally, after post-processing, the scalar fields of the mean streamwise velocity, transverse velocity, and speed, RMS of the transverse and streamwise velocity, RMS magnitude, mean 2-D kinetic energy, 2-D turbulent kinetic energy, two normal stresses (square of the RMS), and Reynolds shear stress are computed and retained for analysis.
CHAPTER 3 – PLASMA CHARACTERIZATION

As a means of quantifying the characteristics of the plasma generated in this study, emission photographs, schlieren images, PIV, and waveforms of the voltage and current have been acquired for an atmospheric discharge in quiescent air. This array of measurement techniques is not only valuable to quantify characteristics of the flow field altered by the plasma, such as induced fluid motion and the presence of vortical structures in the flow, but also provides valuable quantitative information for comparison with present and future computational modeling efforts.

3.1 Preliminary Measurements

Using the electrode arrangement of Figure 8, the potential difference, current, and power between the electrodes versus time for a single electric arc discharge are shown in Figure 23. The control input signal was operated at 5 kHz with a 10% duty cycle, which equates to a 20 microsecond on-time (0-20 μs in the figure). For these waveforms, the DC power supply was operating at a steady 7.4 kV, which, given the 30 kΩ total ballast resistance, corresponds to an expected current of slightly less than 250 mA when the plasma is active. The electrodes were 4 mm apart. The plasma creation can be detected by the sharp drop in voltage across the electrodes. The voltage peak is allowed to extend off the graph for the sake of improved voltage resolution while the plasma was formed. The peak potential difference is generally between 4-6 kV for this separation at atmospheric pressure, but it decreases with decreasing pressure and increasing current and frequency. The breakdown causes some electromagnetic interference as detected in the three signals. It also comes at a few microseconds delay relative to the control input due to the inductance of the transmission wire and the capacitance between the two electrodes. This delay time can be reduced by using shorter leads, closer electrodes, higher frequencies, higher on-times/duty cycles, or larger currents. The shorter breakdown time is achieved by reducing the time constant for voltage ramp-up and/or by shortening the plasma initiation process as a result of residual ions and pre-heated electrodes. For example, higher current discharges are achieved with lower ballast resistance that reduces the effective RC charging time constant. The residual ions and/or pre-heated electrodes reduce the electric field or voltage differential necessary for breakdown, thereby, shortening the time to plasma formation.

After breakdown, the voltage and current settle at approximately 530 V and 220 mA, respectively. The current is determined by Kirchhoff’s Law and is equal to the ratio of the driving voltage from the DC power supply to the in-series resistance. The voltage depends on several factors, including the conductivity of the plasma and cathode and anode layers. It is typically a strong function of current. The voltage is observed to vary occasionally between two distinct levels, which will be discussed in greater detail below. The power can be determined by taking the product of the voltage and current across the electrodes and is about 120 W.

Figure 24 shows the trend in electrode voltage differential for a constant current (250 mA) discharge as the electrode separation is varied. There tends to be a slightly positive correlation between the two variables, which is most likely due to the extension of the positive column. While the positive column has a slight effect on the voltage differential, the majority of the voltage differential occurs very near to the electrodes’ surface in regions known as the cathode and anode layers. The cathode and anode layers are regions of positive and negative space charge as
mentioned previously. The lack of quasi-neutrality causes the electric field and potential difference. Since the cathode and anode layers are proximity dependent, they are not strongly affected by extension of the electrode gap. Lastly, the correlation between plasma current and voltage is shown in Figure 25 for a constant electrode separation of 2 mm. A sudden drop-off in plasma voltage is observed at about 350 mA with higher voltages occurring for lower currents. The possible source of this trend will be elaborated upon more below, but the trends exhibited in Figure 24 and Figure 25 suggest that higher plasma discharge powers can be realized for lower current (around 250 mA) and larger separations.

![Graph](image)

**Figure 23.** Plasma actuator electrode potential difference, plasma current flow, and plasma power dissipation versus time for a nominal 250 mA current, 4 mm electrode separation, and a control input from 0-20 μs.

Initially, emission photography was obtained for two opposing 1.6 mm (1/16”) diameter electrodes that were positioned in free space within a few millimeters of each other. Forty-three images of the plasma were obtained using a neutral density filter and were ensemble-averaged to produce **Figure 26.** The perspective in Figure 26 was created by superimposing the average arc image to a longer exposure image of the electrodes to create a false background. Generally, the arc is seen to form in the same path between the two electrode tips with extra bulbous regions near the cathode. However, on occasion, striations or filaments form out of the direct path between the two electrodes (above arc column center, for example).
Figure 24. Plasma actuator voltage versus electrode separation at 250 mA discharge current.

Figure 25. Plasma actuator voltage and power dissipation versus current at 2 mm electrode separation.
Figure 26. Averaged emission image of the electric arc plasma discharge between two 1.6 mm (1/16”) electrodes supported in free space with no external flow.

Schlieren imaging of the near field around the plasma actuator has also been acquired while it was mounted in a solid piece of boron nitride (BN). Two configurations have been used to date. The first has a normal or 90-degree cavity that is recessed about 3 mm into the BN, and the second has a 45-degree inclined cavity of a similar depth. Figure 27 shows two instantaneous (single, not averaged) schlieren images of these cases. The blast wave produced by the arc can be seen in the far field. By tracking the growth of the wave in phase-locked images for different delay times, it has been determined that the blast wave travels at approximately 360 meters per second, or approximately Mach 1. The plume from several successive discharges can also be seen emanating from the cavity. The appearance of the plume does not change substantially for different delay times, and is, therefore, likely the effect of heated air ejected from the cavity by the arc and the electrodes. This plume and its corresponding velocity field were investigated by PIV, which will be discussed below. From these experiments, it appears that the plume is controllable by the inclination angle of the cavity. The plume direction is unaffected by electrode orientation, but it is essential that the electrodes be adequately contained within the cavity in order for the cavity to have a directional effect.

3.2 Intensified Emission Imaging

Four hundred intensified emission images (see Figure 11 for configuration) were acquired at each delay time to track the plasma development throughout breakdown, plasma formation, and extinction. These 400 images were phase-averaged to produce the images in Figure 28. For all phase-averaged images, the drop in voltage as measured between the two electrodes (i.e., voltage breakdown) was used as the zero point for delay times. This was found to be one of the earliest ways of detecting the plasma formation and was more reliable than detecting the current ramp-up or the light emission collected by a photodiode because of the influence of EMI. When the voltage dropped below 2 kV, the camera was triggered. Another 25 ns was required by the camera head in order to gate the sensor. While this point is denoted as 0 ns in the emission images acquired, some light was emitted prior to the camera being triggered. Through investigation with triggering from a pulse generator, it was found that during the
voltage ramp up no significant light was detected by the ICCD at the previously mentioned exposure time and gain settings. However, emission similar in intensity distribution to that for the 0 ns delay time was detected that was slightly more intense around the time of breakdown of the plasma. This is presumed to be the emission that occurs prior to that acquired when the camera is triggered by the voltage drop. The pulse generator timing was not used as the primary timing source because of variability in when the plasma breakdown occurs. Since breakdown occurs at different voltages, and therefore different delay times, it was essential to use the voltage breakdown as the triggering source in order to acquire images of the plasma with consistent shape and intensity for a particular delay time. It was also observed that the plasma would occasionally form at different locations on the surface of the electrodes. This is the reason for the distinct bright regions near the anode in images c, d, and e. The plasma did not form into multiple paths for individual arcs. It always formed in a consistent, single path for each individual breakdown, but occasionally the emanation point on the anode varied. This behavior was not observed for the cathode, and may have been due to different electrode geometries or the observed spherical shape of the cathode layer.

Figure 27. Schlieren images of the electric arc plasma discharge in quiescent air while mounted in a recessed cavity in a piece of boron nitride at (left) 90-degree [normal] and (right) 45-degree inclination.

In Figure 28(a), a perspective image of the electrodes in the cavity is observed. A sharpened cathode electrode (1 mm diameter) is faintly evident in this image on the right side. The anode is on the left. The electrodes were sharpened to a blunt tip so that the arc would form at a fairly consistent location on the tungsten surface in order to facilitate ensemble-averaging of the emission images. Also, if a sharp tip was used instead, the tip of the electrode can heat excessively causing the tungsten to melt.

In Figure 28(b), it is observed that the emission at 0 ns delay is already very intense, especially in the vicinity of the anode, but that it stretches across the entire gap. However, within 160 ns after this initial image (Figure 28(c)), the majority of the emission has diminished. Small luminescent regions are observed at the
electrodes, but otherwise, the emission is absent. In another 180 ns after this second image time (Figure 28(d)), the emission returns nearly to its previous intensity, but in this instance, the most luminescent region emanates from the cathode. As time progresses, the bright region connected to the cathode is observed to stretch from the cathode out towards the anode. The rise and fall of luminosity is a documented phenomenon known as photo successors. It is believed that the first phase of photo emission is caused by the initial release and collision of high speed electrons with the anode and other gas molecules. This initiates the transport of a significant number of slow moving, free ions that eventually impact with the cathode to energize and heat up the surface electrode material. This is likely the cause of the second very luminous phase that emanates from the cathode and is directed towards the anode. The hot electrode is a critical component of the arc as it stimulates a significant number of free electron emissions. In a glow discharge, only about 1% of the free electrons come from secondary electron emission from the electrodes. In contrast, it can constitute up to 70-90% of the free electrons in an arc. High-energy ion impacts can release on average 2-9 times as many electrons from the cathode.

![Figure 28. Phase-averaged emission images of the electric arc plasma discharge between two 1 mm diameter electrodes mounted in a boron nitride cavity for (a) no arc/long delay time perspective image, (b) 0 ns, (c) 160 ns, (d) 340 ns, (e) 18 μs, and (f) 100 μs; anode on the left, cathode on the right.](image)

In the next few hundred nanoseconds, the intensity diminishes rapidly to a level that is maintained for the rest of the discharge. When using a photodiode to observe the arc formation, an intense light emission peak is noticed just after breakdown. This peak is now thought to be representative of the progression in images b-d.
(e) is acquired at 18 μs, which is very near the 20 μs plasma shut down time. A soft glow stretching from one electrode to the other can be observed along with a faint glow around the cathode that could presumably be due to cathode heating. Another possibility is that the formation could be the plasma switching to a different plasma state, such as a glow discharge. After the plasma has shut down, the emitted light ceases within a few microseconds. A faint glow lingers around the cathode for tens of microseconds more, however. The glow can just barely be detected in Figure 28(f) (100 μs delay), and may be the lingering infrared signature of the heated cathode due to impinging cations. Figure 28(f) has enhanced brightness relative to the other emission images. All of the other images have constant brightness and contrast levels for easier comparison purposes.

Figure 29 shows the potential difference across the electrodes, the current flowing between the electrodes, an avalanche photodiode signal from the electric arc light emission, and the camera gate TTL output signal versus time. The control input signal was operated at 1 kHz with a 2% duty cycle, which equates to a 20 microsecond on-time (roughly -1 to 19 μs in the figure). For these waveforms, the DC power supply was operating at a steady 7.7 kV, which corresponds to an expected current of approximately 250 mA. For this set of experiments, the electrodes were 2 mm apart, which generally requires between 3-4 kV to induce breakdown at atmospheric pressure. The breakdown again comes at a few microseconds delay relative to the control input and causes some EMI similar to Figure 23. After breakdown, the voltage and current settle at approximately 485 V and 238 mA, respectively, for this experiment. The displayed voltage trace is primarily indicative of the “high-voltage” mode of operation that will be described below. The resultant power is about 115 W. Figure 30 displays the corresponding emission photograph acquired for this specific voltage and current trace. For comparison, the image is shown for two different brightness and contrast levels. The cathode is on the right and the anode is on the left.

While the current was found to be fairly steady over the duration of the arc, the voltage seemed to vary between two distinct modes, or values, and occasionally oscillated between the two values even mid-discharge. In attempting to better understand this variation, it was considered that it could possibly relate to the intensity or distribution of the emission or the emanation point of the discharge on the surface of the electrode. With this in mind, variations in gas voltage while the plasma was “on” were evaluated for influences on the emission images. The correlation between the plasma emission and the current was not evaluated because of the high degree of pulse-to-pulse consistency. No observable trend was noticed at the lower gate delays that correspond with the start-up transients of the plasma. However, the plasma emission did display one significant tendency at high gate delays. A consistent trend was noticed between the gas voltage and the luminous region around the cathode. The high-voltage condition, which was by far the most prevalent for the emission imaging experiments, corresponded to a diffuse glow around the entire cathode, while the low-voltage condition corresponded to a much brighter and more concentrated emission “spot” on the cathode. A comparison is made in Figure 31. The time-averaged voltage for the high-voltage condition was between 450-500 V, while the low-voltage gas potential averaged between 100-150 V. The difference in emission for the two cases held true regardless of whether the plasma underwent a transition mid-discharge. In other words, the present voltage state at the time of image acquisition determined the shape of the luminosity around the cathode. It is theorized that this variation may be due to the restriction of the current in the
arc by the ballast resistors. The restricted current may allow the plasma to transition to a glow discharge mode (described in Chapter 1).

As the current is increased for a glow discharge, the bright glow that gives this plasma its name will extend over the entire electrode surface until it transitions to an arc, similar to what was observed in this experiment. Glow discharges generally exist at lower currents than arcs. According to Fridman\textsuperscript{81}, arcs typically exist at currents above 0.5 A. In arcs, positive ions impact the cathode rapidly enough that free electrons are produced as a result of its elevated temperature. Other noted parameters by Fridman that support this hypothesis are gas voltages between 10-100 V for arcs and 100-1000 V for glow discharges, typical currents above 1 A for arcs and below 0.5 A for glow discharges, and power levels between 40-100 W for arcs and around 100 W for glow discharges. Indeed, the mid-discharge variations in voltage are non-existent for plasmas driven at 1 A. However, due to cost constraints, each power supply is intended to operate four actuators, which is why 0.25 A was selected as the baseline for the current study. Further investigations into the plasma physics have not been conducted, but at this time, it is believed that this explanation is the most plausible proposal. Furthermore, the spontaneous change of plasma mode from glow discharge to arc discharge with increasing current may be the cause of the significant voltage drop for currents above 350 mA in Figure 25.

![Graph](image)

**Figure 29.** Plasma actuator electrode potential difference, plasma current flow, avalanche photodiode signal, and camera trigger/TTL input versus time for a 7.7 kV DC driving voltage and 2 mm electrode separation; shown from a sample of the 0 ns ICCD emission photographs with gas potential in “high-voltage” mode.

![Images](image)

**Figure 30.** Sample instantaneous ICCD emission photographs at 0 ns delay; the images correspond to the electric traces shown in Figure 29 and are shown at two different brightness and contrast levels; anode on the left, cathode on the right.
Figure 31. Plasma actuator ICCD emission photographs at 18 μs delay for a (left) “high-voltage” and (right) “low-voltage” discharge.

3.3 Particle Image Velocimetry

PIV of the LAFPA in quiescent air was conducted in order to determine the induced velocity field for a normal cavity electrode configuration (see Figure 11 for configuration). A total of six cases were investigated. The baseline condition was that of a frequency of 1 kHz, a plasma on-time of 20 μs (duty cycle = 2%), and a plasma current of 0.25 A. Each of the other five cases varied a single parameter while holding the other parameters constant. The five cases are as follows: 10 μs on-time, 40 μs on-time, 500 Hz, 5 kHz, and 1 A. Voltage and current traces were obtained for each PIV image pair in order to correlate the velocity fields to their respective voltage and current behavior. These data were also acquired for the sake of validating that the plasma was formed and that the current and voltage characteristics were nominal and repeatable over many different samples. As noted in the ICCD discussion, occasionally, the plasma voltage behavior can change, even mid-discharge, and it is important to understand the repercussions of these changes on the fluidic forcing and on the spatial variation of plasma formation. The mean voltage, current, and power data for each case is presented in Table 3 along with the mean and standard deviation of the breakdown time for each case.

Table 3. Experimentally monitored values from the PIV acquisitions, including mean and standard deviation of breakdown time, mean gas voltage, mean plasma current, mean plasma power, the range of breakdown times used to determine if an image pair was retained or dismissed, and the average number of frames that went into the PIV data analysis for all delay times in a given condition.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Breakdown time (mean) [μs]</th>
<th>Standard deviation [μs]</th>
<th>Gas voltage (mean) [V]</th>
<th>Plasma current (mean) [mA]</th>
<th>Plasma power (mean) [W]</th>
<th>PIV breakdown window [μs]</th>
<th>Mean # averaged [out of 315]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>3.58</td>
<td>0.57</td>
<td>157.0</td>
<td>261.1</td>
<td>41.0</td>
<td>3.0-3.5</td>
<td>185</td>
</tr>
<tr>
<td>10 μs on-time</td>
<td>3.23</td>
<td>0.17</td>
<td>166.2</td>
<td>248.6</td>
<td>41.3</td>
<td>variable*</td>
<td>302</td>
</tr>
<tr>
<td>40 μs on-time</td>
<td>2.85</td>
<td>0.27</td>
<td>176.1</td>
<td>259.2</td>
<td>45.6</td>
<td>2.25-3.75</td>
<td>294</td>
</tr>
<tr>
<td>500 Hz</td>
<td>5.25</td>
<td>0.31</td>
<td>180.2</td>
<td>277.1</td>
<td>49.9</td>
<td>5.0-6.0</td>
<td>276</td>
</tr>
<tr>
<td>5 kHz</td>
<td>0.76</td>
<td>0.04</td>
<td>195.0</td>
<td>242.6</td>
<td>47.3</td>
<td>0.7-0.8</td>
<td>278</td>
</tr>
<tr>
<td>1 A</td>
<td>0.78</td>
<td>0.09</td>
<td>111.7</td>
<td>990.6</td>
<td>110.7</td>
<td>0.6-1.0</td>
<td>311</td>
</tr>
</tbody>
</table>

*See explanation in text or Table 4 for correlation between initiation delay time and breakdown delay time
Ensemble-averaged velocity vector fields for a quiescent electric arc discharge are presented in Figure 32 for the baseline condition. The ensemble-averaged velocity fields are calculated from the instantaneous velocity field realizations of several hundred image pairs. No temporal dependence or bi-modal variation in the velocity field between successive plasma discharges has been observed in this PIV arrangement, unlike that previously experienced. The time delay ranges of the two laser pulses relative to the TTL initiation pulse are listed at the top of the image. The first number listed corresponds to the measurement time of the first laser pulse, which is the delay time from the voltage ramp-up (see Figure 29). The second number is the delay time to the second laser pulse which was adjusted to achieve a pixel displacement within the range discussed above. Thus, this time range is also the time over which the velocity measurements are averaged. The respective contour plots have been conditionally averaged by breakdown time and voltage level to minimize uncertainty due to variations in breakdown time and inconsistencies caused by varying plasma discharge powers. The breakdown time window used for each case is listed in Table 3 and was arbitrarily chosen to minimize the spatial variation in the velocity field due to occasional outliers. The conditional averaging was done to improve confidence when comparing to numerical simulations as the breakdown time for each arc could not be known a priori. Since the laser needed to be optically pumped to a consistent intensity for several hundred μs prior, it was deemed that the best solution would be a simultaneous measurement of the voltage and current and an a posteriori sorting. Histograms of the breakdown time have positive skewness (skewed right) and so it is valuable to exclude the excessively high breakdown times that would otherwise result in spatial uncertainty.

The contour plots were then generated by accepting only those realizations that fell within the predetermined breakdown time window and that met a constraint on the maximum average voltage (less than 300 V). Table 3 also lists the number of accepted realizations that met both criteria out of the 315 original acquisitions. The breakdown time was so variable for the 10 μs discharge time case that one value is not listed. The limits were always greater than 1.4 μs and less than 4.75 μs. All ranges for the 10 μs discharge time case were smaller than 0.6 μs except the 8 μs laser delay case that was 2 μs wide. Table 4 provides a correlation between the delay time from voltage-ramp up or initiation to that of breakdown time for all conditions and delay times. From these data, some of the variation in wave front location and plasma jet evolution in the contour plots can be understood and attributed to variations in breakdown time.

In Figure 32, both color contours representing average speed and velocity vectors are shown in the images in order to better indicate magnitude and directional trends of the flow. The color bar scale is adjusted between the earlier images (left) and the later images (right) as the maximum fluid velocities are an order of magnitude different. The PIV data are acquired in a square region just slightly larger than 3.5 mm across that is located directly over the BN cavity. The center of the electrode cavity was located at the origin of the axes placed on the images. The edges of the cavity are located at ±0.8 mm, and the surface of the boron nitride is located about 0.1 mm above the bottom of the image at the 0 mm marker on the ordinate. The surface of the boron nitride is artificially masked out in the PIV contour plots. The laser sheet is oriented normal to a line between the electrode tips and, therefore, to the nominal path of the arc.
For 1 kHz actuation (1 ms period) with 2% duty cycle (20 µs discharge time), a maximum measured speed of approximately 41 m/s was induced by the plasma arc as is seen in image (a) of Figure 32. This occurred shortly after breakdown (measured between 8 and 9 µs), and the largest velocity vectors were generally directed outward and normal to the cavity opening at that time. Other observations made from the PIV results include a blast wave for short delay times, denoted by a well-defined semi-circular boundary with a large velocity gradient and radially outward velocity vectors. The wave can be seen at the edge of Figure 32(b). The front of the wave is moving at about 350 m/s, or roughly Mach 1. Once the discharge stops, a strong cavity “refilling” effect is evident that draws some of the expelled fluid back into the cavity as is evident in Figure 32(d). The generally outward flow witnessed in prior images has reversed to an inward direction along the lower edge of Figure 32(d) that is likely due to refilling of the cooling cavity. Later still, in Figure 32(e), a weaker upward vertical velocity column is evident, which is probably caused by buoyancy effects from heat transferred to the gas by the hot electrodes and cavity walls.

Table 4. Correlation between the nominal delay times measured from voltage ramp-up and those measured from voltage breakdown (plasma formation) for all conditions and acquisition times.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Delay time from initiation [µs]</th>
<th>Average delay time from breakdown [µs]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>baseline</td>
<td>10 µs on-time</td>
</tr>
<tr>
<td>8</td>
<td>4.75</td>
<td>4.25</td>
</tr>
<tr>
<td>12</td>
<td>8.75</td>
<td>9.2</td>
</tr>
<tr>
<td>16</td>
<td>12.75</td>
<td>14.4</td>
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<td>20</td>
<td>16.75</td>
<td>16.7</td>
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<tr>
<td>24</td>
<td>20.75</td>
<td>20.7</td>
</tr>
<tr>
<td>28</td>
<td>24.75</td>
<td>24.7</td>
</tr>
<tr>
<td>32</td>
<td>28.75</td>
<td>28.7</td>
</tr>
<tr>
<td>40</td>
<td>36.75</td>
<td>36.7</td>
</tr>
<tr>
<td>60</td>
<td>56.75</td>
<td>56.5</td>
</tr>
<tr>
<td>200</td>
<td>196.75</td>
<td>196.5</td>
</tr>
</tbody>
</table>

In general, a slight asymmetry is apparent in some of the images in Figure 32. The higher velocities seem to favor the right side of the image somewhat. Investigation into this anomaly provided two insightful conclusions about its likely cause. The first conclusion is that the rightward velocity preference is not due to room currents, fans or the particle seeding method as the small rightward velocity is not evident without the plasma. Second, it appears that the most probable cause is a slight preference for the arc to form to the bottom left side of the cavity. The location of the electric arc results in the average induced velocities being slightly biased toward the right side due to shielding by the left wall of the cavity and asymmetric gas expansion. At higher currents and frequencies, the path of the electric arc formed with less pulse-to-pulse spatial variation. This resulted in a more symmetrical induced velocity field than for the baseline 1 kHz mode of operation.
PIV data for the 5 kHz discharge case (other parameters held constant) are shown in Figure 33. The data are highly consistent and symmetric, somewhat in contrast to the 1 kHz case. Yet, the general trends remain the same. The discharge was observed to form consistently and directly between the two electrodes for this case. The measurements acquired at a repetition rate of 5 kHz suggest that the maximum fluid velocities are decreased relative to the 1 kHz case. The maximum measured speed is about 18 m/s in Figure 33 (the maximum velocity of the color bar scale for the 5 kHz case is half that of the 1 kHz case) as the faster pulsing sequence seems to reduce the plasma-fluid coupling. These observations are similar to those noted by researchers at the University of Texas at Austin for their related pulsed-plasma jets. The reduced plasma-fluid coupling is likely caused by the decreased amount of time the cavity has to “recharge” with fluid and the reduced subsequent breakdown voltages for higher frequencies. Besides the direct consequences of the reduced “recharge” time, operating at higher frequencies may also result in higher residual cavity gas temperatures and thus lower gas densities while operational. It was also noticed that the first breakdown in a high frequency pulse train always required a greater voltage for breakdown than the subsequent discharges. This is likely due to higher electrode temperatures and residual charge carriers that linger in the plasma channel from a previous discharge and assist with secondary breakdowns. Regardless of the reason, the lower breakdown voltage implies a lower maximum electric field between the electrodes and a reduced amount of energy stored capacitively between the electrodes before breakdown. The lower electric field may couple less energy into the gas at breakdown resulting in less dilatation and thermal gas expansion. The reduced velocities at higher frequencies are likely due to a combination of the limited refill time and reduced breakdown voltage effects.

Figure 34 displays color contour plots with vector overlays for all six cases acquired 12 μs post discharge initiation (except for the 500 Hz case that shows a 16 μs delay because of its longer breakdown time; the delay time from breakdown is more similar in this way). In all cases, the image with delay time from plasma breakdown closest to 10 μs was selected to capture the evolution at as similar a state as possible. While some differences are due to the inherent variation in breakdown time, the obvious parameter-induced differences dominate. The 10 μs on-time case (Figure 34(b)) has a very weak blast wave and synthetic jet plume. The 40 μs case (Figure 34(c)) seems to have a slightly higher maximum velocity as compared to the baseline case. It also has a highly asymmetrical nature similar to, but more extreme than, the baseline case that results in a wide range of velocities (from about 5-25 m/s, from right to left) at the surface of the cavity opening.

The variation due to frequency is clearly discernible by comparing images (a), (d), and (e) of Figure 34. The trend clearly shows that increased frequency leads to reduced plasma-gas coupling again possibly owing to reduced refill time, lower-density residual air in the cavity, warm electrodes, and/or decreased time for ion quenching that allows breakdown at a lower potential. The 5 kHz image’s peak speed is less than 65% of the baseline case (1 kHz), while the 500 Hz image’s peak speed is almost 80% greater than that of the baseline case. The 1 A case, Figure 34(f), appears to have the strongest residual jet at this instant in its development suggesting that the higher current and gas temperatures induce a stronger ejection of mass.

A synopsis of the variations of each case with delay time is presented in Figure 35. The figure highlights the time variation of the average PIV speed contained within a sub-region extending from -0.8 mm to +0.8 mm on the abscissa and from 0.0 mm to +0.8 mm on the ordinate (shown as a white box in Figure 34(f)) for variations in
on-time, frequency, and plasma current. Prominent and common features include an initially large peak velocity representative of a jet-like ejection of mass, which is typical of zero-net-mass-flux-type jets. The large peak is generally followed by a dip in velocity near the time the actuator shuts off and then a small (few m/s) recovery in average speed. The recovery in speed that occurs after the discharge is turned off is mostly due to an inward suction of fluid back into the cavity as these average speed plots retain no directional information. Finally, as time progresses, a nearly equilibrium condition arises as a small, but non-zero, speed is maintained within the sub-region for long extents of time. At these higher delay times, a balance is set up between incoming cool fluid being sucked into the cavity from the edges and warm highly buoyant fluid being convected vertically out of the center of the cavity.

The time evolution in Figure 35(a) for various on-times suggests that the maximum average speed in the aforementioned sub-region occurs for the baseline (20 μs on-time) case. The 10 μs pulse is weaker and shorter in duration by comparison. The 40 μs pulse endures much longer, but also suffers from reduced maximum velocity. This may be due to the asymmetry of the discharge that reduces the average speed in the sub-region, but could also be influenced by increased heating and on-time. The greater on-time could leave behind warmer walls and electrodes, a lower gas density, and an increased number of lingering ions that can lead to weaker subsequent breakdowns and fluidic forcing.

Frequency variation, Figure 35(b), presents the starkest contrast, as the peak average speed difference between the 1 kHz and 5 kHz cases is over a factor of three. The 500 Hz case is relatively similar to the baseline case, but develops more slowly than the baseline case. Interestingly, all of the cases appear to settle to the same interim value between pulses.

The 1 A alteration, Figure 35(c), does not produce significant variations in maximum speed or evolution except for a delay in the maximum speed. The apparent lack of increase in speed for the 1 A case may be partly caused by the moderate temporal resolution of the speed plots. It is interesting to note that breakdown for the 1 A case happened consistently earlier than that of the baseline case yet its peaks are delayed relative to the baseline case. It is hypothesized that this may be due to the increased gas temperatures achieved in the plasma that cause the mass ejection and refilling to be more intense and sustained over a longer duration. Some of the delays may also be due to the cascade of energy as it transitions to different molecular states on successively longer vibrational-to-rotational and rotational-to-translational time scales.

Figure 36 presents the average centerline speed (averaged from -0.2 mm to +0.2 mm on the x-axis) versus y-axis location for the same images as presented in Figure 34. As mentioned above, all of the images are selected so that the delay time from breakdown to the start of image acquisition (the first laser pulse) is as close to 10 μs as possible. The curves are sorted into separate images based on the parameter that was varied. Therefore, the baseline case is always reiterated in each plot.

For this particular time delay, the plots representing variation in on-times, Figure 36(a), are quite similar as might be expected, except for the fact that the jet and induced velocity from the propagating blast wave for the 10 μs case is quite weak and short in duration. This might be anticipated as the discharge is already off at this particular time delay. As the temperature drops, owing to the termination of the discharge, the refilling process begins pulling
fluid back towards the cavity. The speed almost drops to zero in between the cavity opening and the blast wave. The induced fluid motion behind the blast wave for the 40 μs case is the highest. There is also a secondary hump in between these two peaks for the 40 μs case that is due to the asymmetrical formation of the jet and blast wave. It is possible that this hump is due to a reflection of the blast wave off the cavity’s right-side wall since the discharge was observed to occur in close proximity to the left-side wall.

The second plot (Figure 36(b)) displays the centerline speed profile for variations in frequency. The differences for this case are the most significant of any of the parameters varied as the fluidic forcing seems to be monotonically diminishing with increasing frequency. Similar to the discussion above, the peak speed, located near the jet origin, is reduced by a factor of 2 for a 10 fold increase in frequency. The differences seem to apply to the strength of the blast wave, too, as the induced velocity behind the wave is diminished also for higher frequencies.

The final image in Figure 36, Figure 36(c), shows the difference between the average centerline speeds for a single variation in current. The differences are also quite stark, likely due to the increased power input and gas temperatures as described above for the 1 A case. The higher speeds occur in spite of the fact that the 1 A case has had longer to evolve and expand because its breakdown time is shorter than for the baseline (0.25 A) case. The fact that the wave’s induced velocity has moved further away from the jet origin corroborates this fact; yet, its peak velocity is still significantly larger than for the baseline case. The induced fluid velocity behind the blast wave appears to be about the same for either current, again, even though the 1 A case has had longer to expand and covers a larger area.

Interestingly, for the PIV experiments, the low-voltage mode of operation was predominant, which is opposite in comparison to the emission imaging experiments. While the current was intentionally maintained at nearly the same value between both experiments, it has been observed that the configuration of the cavity can have a substantial influence on the preferred mode of operation and, more specifically, on the current for which the change between the two modes occurs. For example, the boron nitride test plate was oriented on its side (vertically) with a horizontal electrode gap for the emission imaging experiments to be able to view the emission from the side. For the PIV experiments, the boron nitride plate was oriented horizontally but still with a horizontal electrode gap for optimum viewing of the induced fluid motion. The change in orientation can lead to an alteration in the thermal feedback mechanism from the plasma to the electrodes.

With this in mind, voltage variation was analyzed for its influence on the PIV results. Due to the high level of consistency in the voltage, only limited trends could be gleaned, but for the few runs that had enough high-voltage discharges to form meaningful averages, it does appear that the higher voltage discharge (higher power) yields a slightly higher velocity distribution. Only six sets of images pairs (315 image pairs per set) out of 59 had more than three high-voltage realizations. Figure 37 contrasts the speed contour plots of one of those cases that had a significant portion of high-voltage realizations. There were 191 low-voltage and 53 high-voltage realizations, respectively, for this case (40 μs on-time, 12 μs nominal delay, also shown in Figure 34(c)) that also satisfied the breakdown time criterion. While the speed plots and their distributions appear very similar for both cases, the high-voltage case produces about 20-30% greater induced velocity in the core flow near the cavity. A comparison of a full time sequence was not able to be made because of the high-voltage mode’s infrequent manifestation.
As previously mentioned, it is currently speculated that the difference between the high- and low-voltage cases may be a different mode of plasma operation altogether. It is generally known that glow discharges can be sustained up to about 0.5 A in certain conditions. From the ICCD emission images, it is believed that the high-voltage realizations may represent the plasma operating in a glow discharge mode. It is significant to note that regardless of the mode of operation, the induced velocity field is approximately the same besides some small differences likely attributable to the increased power dissipation in the glow discharge mode. The average voltage for the low-voltage and high-voltage modes, respectively, was 137.8 V and 466.6 V. With approximately the same current conducted in either mode, the resultant average power dissipated through the plasma is 35.8 W and 115.8 W for the low-voltage and high-voltage modes, respectively. Additionally, using the core jet sub-region averaging technique described above and presented in Figure 34(f), the average speeds were calculated for the low-voltage and high-voltage modes to be 12.0 m/s and 14.8 m/s for this case, respectively, an increase of 23.7%.

3.4 PIV Uncertainty & Particle Thermophoresis

Estimates of the mean uncertainty of the quiescent PIV results were made following a similar, but simplified version, of the procedure outlined by Lazar, et al.\textsuperscript{108} By combining the many different sources of potential imprecision, the equipment uncertainty was estimated at 0.6%. The low Stokes number estimated for this flow implies high-fidelity tracking of the seed particles and generally low particle lag uncertainty. Therefore, this uncertainty is estimated at 1% or less.\textsuperscript{109} Due to the temporal and spatial variations of each discharge, a moderate amount of sampling uncertainty is contributed to the overall uncertainty. It was observed that generally the local root-mean-square (RMS) of the speed is half the local speed. This implies an uncertainty of roughly 2.8% for a nominal sample size of 315 realizations. Finally, the algorithm uncertainty of the particle displacement in a pixel-based reference frame was estimated at 0.1 pixels. While the local particle displacement varies in a dynamic flow like this, the maximum was about 21.5 pixels with an estimate of the mean particle displacement made at approximately 5.1 pixels. The uncertainty due to the processing algorithm and technique is, therefore, estimated at 2.0%. The RMS combination of all four of these sources of uncertainty produces a net uncertainty of 3.6% within a confidence interval of one standard deviation.

One additional source of possible bias was analyzed for the quiescent PIV case. Occasionally, in high temperature gradient flows, particle displacement can occur because of the difference in molecular impact velocity on opposite sides of the tracer particle. The force that produces this displacement is known as the thermophoretic force and the process is known as thermophoresis. Consequently, an additional velocity, or displacement as is the case in PIV, is produced in the direction of decreasing temperature that can bias the velocity fields. The displacement is not representative of an actual fluid displacement and is an artifact of the tracer particles being submerged in the varying temperature flow. The magnitude of the bias velocity can be estimated by balancing the thermophoretic force with Stokes drag law. Essentially, the thermophoretic force will produce a terminal velocity differential for the particles relative to the true flow velocity that causes a drag force equal and opposite to the thermophoretic force.
Figure 32. Average PIV speed contours and velocity vectors for pulsing frequency of 1 kHz, plasma on-time of 20 µs, and plasma current of 0.25 A for laser pulse time ranges of (a) 8-9 µs, (b) 12-13 µs, (c) 16-17 µs, (d) 32-38 µs, (e) 40-46 µs, and (f) 60-66 µs.
Figure 33. Average PIV speed contours and velocity vectors for pulsing frequency of 5 kHz, plasma on-time of 20 µs, and plasma current of 0.25 A for laser pulse time ranges of (a) 8-10 µs, (b) 12-14 µs, (c) 16-18 µs, (d) 24-32 µs, (e) 32-40 µs, and (f) 40-48 µs.
Figure 34. Average PIV speed contours and velocity vectors for 12 µs delay time from discharge initiation for all six plasma conditions (a) baseline (20 µs, 1 kHz, ¼ A discharge), (b) 10 µs discharge, (c) 40 µs discharge, (d) 500 Hz, (e) 5 kHz, and (f) 1 A. The laser pulse separation times are listed above the images.
Figure 35. Average PIV speed contained within a sub-region extending from $x = -0.8$ mm to $+0.8$ mm and from $y = 0.0$ mm to $+0.8$ mm (see box in Fig. 9(f)) versus delay time for variation in (a) discharge on-time, (b) frequency, and (c) current.

Figure 36. Average centerline velocity (from $x = -0.2$ mm to $+0.2$ mm) versus location for variation in (a) discharge on-time, (b) frequency, and (c) current.
Figure 37. Average PIV speed contours and velocity vectors for 12 µs delay time from discharge initiation for the 40 µs discharge case. Image (a) is the average of 191 low-voltage realizations and image (b) is the average of 53 high-voltage realizations.

In order to estimate the magnitude of this velocity bias for the quiescent PIV data, numerical results were utilized in order to estimate the pressure ($p$), temperature ($T$), and temperature gradient fields. These numerical results were originally computed and validated using the electrical, spectroscopic, and PIV measurements discussed in this document for the quiescent plasma actuator experiments. From comparison of several time steps of the numerical simulation, the maximum velocity bias above the surface occurs just after the breakdown is terminated as the heated plume first reaches and extends beyond the surface of the cavity. The maximum temperature and temperature gradient decrease rapidly post discharge due to the increased heat conduction at elevated air temperatures. Buoyancy effects were not included in the numerical simulation because of the short time scales for which the analysis was performed. The numerically simulated temperature, temperature gradient, and density fields are shown in Figure 38 for a small portion of the total computed field. The area encompasses a region 0.5 mm above and below the surface of the cavity, as well as 0.5 mm right and left of the center of the cavity opening. The PIV was acquired in roughly a 3 mm x 3 mm region above the cavity so only the top half of the displayed region in Figure 38 is relevant to the experimental PIV data set comparison. The fields were then used to estimate the thermophoretic force ($F_{th}$) at every grid point using the following equation:

$$F_{th} = -\frac{p\lambda d_p^2 V T}{T}$$  (3)

where $\lambda$ is the gas mean free path and $d_p$ is particle diameter. Waldmann and Schmitt then solved for the terminal velocity bias ($V_{th}$) by balancing the thermophoretic force with Stokes drag to obtain the equation:

$$V_{th} = \frac{-0.55\mu_g V T}{\rho_g T}$$  (4)

where $\mu_g$ is the gas dynamic viscosity and $\rho_g$ is the gas density. The thermophoretic coefficient of 0.55 was originally theoretically computed by Waldmann and Schmitt for the free molecular regime with Knudsen number.
(Kn = λ/d_p) greater than one, but subsequent theoretical and experimental investigations demonstrated that a thermophoretic coefficient of 0.55 was also appropriate for the transition regime (Kn ≈ 1). This fact is important because the Knudsen number is approximately equal to or slightly larger than the one for the specified temperature regime. The viscosity \( \mu \) of the high temperature, ionized gas was computed from statistical mechanics predictions and is tabulated in NACA TN 4150. The formula taken from NACA TN 4150 and used to reproduce the viscosity field data is:

\[ \mu_g = 1.462 \times 10^{-5} \times \frac{T^{1.5}}{T + 112} \left[ \frac{g m}{cm \cdot sec} \right] \]  

(5)

The viscosity formula is very similar to Sutherland’s formula for the temperature range in question and yields comparable results.

Figure 38. Quiescent PIV thermophoresis contour plots displaying (top-left) temperature, (top-right) temperature gradient, (bottom-left) density, and (bottom-right) induced thermophoretic velocity.
The velocity bias equation used to compute the induced thermophoretic velocity does ignore the effects of internal particle heat conduction, which generally becomes significant for \(d_p\) greater than \(\lambda\) (\(Kn < 1\)). Although \(d_p\) is occasionally larger than \(\lambda\) for this flow, the heat conduction effect acts to reduce the effect of thermophoresis by conducting heat through the particle. Therefore, the simple formula presented above is considered a worst case scenario that adequately estimates the largest order of magnitude for the thermophoretic effect. The difference is minimal for sub-micron diameter particles, and the influence of particle heat conduction is further reduced by the fact that there exists less than one order of magnitude difference between the thermal conductivities of air and the tracer particle substance (mineral oil).

Performing this analysis on the computational data yields the induced velocity bias contour plot shown in Figure 38. As is apparent from the figure, the vast majority of the investigated PIV region and interrogation spots are not significantly affected by thermophoretic effects, as the PIV field-of-view was generally above the regions of highest thermophoretic velocity. The most dynamic and interesting areas shown in Figure 38 are below the cavity opening. However, a moderate influence is present above the surface of the boron nitride that reaches a maximum of roughly 0.5 m/s. This maximum is induced a few tenths of a millimeter above the boron nitride surface. The maximum 0.5 m/s bias represents about a 2.5% error. However, the maximum bias is very localized with the majority of the interrogation regions further away from the surface of the cavity having \(< 0.1\%\) added estimated uncertainty from the thermophoretic effect. It is valuable to note that the worst case 2.5% uncertainty is still less than the estimated uncertainty for the PIV from other sources, such as equipment, particle lag, sampling, and processing algorithm. It is, therefore, deemed that the thermophoretic influence more than about a mm away from the cavity opening is a negligible effect. Thermophoretic effects are likely negligible for the base flow PIV data also as the closest data point is always greater than 1 mm away from the cavity openings.

### 3.5 Summary

Several diagnostic methods were used to characterize the plasma produced by a localized arc filament plasma actuator system. These diagnostics included: intensified emission imaging, current and voltage traces, and PIV. Analysis of the data from the diagnostics suggested several conclusions on how variations in plasma properties, such as voltage, current, plasma on-time, and plasma frequency affect the overall velocity field evolution and electromagnetic emission. Velocity measurements obtained from PIV show a maximum induced velocity field from the plasma actuators of approximately 40 m/s for the baseline case operated at 1 kHz pulsing frequency, 0.25 A plasma current, and 20 µs plasma on-time. Results indicate increasing maximum induced velocities with decreasing actuation frequency, which may suggest that with increased off-time the cavity may cool and refill to a greater air density. In turn, this allows a greater fluidic forcing effect. It was also noticed that high frequencies reduce the required breakdown voltage, which may suggest that decreased breakdown voltage reduces the amount of fluidic coupling by reducing the amount of energy that is transferred into the flow. The 1 A discharge appears quite strong, but interestingly is delayed in its evolution relative to the other cases.

It is even proposed in these experiments that the arc may at times be switching into a glow discharge mode at the lower currents. While the PIV results shown and discussed here have been conditionally averaged to only
include low-voltage (arc-type) discharges, a comparison was made with the high-voltage mode for its potential to cause a stronger fluidic effect. Perhaps most interestingly, the results are quite similar between the two different modes. Of all the frequencies, on-times, currents, and potential plasma types that were investigated, it is perhaps most illuminating that all of the maximum induced velocities are within a fairly reasonable proximity to one another. For example, a four-fold increase in current yielded little change in the evolution of the velocity field even though it discharged more than twice as much power. Additionally, a 10-fold increase in frequency yielded only a two-fold decrease in maximum fluid velocity. This suggests that plasma forcing is likely not particularly sensitive to the plasma parameters. Moderate currents and plasma on-times might be recommended for future researchers due to their small return on investment. Therefore, the greatest potential fluidic influence will likely be realized by tuning the frequency or mode of operation to excite natural instability mechanisms already present in the flow. It is believed that understanding the behavior of the velocity and emission characteristics with respect to changes in voltage and current will be valuable towards better understanding the implications of flow control initiatives with electric arc plasma actuators. This array of measurement techniques is not only valuable to quantify characteristics of the flow field altered by the plasma, such as induced fluid motion, but has also provided valuable quantitative information for comparison with present computational modeling efforts.
CHAPTER 4 – BASE FLOW INVESTIGATION

4.1 Interrogation Techniques and Forcing Parameters

As a means of quantifying the influences of the plasma generated in this study on a supersonic axisymmetric base flow, schlieren images, particle image velocimetry (PIV) measurements, and base pressure measurements have been acquired. Voltage and current measurements were obtained for at least one channel for all data sets. These data are not only valuable to quantify characteristics of the flow field altered by the plasma, such as induced fluid motion and the presence of vortical structures in the flow, but also provide valuable quantitative information for comparison with present and future computational modeling efforts. The techniques performed for each set of experiments were based on what was possible given the significant electrical noise signatures of the plasma actuators and on initial indications of the perceived influences from preliminary and exploratory attempts with each investigative technique.

As this is one of the first experimental time-dependent active control studies attempted in an axisymmetric base flow, one important criterion to consider is the frequency with which the electric arc plasma actuators were fired. Several Strouhal numbers were selected for various reasons and are summarized in Table 5 along with their corresponding frequency, period, typical on-time, and distance covered in the freestream in one period. The no-control case was used as reference for all control cases. Two of the frequencies listed in the table were chosen based on the discussions of Dahan et al.\textsuperscript{115}, which were for low Mach number and Reynolds number flows. A Strouhal number based on base diameter of 0.05 was chosen because of their observations concerning forcing a shear layer from a rearward-facing step. Dahan et al. noticed that a Strouhal number less than 0.1 (based on step height) caused a positive increase in base pressure. Dahan et al.\textsuperscript{115} and Hasan et al.\textsuperscript{116} also argued that the better choice for non-dimensional scaling may be the approach boundary layer momentum thickness, $\theta$. Hasan found that for turbulent separation the shear layer instability mode, linked to the Kelvin-Helmholtz instabilities, scales with $\theta$ and is characterized by $St_\theta = 0.011$. $St_\theta = 0.0092$ was also selected based on the recommendations of Hasan.\textsuperscript{117} A control frequency of 850 Hz ($St_D = 0.09$) was selected as a candidate forcing frequency as it is the dominant fluctuating frequency of the base pressure.\textsuperscript{43} A Strouhal number of 0.3 (based on diameter) was selected because of previous LAFPA experiments that noted this frequency to be optimum for high-speed jet actuation.\textsuperscript{78} Numerical research by Sivasubramanian et al.\textsuperscript{60} suggested the possible beneficial effects of $St_D$ between 0.83 and 4.97, especially when forced in the axisymmetric mode. A frequency of 60-70 kHz ($St_D = 6.63-7.73$) was selected due to observations of the time separation of large-scale structures shedding in the shear layer.\textsuperscript{66} Lastly, 100 kHz ($St_D = 11.0$) was selected as it was the highest possible frequency using the current setup and was hypothesized to possibly disrupt and breakup the large-scale structures that are responsible for a significant portion of the mass entrainment from the recirculation region (RR). The Strouhal numbers selected provide a reasonable spread of control frequencies within the capabilities of the actuators. The candidate forcing frequencies were used exclusively initially, but were later down-selected or otherwise modified based on preliminary experimental observations. It should be noted that, due to limitations of the switches used for the current experiments, forcing frequencies over 40
kHz were operated in duty cycle or burst mode. Several hundred plasma actuation cycles were initiated, and phase-locked measurements were acquired near the end of the sequence of discharges.

Table 5. Frequencies of acquisition and justifying rationale.

<table>
<thead>
<tr>
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<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>No Control; baseline</td>
</tr>
<tr>
<td>450</td>
<td>2222</td>
<td>0.05</td>
<td>0.00021</td>
<td>20</td>
<td>1278</td>
<td>Dahan et al.115</td>
</tr>
<tr>
<td>850</td>
<td>1176</td>
<td>0.09</td>
<td>0.00039</td>
<td>20</td>
<td>676</td>
<td>Base pressure dominant frequency$^{31}$</td>
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<tr>
<td>2700</td>
<td>370</td>
<td>0.30</td>
<td>0.0012</td>
<td>20</td>
<td>213</td>
<td>Jet sensitive $S_{θ}^{78}$</td>
</tr>
<tr>
<td>7500</td>
<td>133</td>
<td>0.83</td>
<td>0.0034</td>
<td>10</td>
<td>76.7</td>
<td>Sivasubramanian et al.$^{60}$</td>
</tr>
<tr>
<td>20000</td>
<td>50</td>
<td>2.21</td>
<td>0.0092</td>
<td>5</td>
<td>28.8</td>
<td>Most responsive mode based on momentum thickness$^{117}$</td>
</tr>
<tr>
<td>25000</td>
<td>40</td>
<td>2.76</td>
<td>0.011</td>
<td>4</td>
<td>23.0</td>
<td>Dahan et al.$^{115}$ and Hasan et al.$^{116}$</td>
</tr>
<tr>
<td>45000</td>
<td>22</td>
<td>4.97</td>
<td>0.021</td>
<td>2</td>
<td>12.8</td>
<td>Sivasubramanian, et al.$^{60}$</td>
</tr>
<tr>
<td>67000</td>
<td>15</td>
<td>7.40</td>
<td>0.031</td>
<td>2</td>
<td>8.58</td>
<td>Experimental large-scale structure shedding frequency estimate$^{60}$</td>
</tr>
<tr>
<td>100000</td>
<td>10</td>
<td>11.0</td>
<td>0.046</td>
<td>2</td>
<td>5.75</td>
<td>Highest possible freq.; disrupt large-scale structures</td>
</tr>
</tbody>
</table>

One additional plasma parameter that was varied is the phase delay between channels in order to force different modes of actuation. The mathematical expression of the azimuthal modes is given in Ref. 118, and a table outlining each mode attainable for an eight-actuator configuration is presented in Table 6. Modes $m = 0$ (axisymmetric), 1 (helical), 2 (double helical), $±1$ (flapping), $±2$ (double flapping), and $±4$ (quadruple flapping) were forced in the base flow using the eight plasma actuators. Although experimentation of this nature on a base flow has not been performed previously, some numerical work does exist for forcing a base flow at differing frequencies.$^{60}$ Unfortunately, the time-variant forcing in this previous work was only performed for the axisymmetric mode ($m = 0$). Higher mode forcing was modeled for a steady input disturbance only, i.e., with no frequency dependence. Experimentally, firing all eight actuators simultaneously can only approximate the axisymmetric mode modeled in the numerical work. Therefore, some differences exist between experiment and simulation that may confound direct comparison. Experimental or numerical work outlining the preferred mode and frequency combination of applied forcing on an axisymmetric supersonic base flow does not exist to the author’s knowledge and is a primary characterization goal of this endeavor.
Table 6. Description of forced azimuthal modes, adapted from Ref. 119 with permission.

<table>
<thead>
<tr>
<th>Mode, ( m )</th>
<th>Name / Abbr.</th>
<th>Description</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>axisymmetric/ A</td>
<td>The phase delay for all actuators is 0 deg.</td>
<td>All actuators are operated at the same time</td>
</tr>
<tr>
<td>1-3</td>
<td>helical / H, double helical/ DH, etc.</td>
<td>The phase delay between each neighboring actuator is ( m(360/8) ) deg.</td>
<td>The phase delay between actuators 1 and 2 is 45, 90, and 135 deg. for ( m = 1, 2, ) and 3, respectively.</td>
</tr>
<tr>
<td>±1</td>
<td>flapping / F</td>
<td>The top three actuators (1, 2, and 8) and the bottom three actuators (4-6) are operated at the same time, but 180 deg. out-of-phase with each other.</td>
<td>The node points are at actuators 3 and 7; hence, forcing mode 1 (two nodes per wave).</td>
</tr>
<tr>
<td>±2</td>
<td>double flapping / DF</td>
<td>Two consecutive actuators are grouped together (1-2, 3-4, 5-6, 7-8) and the first and third group are operating in-phase; the second and fourth group are operating in phase, but 180 deg. out-of-phase with the other two.</td>
<td>There is a nodal point between each neighboring group (e.g., between actuators 2 and 3; hence, forcing mode 2).</td>
</tr>
<tr>
<td>±4</td>
<td>quad flapping/ QF</td>
<td>All odd and all even numbered actuators are grouped together and operated in-phase, but 180 deg. out-of-phase with each other.</td>
<td>There is a nodal point between any two consecutive actuators (a total of eight nodal points; hence, forcing mode 4).</td>
</tr>
</tbody>
</table>

4.2 Approach Boundary Layer PIV Measurements
The approach boundary layer along the afterbody was investigated with PIV. It is important to quantify the boundary layer thickness, displacement thickness, and momentum thickness because they can significantly influence the downstream base flow region. The boundary layer thickness is known to have an influence on the base pressure\textsuperscript{54} and could be an important scaling factor for determining the optimum forcing frequency of the base flow.\textsuperscript{115,116} The experimental boundary layer parameters are frequently used in computational studies to define the incoming flow conditions, especially if comparisons to experiment are intended to be made for the sake of validation. The boundary layer profile for this facility was last measured using LDV over 15 years ago, which was before the recent tunnel modifications were performed. For these reasons, it was deemed valuable to quantify them again with the new modifications and operating conditions. PIV was used to investigate the velocity field immediately up- and downstream of the separation point and centered expansion. The freestream Mach number across the nozzle exit was measured to be 2.44 \( \pm 1 \)% . The turbulence intensity in the freestream is between 1-2%, but reaches about 14% on average in the turbulent boundary layer (as averaged from the closest measurement point off of the surface to half the boundary layer thickness for the last 5 mm just before separation [-0.16 < \( X/R \) < 0.00]). It then rises sharply downstream of separation to 18% on average (as averaged from the closest measurement point off of the surface to half the boundary layer thickness for the first 2 mm [0.00 < \( X/R \) < 0.06] just after separation).

The afterbody boundary layer upstream of the base corner at \( X = -1 \) mm (\( X/R = -0.03 \)) as measured by PIV was compared to that measured by LDV. The two boundary layer profiles are shown together in the left image of Figure 39. The two profiles compare well and have a similar boundary layer thickness. A small red horizontal dash
across the profile at 3.2 mm off the surface of the afterbody represents the reported \( \delta_{99\%} \) (boundary layer thickness) for the LDV data. The LDV data were able to be acquired down to 0.25 mm off the surface of the afterbody as a result of the small probe volume. The velocity measured there was still 62% of freestream, owing to its turbulent nature. The PIV data were limited to a minimum distance off the surface of 0.68 mm due to the glare induced by the laser terminating into the afterbody. At this height, the flow speed was still 77% of its freestream value.

The incompressible displacement thickness \( (\delta^*) \), momentum thickness \( (\theta) \), and shape factor \( (H \equiv \delta^*/\theta) \) are reported in Table 7. The incompressible integral parameters are reported so as to avoid the need to make additional assumptions about the temperature and density profiles, the latter of which is used in the compressible form of the integral parameters.

A Sun and Childs\(^{120}\) curve fit was applied to the PIV data acquired at \( X = -1 \) mm and is shown in the right image of Figure 39. Reasonable agreement between the experimental and theoretical boundary layer profiles is attained for a skin friction coefficient \( (C_f) \) of \( 1.67 \times 10^{-3} \). Table 7 also summarizes the calculated boundary layer parameters from the Sun and Childs curve fit. The dimensionless parameters \( H, \Pi \) (wake strength parameter), and \( C_f \) are typical of those found in equilibrium, compressible, turbulent boundary layers.\(^{121-123}\)

![Figure 39](image_url)  
*(left) PIV/LDV afterbody boundary layer comparison at \( X = -1 \) mm \( (X/R = -0.03) \) and (right) Sun and Childs\(^{120}\) curve fit of approach boundary layer upstream of the base corner as measured by PIV.

**Table 7. Approach boundary layer parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta_{99%} ), mm</td>
<td>3.55</td>
</tr>
<tr>
<td>( \delta^* ), mm</td>
<td>0.46</td>
</tr>
<tr>
<td>( \theta ), mm</td>
<td>0.35</td>
</tr>
<tr>
<td>( H )</td>
<td>1.31</td>
</tr>
<tr>
<td>( \Pi )</td>
<td>0.57</td>
</tr>
<tr>
<td>( C_f )</td>
<td>( 1.67 \times 10^{-3} )</td>
</tr>
<tr>
<td>( u_\tau ), m/s</td>
<td>24.1</td>
</tr>
</tbody>
</table>
4.3 Base Flow PIV Characterization

The original proposal to perform PIV in the RR of the base flow facility in order to quantify the fluid dynamic effects of the plasma actuators on the base flow was ambitious. The facility has been used over the last two decades for base flow experimentation, but PIV has never successfully been able to be performed in the tunnel due to the challenges of high-fidelity, full-field seeding. In order to acquire the LDV data that was obtained in the facility and first published in 1994, special efforts had to be made in the RR to create adequate seeding density and signal intensities. Many studies in the past 18 years, especially those of a numerical nature, have used the LDV velocity field data for comparison and validation. The ability to acquire full-field instantaneous velocity field realizations in the supersonic axisymmetric base flow facility provides new data for comparison with numerical simulations. Therefore, substantial detail will be given on the results of the new technique without the use of flow control.

Even with the high-quality seed that enabled the acquisition of PIV in this challenging supersonic base flow field, there are still some limitations and areas for possible improvement with regard to seeding. Example seeding images are shown in Figure 40. The images cover a square region roughly 90 mm on a side that encompasses the supersonic stream, shear layer, RR, and rear stagnation point (5mm<X<95mm, -45mm<Y<45mm or 0.16<X/R<2.99, -1.42<Y/R<1.42). As seen in the images, non-uniform seeding densities can occur across the shear layer. The seeding density is lowest in the RR very near the base, as expected. Furthermore, the seeding density between the top and bottom supersonic streams can oscillate in intensity. Occasionally, the high density seeding is enough to saturate some pixels of the CCD sensor, necessitating a conditional filtering process. For these reasons, a constraint was placed on the laser intensity so as to not saturate pixels in the well-seeded supersonic stream while still providing adequate signal-to-noise ratios in the less-well-seeded RR.

Over time, the mineral oil used for seeding would deposit onto the sting and nozzle walls. The deposition would accumulate to the point that it would separate, and droplets of mineral oil would pass downstream in the shear layer. These droplets, if caught in the PIV image, could easily saturate the CCD sensor. On one occasion, the camera sensor and camera head fan failed, and while it cannot be determined with certainty that the particles were the cause, the Cooke Corporation repair technician described the CCD failure as consistent with high-intensity laser illumination damage. In order to counteract the deposition, the seeder inlet was moved downstream from just after the control valve to the stagnation chamber. Injecting directly into a low-speed chamber closer to the facility nozzle reduced particle deposition and agglomeration at the expense of decreased mixing time and a less-well-distributed particle density from top-to-bottom. Additionally, several “purge” runs were performed each day to reduce the accumulation of deposition from the previous set of runs. Occasionally, purge runs were performed in between data sets if increased saturation and streaking was noticed in the PIV image data. Many PIV data sets have since been acquired without further camera problems.

Before PIV was acquired, the sting was centered using surface flow visualization and PSP. The two techniques along with the acquisition of base pressure measurements have been historically used to ensure a well-centered sting within the axisymmetric nozzle and a well-centered pressure distribution. The centering process adjusts the nozzle relative to the sting in order to achieve a flow visualization pattern with streaklines that emanate
from the center of the base and extend outward radially. The consistency and repeatability of most measurements are then fairly high. However, even once the base was centered with these traditional techniques, the RR streamlines from the first PIV data sets appeared asymmetric. With further experimentation, it became clear that the average RR streamlines were an even more sensitive method to ensure a well-centered axisymmetric flow. It was further noticed that occasionally the flow RR would appear off-center when averaging only several seconds’ worth of PIV data (20-30 image pairs), but would appear well-centered when as many as 100 image pairs were used. It was evident that as many as 100 image pairs were necessary to guarantee centering by the very sensitive PIV technique as the flow appeared to undergo an oscillation with a frequency on the order of single digit Hertz. The explanation for the low-frequency oscillation and large number of realizations necessary for convergence of the average flow field was later investigated and is discussed below in the baseline PIV section.

Figure 40. Two example PIV particle images.

Once the flow pattern was well-centered by ensuring that the dividing (or stagnation) streamline was centered within the boundaries of the RR, a no-control baseline PIV data set was acquired. Previously, the closest measurement to the base provided by the LDV data set was at 2.5 mm downstream of the base surface. The first pixels on the edge of the CCD in the PIV data sets are acquired at approximately 1 mm off of the surface of the base, and the first PIV vector is centered at about 2 mm downstream of the base. For the first no-control data sets, the field-of-view was only acquired over about a 70-75 mm extent in the streamwise direction (to ~2.20R-2.36R), but the rear stagnation point is located approximately 85 mm downstream (~2.68R). Therefore, in order to evaluate the flow field in the vicinity of and downstream of the rear stagnation point, two side-by-side PIV data sets were acquired. The two sets each contained 1002 image pairs that were then conditionally filtered to remove obviously inaccurate and erroneous data. The majority of removed image pairs were due to sensor saturation caused by agglomerated seed particle droplets in the separated base flow region (as discussed above). Only the image pairs with the most obvious inaccuracies were removed in order to maintain objectivity as best as could be expected.
Each set resulted in 803 and 936 image pairs for the RR and stagnation point/wake views, respectively. The two sets of image pairs were processed and then post-processed.

An example instantaneous velocity field realization is shown in Figure 41 before and after post-processing. The image is a contour plot of speed (2-D velocity magnitude) with overlaid velocity vectors, and flow is from left to right. The flow field spatial coordinates and velocities were non-dimensionalized by the base radius ($R$) and freestream velocity ($V_o$), respectively. A representative base surface is superposed to the left of each image with the coordinate (0,0) representing the base center. The dark spots in the post-processed image represent the removed vectors. The processing procedure is discussed in the base flow PIV experimental setup section of Chapter 2. The final pass of the correlation routine uses 16-by-16-pixel interrogation regions (with 50% overlap) of the particle images. This results in a 249 x 249 velocity vector field (1 vector every 8 pixels for inner interrogation regions), or just over 62,000 evenly-distributed velocity vectors. In the figure, one out of every eight vectors is shown in both the streamwise and transverse directions, so that less than 1.6% (less than 1,000) of the calculated velocity vectors are actually shown in the image. Additionally, no interpolation is used in the processing technique.

The two sets were then ensemble-averaged and stitched together to produce one complete mean flow field that is presented in Figure 42 with both vectors and streamlines overlaid. The stitching line between the two data sets is at an $X/R$ value of approximately 2.3, where $X$ (or $x$) is the streamwise coordinate and $Y$ (or $y$) is the transverse or radial coordinate (sometimes also referenced as $r$, but not generally $R$ to avoid confusion with the symbol used to denote the base radius). Spurious vectors that are removed from an instantaneous vector field are not counted towards the ensemble-average. Therefore, the actually number of vectors that contributed to the ensemble-average varies by location.

The flow field exhibits the typical flow features of a base flow, including a centered expansion, converging shear layer, RR, rear stagnation point, and flow recompression with shocks. In an instantaneous sense, evidence of turbulent mixing in the shear layer is present with significant large-scale variations throughout the RR. In a mean sense, the velocity changes in the shear layer and RR appear much smoother and more gradual as the random turbulence is averaged out.

The base flow PIV uncertainty was estimated using the analysis outlined by Lazar, et al. The full discussion is in Appendix D. The vast majority of points in the velocity field had less than 1% computed total uncertainty using the technique. Sampling uncertainty in the RR appeared to be the largest contributor to uncertainty for the majority of the points, but potential processing errors contributed the largest absolute uncertainties. Equipment uncertainty, while constant when non-dimensionalized by the local velocity, also contributed a moderate amount of uncertainty to the streamwise freestream region when non-dimensionalized by the freestream velocity instead. The particle lag uncertainty contributed the lowest uncertainty to a majority of the interrogation regions, more so than any other component. This is likely because the majority of the velocity gradients are normal to the direction of the flow. However, the analysis does not account for the additional particle lag uncertainty contributed by turbulence as it uses the average velocity field for computation of particle slip velocity. See Appendix D for a more detailed discussion.
In order to ensure high-fidelity particle tracking, the desired particle size is small. However, the desired field of investigation is relatively large in order to capture all of the significant base flow features simultaneously. Given both of these constraints, the resultant particle image size is close to one pixel, which has the potential to contribute additional error through pixel-locking. Pixel-locking occurs when the particle images are too small to allow for sufficient sub-pixel accuracy using peak interpolation. Given the smaller particle image size, the presence of a bias towards integer pixel displacement values was evaluated using the probability density function feature of DaVis. When performed on several instantaneous velocity realizations, the probability density function analysis did show a slight preference towards integer values.

In order to better quantify the effect, DaVis also computes a peak-locking parameter. The DaVis Flow Master manual states that this parameter is calculated from a histogram of the non-integer (or decimal) component of the displacement value. For decimal values greater than 0.5 pixels, one is subtracted from the value and then the absolute value is taken before being binned into the histogram. In this way, the histogram only displays decimal values between 0.0 and 0.5 pixels. Ideally, if no bias was present, the bars of the histogram would all be of equal value and the centroid would be at 0.25 pixels. In order to evaluate the presence of a bias towards integer values, the centroid of the histogram is computed, subtracted from the ideal value (0.25 pixels), and then multiplied by 4. If a velocity field only has integer displacements and is therefore completely pixel-locked, the centroid will be at zero and the peak-locking parameter will be 1. If no integer bias is present, the peak-locking parameter will be 0. The DaVis Flow Master manual also states that a peak-locking bias of less than 10% (peak-locking parameter of less than 0.1) indicates that the peak-locking effect is acceptable. This would allow for the centroid of the histogram to be offset from the ideal value of 0.25 pixels by ±0.025 pixels, which would still constitute a smaller error than typical random error estimates (~0.1 pixels).

For the current example, typical peak-locking parameters are between 0.08 and 0.12. Therefore, the peak-locking effect is deemed borderline, but still acceptable. It would be desirable to have slightly larger particle images in the image plane, but the particle image size was already constrained by the requirements for high-fidelity fluid tracking (small particles) and full-field flow visualizations (relatively large field-of-view). It is likely that the high-density seeding, especially in the freestream, assists with maintaining adequate sub-pixel accuracy. The particle image size was not increased as a slight peak-locking effect was deemed preferable rather than using larger diameter particles or analyzing several smaller fields of view.

For the PIV data, many measures of comparison are very close to that measured with the LDV technique and to theoretical estimates. For example, the average freestream velocity from the top and bottom regions is 555 m/s, which compares well with isentropic estimates of the freestream velocity. There is roughly -0.55% difference between the PIV measurements and isentropic estimates. The difference in freestream velocity as measured by the PIV and LDV techniques is slightly more at 2%, but the majority of the difference is attributable to the change in stagnation temperature. The stagnation temperature was reported as 294 K for the LDV experiments, but was only 283 K for the particular no-control PIV experiments used for comparison here. The 11 K temperature difference causes a 1.9% change in the isentropic freestream velocity estimate, which accounts for the bulk of the discrepancy.
Figure 43 compares the centerline axial velocity component ($U$) from both the LDV and PIV data. Fairly strong agreement is present between the two sets, in general, and several of the typically reported measures of comparison for the centerline axial velocity compare well also. The maximum centerline reverse velocity of the LDV field was reported as -27% of the freestream velocity $V_\infty$ (or $V_{inf}$), whereas the same for the PIV field was estimated as -25.7%. The non-dimensional downstream location of the rear stagnation point was $X/R = 2.65$ and 2.68 for the LDV and PIV experiments, respectively. Lastly, the location of the maximum centerline reverse velocity was reported to occur at 57% of the RR length as measured from the base for the LDV experiments. This length was measured as 55.2% for the PIV technique.

Figure 41. Example instantaneous PIV realizations (speed contour with velocity vectors overlaid) without control (left) before post-processing and (right) after post-processing. The dark spots in the post-processed image are removed vectors.
Figure 42. Stitched full-field PIV speed contour plot for axisymmetric supersonic base flow with (top) vectors and (bottom) streamlines.
Lateral traverses through the LDV and PIV fields comparing lateral (transverse) and longitudinal (streamwise) velocity components are compared in Figure 44. Both the top and bottom PIV fields are compared to the LDV data, which were only acquired for the top portion of the flow field in the facility. The left and right plots display traces for axial station $X/R = 2.36$ and 3.94, which correspond to $X = 75$ and 125 mm. As mentioned above, the rear stagnation point occurs at $X/R=2.68$. So the first station is just upstream of the stagnation point and the second is significantly downstream of it. In both plots, the axial ($U$) and transverse ($V_r$) velocities in the inviscid supersonic stream match well between all three sources. The transverse velocities vanish at the centerline as expected. Both velocities exhibit symmetry across the centerline (even symmetry for axial velocity and odd symmetry for transverse velocity as the negative of the transverse velocity is plotted for the bottom half of the plane of investigation).

The largest deviations between measurements are noticed for the shear layer, though, as might be expected from the strong gradients that exist in this region. Specifically, the largest deviations are actually noticed between the top and bottom traces of the PIV technique. The LDV field and top half of the PIV field show the highest degree of similarity. This is interesting to note since the LDV data were acquired only for the top half of the facility. It is not clear if the LDV data would have shown similar variations if acquired for the bottom portion of the facility, too. In general, though, a high degree of similarity exists between the measurements obtained from the two different techniques.

The component turbulence intensities ($I_U$ and $I_V$), turbulence intensity magnitude $|I|$, and Reynolds shear stress ($\sigma_{uv}$) have also been calculated for the no-control PIV data set. Herein, the turbulence intensity in the streamwise and transverse direction ($I_U$ and $I_V$, respectively) is defined as the standard deviation ($\sigma_u$ and $\sigma_v$) in local velocity divided by the freestream velocity, or:
\[ I_\nu = \frac{\sigma_u}{V_\infty} = \frac{\langle u^2 \rangle}{V_\infty} \quad \& \quad I_v = \frac{\sigma_v}{V_\infty} = \frac{\langle v^2 \rangle}{V_\infty}, \]  

where \( \langle \cdot \rangle \) represents the ensemble-average and \( u \) and \( v \) represent the velocity fluctuation of \( U \) and \( V \) \((u = U - \langle U \rangle \) and \( v = V - \langle V \rangle \)), respectively. The numerator in the above equation is also oftentimes called the RMS deviation or standard deviation. The turbulence intensity magnitude \( |I| \) is the root-sum-square (RSS) of the two component turbulence intensities and is also equal to the square-root of twice the non-dimensional 2-D turbulent kinetic energy \( K \), or:

\[ |I| = \sqrt{I_\nu^2 + I_v^2} = \sqrt{2K}. \]

The Reynolds shear stress is a measure of the correlation between fluctuations in both the streamwise and transverse directions and is defined as:

\[ \sigma_{xy} = \frac{\langle u v \rangle}{V_\infty^2}, \]

and the Reynolds normal stresses in the streamwise \( (\sigma_{xx}) \) and transverse \( (\sigma_{yy}) \) directions, respectively, are defined as:

\[ \sigma_{xx} = \frac{\langle u^2 \rangle}{V_\infty^2} = I_\nu^2 \quad \& \quad \sigma_{yy} = \frac{\langle v^2 \rangle}{V_\infty^2} = I_v^2, \]

which is equivalent to the variance in velocity divided by the square of the freestream velocity.

Figure 44. Streamwise and lateral velocity comparison for a lateral line at (left) \( X/R = 2.36 \) \([X = 75 \text{ mm}]\) and (right) \( X/R = 3.94 \) \([X=125 \text{ mm}]\) downstream of the base surface for the LDV data and top and bottom PIV data.

The streamwise and radial turbulence intensities derived from the no-control PIV data set are shown in Figure 45. The turbulence intensity magnitude is also shown. Flow is from left to right. Each image is again a compilation of two different views stitched together at \( X/R \approx 2.3 \) with the base surface shown in black at the left. From comparison to the LDV data, the PIV data provide higher spatial resolution to help form a smoother image of
the turbulence statistics. The top half of the two component turbulence intensities compares well to the LDV data set (taken for the top half only). The peak streamwise and radial turbulence intensities for the top shear layer are approximately 23% and 13.6%, respectively. The peak turbulence intensities for both directions occur between 81% and 84% of the axial distance from the base to the mean reattachment point, which is consistent with previous results for the top half of the flow. While the PIV data generally have a symmetric distribution between the top and bottom halves of the flow, the bottom shear layer exhibits approximately 15% higher peak intensities than the values of the top shear layer. It is not clear what the underlying cause of the variation is at this time.

The stitched Reynolds shear stress field non-dimensionalized by $U^2$ (without the conventional negative sign) is shown in Figure 46. High values of Reynolds shear stress represent regions where the streamwise and radial velocity fluctuations correlate well with each other and are likely not just manifestations of random turbulence. The top field, in particular, compares well with the previously acquired LDV data. The peak for the top field is about 0.018 and occurs at about 80% of the recirculation length downstream of the base, which, as Herrin et al. have already noted, is in contrast to the location of peak Reynolds shear stress for supersonic flow over a rearward-facing step that reattaches to a solid wall. When attaching to a rigid boundary, the peak values of turbulent kinetic energy and Reynolds shear stress occur downstream of the mean reattachment point. For the bottom shear layer, which has higher shear stresses, the location of peak Reynolds shear stress is shifted slightly downstream (to about 88% of the recirculation length), but still occurs upstream of the mean reattachment point. It is likely that the peak in Reynolds shear stress at this location in the shear layer is due to flapping of the entire RR. More analysis and discussion in support of this proposition will be presented below.

All of the turbulence statistics plots have small regions of increased intensity near the initial development of the shear layers. At this time, it is not clear if these peaks are physical or are a result of the convergence of three high error criteria for PIV. It is possible that the low-seeding density, high-velocity gradients, and image edge effects are causing increased uncertainty in these regions that results in exaggerated turbulence statistics magnitudes. This is further supported by the fact that the turbulence statistics in these regions are affected by different processing parameters.

With the recent addition of instantaneous full-field velocimetry to the viable measurement techniques that can be performed in the supersonic base flow facility, a detailed analysis of the variation between realizations was performed. A principal observation was initially made that on an instantaneous basis the RR did not oftentimes form with two symmetric and equally-sized vortical regions (in this planar view). It was noticed that instantaneously the reverse velocity oftentimes formed off-center and was directed anti-parallel with one of the shear layers. A conditionally averaged investigation was able to support these instantaneous observations.

In this investigation, the average transverse velocity was computed for a rectangular box in the RR extending from $Y/R = -0.16 (-5 \text{ mm})$ to $+0.16 (+5 \text{ mm})$ in the lateral direction and $X/R = 0.79 \text{ (25 mm)}$ to $2.36 \text{ (75 mm)}$ in the longitudinal direction for every image pair acquired. The resultant average transverse velocity was binned into a histogram plot shown in Figure 47. The average transverse velocity in the “core” of the RR is very close to zero and is designated in the figure by a black vertical line. The two large peaks on either side of the average suggest that the flow has a bimodal behavior. While the RR of the mean flow appears centered and
symmetric, it is actually, on an instantaneous basis, predominantly alternating between two modes with asymmetric RRs.

Figure 45. (top) Streamwise turbulence intensity $I_U$, (center) radial/transverse turbulence intensity $I_V$, and (bottom) turbulence intensity magnitude $|I|$ acquired by PIV.
By conditionally averaging only the vector fields that fall within one of three ranges, the trend can be elucidated further. The three ranges selected for comparison have average “core” transverse velocities from $V/V_0 = -0.135 [-75 \text{ m/s}]$ to $-0.045 [-25 \text{ m/s}]$, $-0.045 [-25 \text{ m/s}]$ to $+0.045 [+25 \text{ m/s}]$, and $0.045 [25 \text{ m/s}]$ to $0.135 [75 \text{ m/s}]$ and are termed “downward” (negative transverse core velocity on average), “symmetric”, and “upward” (positive transverse core velocity on average). The three plots are shown in Figure 47 and Figure 48. The ensemble-average velocity field for the downward, symmetric, and upward cases were computed from 263, 187, and 292 realizations (of the 803 total), respectively. The other 61 ‘outlier’ realizations had even more extreme “core” transverse velocities that were outside of the investigated ranges.

Of the three investigated ranges, the “symmetric” RR resembles that of the ensemble-average for all of the fields. However, the other two fields account for the majority of realizations (76.8%) and appear quite different. A large triangular-shaped recirculation pattern forms on one side and occupies the majority of the RR. The remaining recirculation pattern is shaped like a long and slender oval and is positioned adjacent and parallel to the opposite shear layer. The asymmetric RRs appear to have an “S” or “Z”-like flow pattern that transfers fluid from one shear layer to the other (actually from one side of the conical shear layer to the other in a three-dimensional sense).
Figure 47. (left) Histogram of average “core” transverse velocity from $Y/R = -0.16$ (-5 mm) to 0.16 (5 mm) in the lateral direction and $X/R = 0.79$ (25 mm) to 2.36 (75 mm) in the longitudinal direction for every image pair acquired in the baseline dataset focused on the RR, (right) conditionally averaged PIV vector field for symmetric RRs only (average “core” transverse velocity from $V/V_{inf} = -0.045$ [-25 m/s] to +0.045 [+25 m/s]).

Figure 48. Conditionally averaged PIV vector field for (left) “downward” (ensemble average of “core” transverse velocity from $V/V_{inf} = -0.135$ [-75 m/s] to -0.045 [-25 m/s]) and (right) “upward” (ensemble average of average “core” transverse velocity from $V/V_{inf} = 0.045$ [25 m/s] to 0.135 [75 m/s]) transverse crossflow in the RR.
The turbulence intensity magnitude $|I|$ for both the downward and upward modes is shown in Figure 49. By comparison with the same figure for the total ensemble (bottom image of Figure 45), it is apparent that the turbulence field is significantly altered based on the RR mode. The peak turbulence intensity is increased in the shear layer that provides the crossflow on average, but is diminished in the other, by about 15-25%. The shear layer that provides the crossflow also has an enlarged area of elevated shear layer turbulence intensity relative to the turbulence intensity for the full ensemble. The extent of the high turbulence region of the other shear layer is diminished.

The crossflow process appears to be a significant contributor and driving factor behind the high turbulence intensity in this region. The turbulence intensity of the full ensemble of velocity fields again appears to be an average of the turbulence intensity of the two significantly different modes. By observing many instantaneous realizations (e.g., see Figure 41), it appears that on average the shear layer that provides the transverse flow spreads out more rapidly into the RR than the other, changing direction back towards the base as it expands. The crossflow displaces the opposite shear layer slightly, restricting its growth and making the shear layer radial velocity gradient steeper than average (compare shear layer thicknesses in Figure 41). The diminished shear layer thickness is likely caused by the constraint of the impinging crossflow and supersonic stream. The shear layer that the crossflow is directed towards also generally appears to have more variations in shear layer thickness and contains more large-scale structures (also see Figure 41), possibly indicating increased instability. The location of the shear layer that the crossflow is directed towards also is more variable spatially than the one that provides the crossflow. When comparing the mean flow field of the two modes in Figure 48, only a small difference in shear layer thickness and vertical location at the downstream edge of the shear layer is observable, but it is believed that the instantaneous differences in thickness are concealed by the spatial variations. In other words, in an average sense, the thicker but more-steady shear layer appears similar to the thinner but more spatially-varying shear layer.

Furthermore, the increased correlation between the streamwise and radial velocity fluctuations in the shear layer just upstream of reattachment, as noted by the peak Reynolds shear stress there, appear to be partially due to the oscillation of the instantaneous flow field between cross-flow modes. The asymmetric bimodal behavior of the RR constitutes a unique attribute of the axisymmetric (and possibly two stream 2-D) configuration as compared to the single-stream rearward-facing step base flow configuration. For the backward-facing step configuration, a crossbody flow, in the sense reported here, would be prevented by the wall/solid boundary. This unique feature of separated flows past axisymmetric blunt trailing edges may then be a contributing factor to, or even the cause of, the peak turbulent kinetic energy and Reynolds shear stress being located upstream of the rear stagnation point. Since these instantaneous asymmetric flow patterns are not possible for the rearward-facing step configuration, their substantial contributions to the turbulent kinetic energy and Reynolds shear stresses in these regions would be eliminated for this flow geometry.

Moreover, if the oscillating RR asymmetry is a contributing factor to the peak turbulent kinetic energy and Reynolds shear stress being located upstream of the rear stagnation point for this geometry, then it also seems plausible that slight experimental variations in alignment may cause the turbulence quantities to be asymmetric as
well. A small preference for one RR mode or another, over the apparently unstable symmetric RR, could cause the observed variations in the sensitive turbulence statistics.

Figure 49. Conditionally-averaged field of the magnitude of the two component turbulence intensities for (left) downward (ensemble average of “core” transverse velocity from \( V/V_{inf} = -0.135 \) [-75 m/s] to \(-0.045 \) [-25 m/s]) and (right) upward (ensemble average of average “core” transverse velocity from \( V/V_{inf} = 0.135 \) [75 m/s] to \( 0.045 \) [25 m/s]) transverse flow in the RR.

In general, it appears that within the RR the instantaneous flow field actually does not have characteristics substantially like the average flow field. The mean field appears symmetric because it is, for the most part, an average of two similar, but opposite, asymmetric flow patterns whose transverse velocity cancels out along the centerline. The instantaneous RR flow flaps back and forth in the plane of investigation with some unknown frequency (investigated further with base pressure measurements discussed below). However, the flow pattern is likely oscillating azimuthally, and these planar investigations are the 2-D manifestation of some 3-D oscillations. This is similar to behavior noticed by Simon et al.\(^{65}\) in a numerical simulation designed to match the University of Illinois facility conditions. The authors noted that the whole reverse flow slowly undulated at \( St_D = 0.13 \) around the axis of symmetry.

The numerically and experimentally observed phenomena may be related, but it is not clear how the numerically-observed undulation would create the experimentally-observed bimodal transverse velocity behavior with such a reduced number of “symmetric” realizations. More specifically, it is not currently clear what the RR flow field looks like perpendicular to the plane containing the peak crossflow. One might suppose that normal to the plane with the peak crossflow, the “core” transverse velocities might be symmetric on average. However, this would likely add a significant number of “symmetric” realizations to the PIV instantaneous realization ensemble that would make the shape of the histogram in Figure 46 look more Gaussian. In this case, the appearance of a bimodal behavior might be reduced. Experimentally, however, it is quite convincingly bimodal with few realizations near
the mean. Further investigations, possibly with high-speed or stereoscopic PIV, may further illuminate the true nature of the RR’s bimodal planar behavior, help determine its frequency of oscillation, and answer whether or not it is tied to the numerical observations by Simon et al.

4.4 Preliminary Actuator Configuration Study

Base pressure measurements, schlieren imaging, and PIV were used to evaluate the different plasma actuator geometries for their respective influence on the base flow. Prior to these investigations, long exposure digital SLR photographs of the plasma actuators operating with flow-off and flow-on were acquired. Two of the acquired images are shown in Figure 50. Only the inclined cavity (top) and afterbody normal cavity (bottom) actuator geometries were active during the image acquisition. In the images, the brass afterbody and aluminum base plate and nozzle are visible primarily from reflections from the light emitted from the downward-facing afterbody normal cavity actuator. Without flow, the illuminations are generally restricted to very near the BN, but with the flow active, the high-energy plasma is drawn down the shear layer as seen by the two converging light emission streaks. Two reflections are seen in the distance off the surface of the rear window. The light streaks suggest that the ionized plasma is being convected downstream and into the shear layer. It is likely that exothermic processes, such as molecular/atomic transitions and recombination of molecules and electrons, in the shear layer are emitting the light. The inclined cavity illumination seen at the top of the base emanates more directly from the rearward portion of the base, but the afterbody normal cavity illumination appears to originate more from the underside of the base plate, as would be expected for the two different geometries.

Figure 50. Long-exposure (~10 s) digital photograph of the inclined cavity (at top) and afterbody normal cavity (at bottom) actuators operating (left) without and (right) with a supersonic flow.

4.4.1 Base Pressure Measurements

Despite the fact that each actuator geometry was different in the preliminary electrode configuration study, base pressure measurements were still acquired to investigate the magnitude and likelihood of a substantial base
pressure change induced by the arc regardless of geometry. The changes in base pressure due to actuation of the four different actuators over the range of attainable frequencies and modes (axisymmetric, helical, flapping, and double flapping) were always less than 1% and generally, less than 0.5%. The trends were not consistently positive or negative.

It was reasonably well-known a priori that additional actuator locations would need to be added as four actuators are at most only able to stimulate mode $m = 2$. Expanding the actuators to eight would stimulate the higher mode $k = 4$ that was shown to be significant in a recent computational base flow stability analysis and would also better approximate the basic axisymmetric mode of excitation, $m = 0$. In comparison to previous LAFPA studies, Kim et. al noticed substantial influence when forcing eight actuators inward on a 2.54 cm ($1''$) diameter jet at the jet column (preferred mode) instability frequency $St_D \sim 0.3$. The base flow model in these experiments is 2.5 times larger in diameter and 6.25 times larger in area. In addition, the base flow actuators force radially outward rather than being centrally-directed due to the differences in flow geometry. In general, the number of actuators is more limited in the current experiments due to the internal sting mounting requirements of the base flow apparatus relative to the external mounting configuration of the jet.

The noticed changes were small enough that additional base pressure measurements were deferred until eight actuators of a single actuator geometry were installed. Efforts instead were focused on evaluating the five geometries individually through schlieren and PIV rather than attempting to evaluate and understand the complex interplay and full-field influences from a mixture of actuator geometries on the base pressure.

4.4.2 Schlieren Imaging

The schlieren imaging underwent several acquisition and processing iterations before the images were of high enough quality to be of value for comparison. Originally, the phase-locked images were acquired and processed using the formula:

$$I_{processed} = \frac{I_{control} - I_{background}}{I_{flat-field} - I_{background}}$$

(10)

where $I$ is the intensity of the respective set of ensemble-averaged data. A change in choice of flat-field is what improved the clarity of the resulting influence. The initial choice was to use a flat-field correction with both the tunnel and plasma off. However, problems were encountered where spots formed on the windows whether the flat-field was taken before or after the control set of images. While spots would form during the entire run, they formed most rapidly during start-up or shut-down transients. Additionally, the influences did not appear well pronounced, most likely because of line-of-sight spatial averaging through the nominally axisymmetric facility and base flow shear layers and because the influences were being tracked through a shear layer with large density gradients already. Therefore, the decision was made to acquire the flat-field image sets during the same run so that the imperfections would be better matched and so that the processed image would reflect the changes relative to the no-control case.

A plasma-on case that was forced axisymmetrically (synchronously) at 2700 Hz, 1 A, and 20 $\mu$s on-time with a 60 $\mu$s phase delay between plasma actuation and image acquisition was used as the baseline case for
comparisons between different settings. An example 100-image ensemble-averaged plasma-on and plasma-off comparison of the supersonic base flow is shown in Figure 51. The inclined cavity and normal cavity actuator geometries are at the top and bottom of the images, respectively. The other two plasma locations are disabled in this experiment. Flow is from right to left. The black rectangular shape on the right is the base. The visual boundary layer thickness can be seen just before the flow separates over the base. Prandtl-Meyer expansion waves emanate from the corner of the base. Weak Mach waves also emanate from the outer edge of the nozzle and the base plate / afterbody interface just upstream of separation, likely owing to slight imperfections in pressure-match conditions and surface continuity, respectively. The flow direction and shear layer are bent towards each other downstream of the base due to the expansion fan. As the wake reattaches, recompression shocks are seen that reorient the supersonic stream with the freestream direction. The edges of the supersonic stream in the open-jet test section and the nozzle-cell shear layers are seen at the very top and bottom edges of the image. The horizontal nature of the outer shear layers confirms that the supersonic flow and cell pressures are well matched, unlike the base flow shear layer under examination. The streak that appears to pass down the center of the RR actually stems from edges of the chamfered actuator geometry on the far edge of the axisymmetric base and represents one example of the line-of-sight path integration that can confound the schlieren image data comparison. The dark speckling in the bottom right-hand corner exemplifies the dark marks that build-up on the windows and create anomalous disturbances in the processed images. The rounded edges of the images are due to the rounded mirrors while the flat top, bottom, and side surfaces are due to the edges of the fused silica windows/open-jet test section.

Figure 51. (left) Plasma-on and (right) plasma-off ensemble-averaged schlieren image of the base flow when forced at 2700 Hz, 1 A, and 20 μs on-time with a 60 μs phase delay from actuation. The inclined cavity and normal cavity geometries are at the top and bottom of the images, respectively. The arrows represent the location of disturbances.

A very slight dark/light spot at the top/bottom of the plasma-on image (see arrows) is the only consistently discernible difference between the plasma-on/plasma-off images. Both marks are located near where the expansion...
fan visually separates from the shear layer and are generally hard to see given their location. The disturbance can be tracked in time, though, and is appropriately located given the phase delay between plasma actuation and image acquisition. However, in order to highlight differences between plasma-on and plasma-off, an ensemble-averaged image acquired without control (right image in Figure 51) was used as the flat-field in the image processing equation above. The result is shown in the top-left image in Figure 52. While there is obvious, random variation within the flow, the light and dark spots in the images become more recognizable (see arrows), especially for the bottom disturbance. This processing technique also highlights the spatial variation of the wave from the nozzle lip. It is believed that this does not imply that the tunnel is not well matched, but just that the wave changes location slightly on average. This stresses the sensitivity of the processing technique to minute differences between images. Also, shown in the top-right corner in Figure 52 is one of the instantaneous images (with plasma-on) that went into the ensemble-average. While the significant level of variation and turbulent density gradients in the flow is obvious and detracts from making meaningful comparisons of instantaneous images, light and dark regions, highlighted by arrows, can be seen in the anticipated locations of the disturbances known a posteriori from the fully processed images. While the other variations are random and average out for the most part, the light/dark pair from the arcs only amplifies in intensity owing to their phase-locked nature. The bottom-left image of Figure 52 shows the development of the disturbances 100 μs post-discharge (see arrows). On average, the disturbance becomes more diffuse downstream as it lightens in intensity and either grows larger or is spatially more variable. It also seems that the disturbance is wave-like in nature as it is not merely traveling along the local streamline, but propagating out into and across the supersonic stream. For comparison’s sake, Figure 52 also displays the results of the processing technique when performed on two no-control image sets. Two independent sets of 100 images were acquired, both without plasma actuation, during the same run and then processed using the equation above to produce the bottom-right image of Figure 52. No obvious disturbances are discerned. Overall, the schlieren imagery suggests that the actuators are causing a density gradient in the flow field, possibly through wave production, shear layer stimulation, or heat addition.

Figure 53 presents schlieren images for a parametric change in current and frequency while holding all other parameters constant with the baseline case (2700 Hz, 1 A, 20 μs on-time, 60 μs phase delay). The left image is for a ¼ A discharge, while the right image is for a 25 kHz repetition rate. Originally, all of the schlieren data were obtained at the same ¼ A as most past LAFPA actuation experiments have been. However, experimentation with a 1 A discharge with one channel showed that stronger influences could be realized with the higher current actuation. Each HV PS has a rated output of 1 A, and as each HV PS was designed to run four actuators, the ballast resistors were sized to produce ¼ A arcs. By placing the actuators in parallel, the ballast resistance was effectively reduced to ¼ of its original value, thereby, producing the 1 A discharge. This strategy was only able to force one actuator at the higher current, because it used all of the ballast resistors. Furthermore, it was believed that the HV PS would not be able to drive more than one 1 A actuator. Further inquiry with the PS manufacturer clarified that temporarily the HV PS could provide higher current output because of HV capacitors that were installed by the manufacturer. If four 1 A actuators were drawing a total of 4 A from the HV PS at a 10% duty cycle, the time-averaged current draw from the HV capacitors is still only 0.4 A. Therefore, additional replacement ballast resistors were purchased to
convert all four of the plasma actuators per cart to 1 A discharges in hopes of realizing an improved fluidic response. The image on the top-left of Figure 52, as compared to the left image of Figure 53, highlights the apparent improvements realized over the lower current discharge. In general, the ¼ A discharges exhibited a weaker effect over the entire test matrix. Therefore, the text matrix was modified to primarily investigate 1 A discharge effects.

Figure 52. (top-left) Processed and (top-right) instantaneous plasma-on schlieren image of the base flow when forced at 2700 Hz, 1 A, and 20 μs on-time with a 60 μs phase delay from actuation (baseline). The inclined cavity and normal cavity geometries are at the top and bottom of the images, respectively. (bottom-left) processed image acquired with a 100 μs phase delay (same plasma settings) and (bottom-right) processed image between two no-control sets for comparison’s sake.
Figure 53. (left) 2700 Hz, \(\frac{1}{4}\) A, and 20 \(\mu\)s on-time and (right) 25000 Hz, 1 A, and 4 \(\mu\)s on-time (10\% duty cycle) ensemble-averaged and processed schlieren images of the base flow for a 60 \(\mu\)s phase delay from actuation. The inclined cavity and normal cavity geometries are at the top and bottom of the images, respectively. The arrows represent the location of disturbances.

The schlieren image for the higher frequency discharge presented in Figure 53 shows the sequential disturbances that are separated by roughly 40 \(\mu\)s per pulse (25 kHz). The short time delay between pulses can provide an estimate of the convective speed of the disturbances in the flow field and of how the disturbance develops at various time delays (60 \(\mu\)s, 100 \(\mu\)s, 140 \(\mu\)s, etc.). The roughly estimated convective speed is 325 m/s ± 50 m/s, but can be better estimated by the PIV experiments discussed below. The disturbances appear generally less intense than at the lower frequencies. This trend is shown throughout the range of frequencies investigated, and likely is due to the shorter on-time and/or reduced breakdown voltage that is caused by residual ionization or elevated electrode temperature. However, the increased number of pulses per unit time is likely a benefit to the flow actuation technique. It does seem that an optimum balance between disturbance strength and frequency likely exists at some mid-range frequency. Additional experimentation suggests this frequency range to be between 12.5-25 kHz as will be discussed in the base pressure section below.

Several modes of actuation were explored, but similar to the four-actuator base pressure data, no consistent changes in the overall flow field were noticed. The presence and location of the disturbances shifted depending on the channel phase relationships, but no repeatable macroscopic flow field influences were noted.

All presented images are for a horizontal knife-edge configuration, which illuminates the vertical density gradients in the shear layer. A rotated vertical knife-edge configuration was investigated also. While the vertical knife-edge flow field data were interesting and unique in and of themselves, the processed schlieren images either showed no consistent disturbances whatsoever or significantly diminished disturbances. Therefore, future experimentation followed past researchers and used a horizontal knife-edge configuration only in order to help make the dominant flow features more pronounced.
One additional option that was explored was the potential for control through always-on actuation at ¼ A. Obviously, no phase-locked disturbance would be expected. Furthermore, though, no significant modification was noted for any of the global flow features either. Previous characterization of the actuators suggests that the initial breakdown is fundamental to the overall control technique. Additional always-on actuation experimentation was not pursued since it would negate the influence produced through voltage breakdown and since, with multiple actuators, it would potentially overdrive the HV PS and ballast resistors.

A primary objective of the preliminary actuator configuration study was the comparison of the different proposed actuator geometries. Therefore, the base was rotated 90-degrees so that the flush and chamfered geometries could be evaluated simultaneously. The top-left image of Figure 54 shows a typical processed schlieren image evaluating the surface geometries for 2 kHz, ¼ A, 20 μs on-time plasma conditions with a 60 μs phase delay. The slightly lower than baseline frequency should not make a significant difference in the disturbance since the phase-delay was held constant and since the lower frequency only makes the actuation stronger. The flush and chamfered geometries were on the top and bottom, respectively. No significant disturbances could be tracked, unlike the cavity configurations. This could be caused by the fact that the heated plasma was not directed into the supersonic flow and instead stayed contained within the low-speed, subsonic RR. It could also be due to the fact that the gas was not ported into a consistent location of the flow for each discharge. In that case, the surface discharge actuators’ effect, while possibly significant, did not occur at the same spatial location and was averaged-out in the ensemble-average. Whatever the reason, since a consistent influence was not produced/traceable, additional experimentation with the surface actuator geometries was not pursued. The surface geometries were already eliminated from consideration before the 1 A experiments were performed and so 1 A data were not acquired for those two geometries. The lower current may have affected the strength of the actuation, but the surface geometries did not produce any noticeable and traceable influence unlike the cavity configurations did even for the ¼ A configuration. The higher current merely made the disturbance more intense and more easily discernible.

The other three images in Figure 54 compare the fifth actuator geometry, the afterbody normal cavity orientation, to the inclined cavity geometry for three different cases. The top-right and bottom-left images are both for 2700 Hz, 1 A, and 20 μs on-time actuation with a 20 μs and 60 μs phase delay, respectively. The bottom-right image is for 25 kHz, 1 A, and 4 μs on-time actuation with a 10 μs phase delay. With the actuation repeating every 40 μs, the phase delay in the 25 kHz image, can also represent a phase delay of 50 μs, 90 μs, etc. While the actuation into the supersonic stream upstream of the base separation appears more rapidly and is apparently more intense than the inclined cavity discharge, it dissipates and disappears quicker also, likely owing to the dilatation of the centered expansion. A slight modification of the leading edge of the expansion fan is apparent, but no part of the disturbance is seen to propagate through the expansion. The earlier delay times show a slight bow to the disturbance reminiscent of the bow shock formed in front of a jet in a supersonic crossflow. It is theorized that the reason that the inclined cavity disturbance is not apparent at this earlier delay time is due to the intense background gradients of discharging directly into the shear layer and centered expansion. When comparing the effects of the inclined cavity geometry to the afterbody normal cavity geometry at 25 kHz, the time history or string/chain of disturbances is
much more readily discernible for the inclined cavity. Again, this may implicate the expansion fan for diffusing/dilating the influence more rapidly. From the schlieren imaging results, the two surface geometries were eliminated from consideration for possible expansion into the eight-actuator base plate. The influences of the remaining three cavity designs were considered further through the use of PIV.

Figure 54. (top-left) Plasma-on schlieren image of the base flow when forced with surface discharges at 2 kHz, ½ A, and 20 μs on-time with a 60 μs phase delay from actuation; the flush and chamfered geometries are at the top and bottom of the image, respectively. The other three images are forced using the afterbody normal cavity (at bottom) and inclined cavity (at top) geometries for (top-right) 2700 Hz, 1 A, 20 μs on-time with a 20 μs phase delay, (bottom-left) same as previous with a 60 μs phase delay, and (bottom-right) 25 kHz, 1 A, 4 μs on-time with 10/50/90 μs effective phase delays (due to the short period). The arrows represent the location of disturbances.
### 4.4.3 Particle Image Velocimetry

PIV was used to evaluate the influences of three different actuator designs on the shear layer of the supersonic base flow. All three geometries incorporated a cavity into the design. Each cavity was oriented in a different direction relative to the freestream. The “normal cavity” design was positioned on the base surface near the base edge and was directed parallel to the freestream. The “inclined cavity” design was positioned at the same location, but the cavity was inclined 32° degrees relative to the freestream in the axial-radial plane. The last design evaluated, the “afterbody normal cavity,” was located on the afterbody just upstream of separation (~2-3 mm) and incorporated a radially-discharging cavity (normal to the freestream).

Ensemble averages were formed from the processed velocity fields of 170 phase-locked image pairs per test case. For each actuator design, data sets for several frequencies were acquired for one constant delay time and then several data sets were acquired for various delay times but only one frequency. The selected test matrix used to evaluate each actuator geometry is summarized in Table 8. A no-control data set was acquired each day for comparison to the control-on cases. The frequencies investigated were 850 Hz, 2.7 kHz, 7.5 kHz, 25 kHz, and 40 kHz at a delay time of 50 μs from the initiation of the arc. Then, for 2.7 kHz, the delay time was varied to values of 10 μs, 30 μs, 70 μs, and 90 μs, which formed a set of five different delay times including the already acquired 50 μs delay data set. The current was maintained at 1 A for all test cases based on the observations from the schlieren imaging. The typical on-times for a given frequency used in these experiments are listed in Table 5. The on-time of each discharge was restricted to a maximum duty cycle of 10% due to the risk of overheating the ballast resistors at the higher 1 A current setting. For the lower frequencies, a constant on-time of 20 μs was used for simplicity as this provided an adequate on-time to ensure complete breakdown and formation of the plasma. The minimum duty cycle tested was 1.7% at 850 Hz. From the quiescent investigations, a longer on-time was not deemed highly valuable based on the diminishing return on investment observed for increasing on-times.

<table>
<thead>
<tr>
<th>Ctrl. Freq. [Hz]</th>
<th>On-time [μs]</th>
<th>Duty cycle [%]</th>
<th>Delay time [μs]</th>
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</thead>
<tbody>
<tr>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td>50</td>
</tr>
<tr>
<td>2,700</td>
<td>20</td>
<td>5.4</td>
<td>10</td>
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<tr>
<td>2,700</td>
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<td>5.4</td>
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<td>2,700</td>
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<td>90</td>
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<tr>
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<td>7.5</td>
<td>50</td>
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<tr>
<td>25,000</td>
<td>4</td>
<td>10</td>
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</tr>
<tr>
<td>40,000</td>
<td>2.5</td>
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</table>

From the experiments, a noticeable influence was produced by both the “normal cavity” and “inclined cavity” actuator geometries. Conversely, no substantial and consistently traceable influence on the shear layer or
RR was produced by the “afterbody normal cavity” geometry for any of the frequencies or delay times probed. As discussed in the previous section, the lack of a sizeable influence for this actuator geometry is possibly due to the effect of dilatation from the centered expansion immediately downstream of the discharge.

Example PIV speed contour plots with and without control are shown in Figure 55 comparing the RR flow field for a single “inclined cavity” actuator. Flow is moving from left to right. The control-on image has a single “inclined cavity” actuator operating at 25 kHz, 1 A, and 4 μs on-time [10% duty cycle]. The discharge is occurring at the top edge of the base. The vector field is a phase-locked, ensemble-average of 170 instantaneous realizations acquired with a 2 μs laser separation and an average phase delay of 50 μs.

![Figure 55. PIV speed contour plot for the near-base RR of an axisymmetric supersonic base flow for (left) no-control and (right) control using an inclined-cavity forced at 25 kHz, 1 A, and 4 μs on-time [10% duty cycle] with 50 μs phase delay.]

For the no-control case, the contour levels of velocity magnitude through the shear layer are very linear and expand slightly as the shear layer grows downstream. The RR is also noted to be symmetric about the center of the base. However, with the plasma actuator active, a ripple can be seen in the top shear layer due to the actuation. The peak rearward recirculation velocities have shifted towards the opposite shear layer and no longer form a symmetric RR behind the base. The magnitude of the velocity changes in the top shear layer is small in comparison to the high-speed supersonic flow, though.

Therefore, Figure 56 also compares the transverse velocity component for the same data sets, since this component should be more sensitive to the effects of the actuators. The contour levels are set so that they focus on changes in the top shear layer. Comparing the two plots yields three obvious differences. First, the shear layer disturbances, forced with a period of 40 μs, are noticeably more apparent since the contour scale spans only a ¼ of the magnitude of the freestream velocity. The actuator influences appear to counteract the inward velocity component of the supersonic stream, as might be expected. The contours of the velocity component acting to
contract the supersonic stream are displaced due to each discharge. The disruption of the supersonic stream generates the second feature, which is manifested as evident waves propagating through the supersonic outer flow similar to that noticed in the schlieren imagery. Third, a negative (or downward) velocity is induced in the RR on average by the shear layer forcing, likely due to the forcing of an instability mechanism in the shear layer. The asymmetric RR looks similar to the “downward” mode discussed in the bimodal PIV section for the unforced axisymmetric base flow. However, the ensemble-average of 170 instantaneous vector fields shown in Figure 55 and Figure 56 has not been conditionally filtered. The ensemble contains both “upward” and “downward” crossflow realizations, but contains more “downward” realizations and the “downward” realizations generally have a higher crossflow velocity magnitude. It appears that on average a single actuator can trip the shear layer such that there is reduced preference towards a bimodal behavior. Instead, one of the crossflow modes is dominant with the crossflow being provided by the stimulated shear layer.

Figure 56. PIV transverse velocity component contour plot for the near-base RR of an axisymmetric supersonic base flow for (left) no-control and (right) control using an inclined-cavity forced at 25 kHz, 1 A, and 4 μs on-time [10% duty cycle] with 50 μs phase delay.

Analysis of the full spectrum of test cases yielded several general realizations about the effect of the actuator on the base flow and, more specifically, on the shear layer. The disturbance was able to be tracked in space as it progressed downstream. For lower frequencies, only a single disturbance could be observed in the shear layer at a given instant in time. However, as seen in Figure 56, at frequencies above about 10 kHz, multiple disturbances can be tracked in a single PIV realization. Tracking of the average disturbance’s progression in time, or the distance between successive disturbances, can provide estimates of the convective velocity of the disturbance in the shear layer. More will be added on this topic in the eight-actuator PIV discussion. Additionally, pulsing of the electric arc actuator at higher frequencies yielded smaller disturbances spatially and less modulation of the shear layer, which is consistent with the observed actuator performance drop-off at higher frequencies noticed in quiescent air. Besides
the reduced momentum output per pulse at higher frequencies, the smaller spatial extent of the disturbance is also likely due to the reduced on-time, as a constant duty cycle (10%) was maintained for higher frequencies.

Direct comparison of the performance of the two actuator geometries using the test matrix outlined in Table 8 showed many commonalities. Several side-by-side comparisons of the ensemble-averaged transverse velocity fields are made in Figure 57 and Figure 58 for different frequency and phase delay combinations. The sensitive transverse velocity field is again presented to better highlight the changes to the shear layer and recirculation region. The images on the left in the two figures use inclined-cavity actuation, while the right images are for normal-cavity actuation. The top and bottom images in Figure 57 are for 7.5 and 25 kHz actuation, respectively, at a 50 μs phase delay. The top and bottom images in Figure 58 are for 50 and 90 μs phase delays, respectively, at a forcing frequency of 2.7 kHz.

Figure 57. PIV transverse velocity contours for the near-base RR with control using a 50 μs phase delay and (top-left) inclined-cavity forced at 7.5 kHz, (top-right) normal-cavity forced at 7.5 kHz, (bottom-left) inclined-cavity forced at 25 kHz, and (bottom-right) normal-cavity forced at 25 kHz.
It should be noted that the 25 kHz, inclined-cavity disturbance field in Figure 55 and Figure 56 is a separate acquisition (unique data set) from that shown in Figure 57. The magnitude of the disturbances in the shear layer for Figure 57 is not as large as for the other case discussed earlier. With further investigation, it was determined that there is a noticeable variability in the size of the shear layer disturbance and the extent of RR asymmetry for separate runs at the same actuator settings. The case shown in Figure 55 and Figure 56 was selected to better highlight the changes due to the actuators. Both the current and voltage traces are obtained for every PIV acquisition to ensure that the discharge occurred consistently, at the expected phase delay, and with the anticipated voltage and current behavior. Therefore, actuator reliability or timing inconsistencies are ruled out as a possible cause of the variation. It is not currently known why the variability is present in the averaged fields. The different set of data in Figure 57 is used for two reasons. First, the data sets used for comparison in Figure 57 were all acquired on the same day and so are believed to be the best cases to display for comparison. Additionally, display of the two different sets highlights the variability in the PIV results even for ensemble-averages with 170 instantaneous velocity field realizations.

From Figure 57 and Figure 58, it is apparent that disturbances of similar magnitude (top-left corner of each image) are forced in the shear layer and supersonic flow with both actuator types. The progression of a disturbance in time along the shear layer can be seen in particular by comparing the top and bottom images of Figure 58 (top-left corner). Both actuators could also force the RR to be asymmetric (“downward” RR mode, as discussed previously, as the actuators were both located at the top of the base).

However, small differences in the performance of the two actuators were observed. The normal-cavity design forced the RR asymmetry less strongly. Perhaps most importantly, the normal-cavity actuator generally caused a slightly weaker shear layer disturbance than the inclined-cavity design at higher frequencies (compare top-left part of each image in Figure 57). Occasionally, the opposite was true at lower frequencies (compare top-left part of the top two images in Figure 58). However, performance degradation for the normal-cavity design appeared to occur at a lower frequency as seen from the 25 kHz data sets (bottom of Figure 57). This was a particularly significant finding as the higher frequencies were deemed an important component of the test matrix. It was not clear that the lower frequencies, like in Figure 58, would cause disturbances often enough to effectively modify the time-averaged flow field. For example, at an 850 Hz pulse rate ($St_0 = 0.09$), the freestream flow travels more than 10 base diameters between successive discharges. Therefore, frequencies that are an order of magnitude, or more, larger could reasonably be expected to be required for optimal effectiveness. An actuator geometry that has reduced effectiveness at these frequencies would be a serious detriment to its potential as a useful flow control device.

The effect of the actuation on the turbulence statistics was also evaluated. The changes in turbulence statistics were consistent with the amount of asymmetry noticed in the RR for each test case. As mentioned in the discussion of Figure 49, the turbulence statistics for each of the two RR modes was substantially different from the mean flow. Therefore, if the actuator forcing caused one of the RR modes to dominate, the turbulence statistics would more closely resemble the turbulence intensity distribution of that particular mode. No further changes due solely to the actuation could be determined within the uncertainty and normal variability of the measurements.

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Figure 58. PIV transverse velocity contours for the near-base RR with control forced at 2.7 kHz using (top-left) inclined-cavity and 50 μs phase delay, (top-right) normal-cavity and 50 μs phase delay, (bottom-left) inclined-cavity and 90 μs phase delay, and (bottom-right) normal-cavity and 90 μs phase delay.

As the normal-cavity design was oriented directly downstream, it did not force the shear layer as close to the sensitive separation point as the inclined-cavity design did. The normal-cavity design also had added manufacturing, installation, and operating concerns as a result of the thin flat wall between the cavity and the base edge. Several cracks and blow-outs of the ground electrode had occurred in the past, and the normal-cavity design was particularly susceptible to such failures. Therefore, the inclined-cavity design was selected, instead of the normal-cavity design, for use in the eight-actuator base assembly in order to explore the actuators’ potential for flow control at different forcing frequencies and modes. The normal-cavity and inclined-cavity designs only exhibited
minor differences in forcing. Experimentation with either design would have likely yielded fairly similar results. Given the similarities, the structural considerations illuminated during the actuator geometry study were a significant factor in the selection of the inclined-cavity actuator design.

4.5 Eight-Actuator Flow Control Investigations

The final flow control experiments were performed with eight actuators all of a similar inclined-cavity design. The influences of the actuators on the supersonic axisymmetric base flow were evaluated with base pressure measurements and PIV. The actuators were operated at different frequencies, on-times/duty-cycles, phase delays, and currents. The frequencies outlined in Table 5 were used as a guide for the investigations, but the frequencies probed were modified slightly based on the observations of the earlier experiments. The lowest frequency (450 Hz) was eliminated due to the length of time between pulses. The higher frequencies (greater than 40 kHz) were only able to be probed in “burst” mode due to limitations of the switches. In this mode, several hundred pulses were strung together in a pulse train, and the PIV image pairs were acquired just before the end of the pulse train (a few pulses prior). This methodology was used to allow modification of the base flow for several flow-through times before images were acquired. Base pressure measurements for these cases are confounded by the cyclical nature of the actuation and so are not included in the discussion of the cases for which the plasma actuators were continually active (non-burst mode). Additional frequencies were added in the most sensitive region of the frequency band (5-30 kHz) as determined from the preliminary actuator geometry studies. The additional frequencies are 5 kHz, 12.5 kHz, 15 kHz, and 30 kHz, and were added to evaluate the sensitivity of the base pressure to fine tuning of the forcing frequency. The test matrix used to evaluate each forcing mode is presented in Table 9.

Table 9. Frequency, on-time, and duty cycle test array for the final flow control investigations; evaluated for each forcing mode; the discharge current was 1 A and the delay time was 50 μs unless otherwise specified.

<table>
<thead>
<tr>
<th>Ctrl. Freq. [Hz]</th>
<th>On-time [μs]</th>
<th>Duty cycle [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Control</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>850</td>
<td>20</td>
<td>1.7</td>
</tr>
<tr>
<td>2,700</td>
<td>20</td>
<td>5.4</td>
</tr>
<tr>
<td>5,000</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>7,500</td>
<td>10</td>
<td>7.5</td>
</tr>
<tr>
<td>12,500</td>
<td>7</td>
<td>8.8</td>
</tr>
<tr>
<td>15,000</td>
<td>7</td>
<td>10.5</td>
</tr>
<tr>
<td>20,000</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>25,000</td>
<td>5</td>
<td>12.5</td>
</tr>
<tr>
<td>30,000</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>40,000</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>67,000</td>
<td>1.5</td>
<td>10.5</td>
</tr>
<tr>
<td>100,000</td>
<td>1.5</td>
<td>15</td>
</tr>
</tbody>
</table>

Forcing of the axisymmetric mode was only approximate given the discrete locations and finite size of the eight actuators. Each arc was about 2 mm long and each actuator width (direction along the base edge) was 4 mm.
Therefore, the eight arcs cover only about 16 mm of the circumference, or the eight actuators cover about 32 mm of the circumference. This amounts to about 8%-16% of the entire 200 mm circumference. A typical axisymmetric disturbance would affect the entire circumference simultaneously. The forcing employed in these experiments is an approximation of the ideal case given the capabilities of the actuators and may be better designated as synchronous firing instead of suggesting a true axisymmetric forcing.

Also, due to the slightly arbitrary nature of the definition of frequency for the double helical mode, the frequencies examined for this mode were slightly altered relative to the standard test matrix. The discrepancy in frequency definition arises due to the two helical firing patterns that move synchronously around the base at 180° phase separation angle. The frequency can be defined based on either (1) the period of time between the two helixes crossing the same point (the time between successive firings of the same actuator) or (2) the time it takes for each of the helixes to make a full revolution. In the latter definition, each actuator would fire twice per period. The PIV data sets were originally acquired based on the second definition, but are reported here using the first definition for two reasons. First, the first definition maintains consistency with past LAFPA experiments. Secondly, it provided a more natural comparison with the other modes. The base pressure data seemed to scale with the first definition better. In other words, the base pressure changes occurred at a lower frequency than the other modes as a result of the two pulses that occurred per period. Therefore, the definition was altered. All frequencies reported herein are consistent with the first definition. Fortunately, several of the frequencies tested are separated by a factor of two (7.5 kHz/15 kHz and 12.5 kHz/25 kHz, for example), which implies that many of the same test frequencies were still examined even given the a posteriori alteration in frequency definition.

In comparison to the quiescent experiments, the pressure and density are significantly lower on the surface of the base with supersonic flow than for the ambient quiescent conditions used to characterize the actuators. As a result, the plasma actuator breakdown occurs at a lower voltage because of the lower pressure, and the synthetic jet production may be less intense because of the lower amount of mass contained within the cavity prior to initiation. The induced velocity for the quiescent experiments at ambient conditions was already small relative to the freestream velocity of the base flow. The peak velocity over the range of frequencies and currents tested occurred for a few microseconds just after breakdown and was measured to be 40 m/s, or just 7% of the freestream velocity of the base flow. Therefore, the peak velocity magnitude due to each discharge in the base flow may be less than 7% of the base flow freestream velocity. Additionally, a negative trend for peak velocity magnitude was noticed with frequency, but higher frequencies may be necessary to stimulate the flow frequently enough to cause time-averaged alterations to the flow. The higher frequencies will likely further reduce the momentum output per pulse. Therefore, to be effective, the LAFPA forcing is most efficient if coupled to natural instabilities in the flow.

Schlieren imaging was not acquired for the eight-actuator setup because of the limited value observed with its use in the preliminary actuator geometry investigations in comparison to PIV. The images were frequently clouded by imperfections that formed on the windows from the recirculation regions between the supersonic flow and the glass. The technique also provided limited additional information relative to PIV due to the small magnitude of the disturbance observed, the fact that the disturbances were frequently occluded by the strong gradients already
in the shear layer, the high level of turbulence and inherent fluidic variation, and the path, or volumetric, integration inherent with the schlieren technique.

Voltage and current measurements were always acquired for “channel 1” (located at the top of the base or at 12 o’clock, in the plane of the PIV light sheet) in order to verify the appropriate time/phase delay and voltage and current behavior for each PIV image pair. Additionally, either the current or voltage was always monitored for “channel 5.” Channel 5 was located at the bottom of the base (6 o’clock) and was also in the laser sheet. The remaining channels were numbered clockwise (facing the base) with 45° spacing between each actuator (e.g., channel 3 was at 3 o’clock). Cost restrictions limited the ability to monitor all of the high-voltage and current channels simultaneously. In order to do so, 16 oscilloscope channels, 8 voltage probes, and 8 current monitors would be required.

Channels 1-4 and 5-8 were each powered and controlled by a separate and independent plasma actuator system (a separate plasma “cart”). Therefore, in addition to the fact that they were positioned within the PIV laser sheet, channels 1 and 5 were selected for voltage and current monitoring since they were on separate plasma carts. Each cart had its own PCB and four-channel pulse generator to control the timing of each channel (see Figure 6). A schematic of the measurement timing and control sequence is presented in Figure 59. Black, single-headed arrows represent one-way coaxial BNC timing/voltage signals whereas the double-headed purple arrows represent two-way USB data transmission interfaces. A master pulse generator synchronized the laser and the two slave pulse generators used to regulate the eight HV switches that control the formation of the arcs. The initiation of the charging sequence (optical pumping) of one of the two flash lamps was used to trigger the camera to acquire an image pair at a delay synchronized to the q-switch triggers/laser pulses. The camera shutter was then used to trigger the PC oscilloscope (Picoscope) to retain the associated voltage and current trace from its internal memory buffer. Both the image pair and voltage and current traces were transferred to a PC for storage and analysis.

![Figure 59. Timing and control logic diagram used to synchronize the arc discharges to the acquisition of voltage, current, and PIV; black arrows represent one-way BNC timing signals, double-headed purple arrows represent two-way USB data transmission connections.](image-url)
Occasionally, like for the helical mode, the discharge of the other channels could be observed by the EMI induced in the voltage probe and current monitor. The electronics for each successive channel were located progressively further away from the monitored channels, and so the magnitude of the EMI would diminish as each successive channel was discharged showing that the channels were discharging in the right order and at the right time.

Lastly, the PIV seed fog would occasionally build up as a light film on the base and other internal wind tunnel surfaces. The surface contamination also made it into the actuator cavities. The mineral oil did not seem to have a significant effect on the voltage, current, or visual behavior of the actuators. Occasionally, sparks were seen traveling downstream in the flow. It is possible that the sparks are the result of the high temperature arcs igniting some of the locally accumulated mineral oil. The concentration of oil and the air pressure and temperature, especially very near the base, is low, though, which would generally prevent ignition. Problems with flammability of the mineral oil were not experienced. Furthermore, the dielectric strength of mineral oil is slightly higher than air. Therefore, the arc breakdown voltage would not be reduced by the presence of the mineral oil. A light surface coating might actually increase the breakdown voltage slightly. However, the presence of the oil in the cavities is considered to be non-ideal as it may alter the gas chemistry of the arc. Its presence is tolerated solely on account of the necessity of using the seed to evaluate the velocity field, but as mentioned before, significant alterations in performance were not observed either.

4.5.1 Base Pressure Measurements

As described in the experimental setup section, the base pressure \( (P_b) \) was measured at three distinct radial locations along a diameter that bisects channel 1 and channel 2 (22.5-degree offset). The pressure was measured with 0.40 mm (1/64") diameter circular taps at radial locations of \( r_1 = 9.53 \text{ mm (3/8")} \), \( r_2 = 17.46 \text{ mm (11/16")} \), and \( r_3 = 25.40 \text{ mm (1.0")} \). When non-dimensionalized by the base radius \( R \) of 31.75 mm (1.25"), the three tap locations become 0.30, 0.55, and 0.80. The taps were denoted as inner (or tap 1, corresponding to \( P_1 \)), middle (or tap 2, \( P_2 \)), and outer (or tap 3, \( P_3 \)).

The base pressure changes caused by the eight LAFPA actuators positioned azimuthally at the base edge of a 63.5 mm (2.5") diameter base were explored for the frequency and mode combinations discussed above. Figure 60 displays the percent change in area-weighted base pressure measured for different current, frequency, and forcing mode combinations. Each of the data points shown in the figure is the average of a number of independent (1-3) runs. The base pressure at each tap was acquired for about 30-40 seconds with flow and plasma actuators active. This translates into about 150-200 instantaneous base pressure data points per run. The average at each tap per run was calculated and then used to compute the area-weighted average base pressure \( P_{b,AW} \) using the formula:

\[
P_{b,AW} = \frac{(A_1 P_1 + A_2 P_2 + A_3 P_3)}{A_T}
\]

where \( A_T \) is the total area of the base (in either dimensional or non-dimensional form). \( A_1, A_2, \) and \( A_3 \) are the representative areas of each tap taken to be the area between two concentric circles.
\[ A_k = \pi (r_{i\text{max}}^2 - r_{i\text{min}}^2) \]  \hspace{1cm} (12)

where \( r_{i\text{max}} \) and \( r_{i\text{min}} \) are the maximum and minimum radii of the representative circles, for \( i = 1, 2, \) and 3. For example, for the inner tap, the maximum radius was taken as the average radius of the inner and middle tap, or:

\[ r_{i\text{max}} = \frac{r_1 + r_2}{2} \]  \hspace{1cm} (13)

and the minimum radius was taken as zero. The maximum radius of tap 3 was taken as 31.75 mm (1.25”), or unity in non-dimensional coordinates.

Figure 60. Percent change of area-weighted base pressure (using three base pressure taps) relative to the no-control case for different LAFPA current, frequency, and forcing mode combinations.

The uncertainty of the mean base pressure ratio due to the pressure scanner and the random sampling variation of the measurement was calculated to be about 0.0006 or 0.1%, which is approximately the size of the square markers used in Figure 60. The uncertainty contributed from the two sources considered was roughly equal. The uncertainty of the pressure scanner measurements was made larger by the fact that the manufacturer quotes the uncertainty as a percent of the full scale of the transducer, but the measured base pressure was only about 12% of full scale.
The baseline no-control base pressure was acquired each day before and after the acquisition of flow control runs as the no-control base pressure ratio was observed to fluctuate as much as a few percent from day-to-day. The repeatability of the mean base pressure ratio between runs on the same day for the no-control case was very high, though. Typically, the base pressure ratio (~0.55) would vary by less than 0.001 (less than 0.2%) and occasionally only by a few ten-thousandths (less than 0.1%). However, the base pressure repeatability for forced cases, especially at higher frequencies, was markedly decreased. The variation between runs with the same plasma actuator conditions could be on the order of a full percent or more. This observed variability in base pressure was the motivation behind averaging all runs with the same plasma conditions together in Figure 60. It is not clear currently why the underlying variability of the base pressure measurements increases with active plasma actuators, but the voltage and current were actively monitored during the base pressure acquisition to ensure similar and repeatable actuator characteristics between runs. It is possible that either the actuator has some inherent variability run-to-run or that the actuator can interact with the fluid differently for successive runs. It is also possible, but considered unlikely, that EMI could cause some of the run-to-run variation in base pressure.

Despite the variability, some consistent trends are obvious in Figure 60. First, the plasma actuators clearly decrease the base pressure with increasing frequency up to about 20 kHz, at which point the base pressure seems to increase with frequency though perhaps more weakly than the decrease. For the 1 A tests, only one set of conditions showed a positive change in base pressure over the no-control case of the more than 50 different cases. In general, the reduction in base pressure for the different cases is small, typically a drop of between 1-3 %. The trends are statistically significant and consistent, though.

To confirm the significance of the trends, four runs at two different plasma conditions were performed where the actuators were off for the first half of the run and then turned on for the second half of the run. Statistically significant changes to the mean base pressure ratio were noted between the two portions of the same run for all cases investigated. The same comparisons were made on two runs without control, and neither showed statistically significant changes between different portions of the same run.

The maximum percent change in base pressure is realized for frequencies between 10-25 kHz. It is considered likely that these frequencies are where the net momentum exchange between the cavity and flow field is maximized. Given the range of frequencies that had similar base pressure changes, it is difficult to pinpoint any one particular frequency that is significantly superior than the others with regard to effectiveness of altering the base pressure.

It is interesting to note that the most sensitive range of frequencies also corresponds with recommendations from Dahan et al.\textsuperscript{115} and Hasan et al.\textsuperscript{116,117} for low-speed 2-D rearward-facing step experiments and those of Sivasubramanian et al.\textsuperscript{60} for numerical simulations (at the experimental test conditions used herein). Dahan, Hasan, and their colleagues argued that for turbulent separation the shear layer instability mode scales better with the approach boundary layer momentum thickness, $\theta$. For the current experimental investigations, this corresponds to a frequency estimate of 25 kHz ± 5 kHz.

In Figure 60, the magnitudes of change at low frequencies are diminished relative to the middle frequencies. In a time-averaged sense, this is likely due to the larger separation time between each pulse. At higher
frequencies, all of the modes exhibited less base pressure change with respect to the no-control case. This is possibly due to the decreased momentum exchange as the electrode and cavity gas temperatures reach a near steady-state condition with decreased cooling time between pulses. This explanation would be supported by the fact that lower exhaust velocities were observed for higher frequencies in quiescent ambient air. If this explanation is correct, then for the middle frequency band, a balance is reached between forcing frequently enough to affect the time-averaged flow and not forcing too frequently such that the actuator performance degrades.

It is also possible, as witnessed in recent numerical investigations by Sivasubramanian et al., that the base pressure changes would become positive at even higher frequencies. The authors of that particular study noted that the base pressure changes caused by the pulsation of axisymmetric “jets” (actually, by the addition of radial momentum) upstream of separation caused decreases in base pressure at lower frequencies ($St_D = 0.83$ or near 7.5 kHz for this configuration), but at higher frequencies, the direction of change was reversed. A maximum increase of $+5\%$ was reported by the authors at $St_D = 5.0$ (~ 45 kHz for this study). Notable differences of the numerical study from the current experimental effort include that the radial momentum addition was fully axisymmetric, had a constant amplitude (it was not frequency-coupled like the plasma actuators appear to be), and was added upstream of separation. These differences likely contributed to the fact that in the numerical study the maximum percentage decrease in base pressure was larger than realized in the current experimental investigations (-$10\%$ vs. -$3\%$).

The second observation made from Figure 60 is that the mode of forcing does not seem to have a major influence on the performance of the actuators with regard to base pressure. At constant frequency, a similar magnitude of change, albeit small, is realized for all modes of forcing investigated. In fact, at almost all frequencies investigated the percent difference change in base pressure between different modes is less than $1\%$. These differences are within the range of possible variation caused by RR asymmetry. More details are presented below on the magnitude of change that can be caused by the RR asymmetry, but it is estimated to be approximately $\pm 1\%$.

The one $\frac{1}{4}$ A data set (axisymmetric mode) shown in Figure 60 does exhibit some positive base pressure changes with respect to the no-control case, but most of the changes are small. Some of the observations, such as the reversing direction of base pressure change for a monotonically increasing frequency, provide some uncertainty about the results. The general trend for the axisymmetric $\frac{1}{4}$ A data, especially above 15 kHz, may be one of little-to-no change, especially relative to the magnitudes of change for the 1 A data. Given the small changes in base pressure and the minor influences in the schlieren imaging for the $\frac{1}{4}$ A case relative to the 1 A data sets, the decision was made to complete the remainder of the experiments with 1 A discharges.

Frequencies higher than 40 kHz were also investigated (up to 100 kHz). However, as mentioned previously, the actuators were operated in ~50-100 burst pulse trains in order to acquire PIV data (discussed below) of the flow field under high-frequency actuation. The actuators were generally active for approximately a millisecond, shut off for another millisecond, and then turned back on again (active 50% of the time, not to be confused with 10% duty cycle while active). Base pressures were also monitored for these runs, and although they are confounded by the cyclical firing of the plasma actuators, no statistically significant changes in base pressure were observed for the high-frequency cases. The base pressure measurements were not able to be phase-locked to the discharge, like the PIV acquisition could be. Moreover, the base pressure tubing used to plumb the base pressure
lines to the pressure scanner had a frequency response of approximately 5 Hz. Therefore, time-synchronized base pressure acquisitions would not reflect the effects of the short duration pulse trains anyway. High-speed surface pressure measurements could be time-synchronized, but were not attempted due to the previous challenges experienced with EMI when using high-speed pressure transducers near electric arcs (see high-frequency pressure measurement discussion in DC arc discharge results and discussion section of Appendix A).

In addition to the investigation of the effect of current, frequency, and mode, the investigation of on-time, or more specifically duty cycle, was investigated to determine its influence, if any, on the base pressure. For the majority of the previously reported measurements, a maximum duty cycle of 10% was enforced because of the ballast resistors’ power dissipation limitations. The original design of the plasma actuator system was to produce ¼ A discharges. With the observation of increased actuator performance for 1 A discharges, the decision to expand all actuators to 1 A operation was made, increasing both the current and power by a factor of four. However, in order to thoroughly evaluate a wide range of duty cycles at 1 A, the decision was made to drive the resistors at up to 20% duty cycle for a few exploratory tests.

Previous research on the efficacy of LAFPAs at differing duty cycle to affect the shear layer growth rate of a Mach 0.9 jet found that lower duty cycles were optimal.\(^\text{93}\) It was argued that the energy input at breakdown was substantially larger and more influential on the flow than the input or effect induced when the plasma was active. Longer on-times/duty cycles were claimed to be detrimental to the actuators’ performance by increasing heating and residual ionizations and decreasing refill/cooling time. The warmer electrodes and free electrons would decrease the breakdown voltage, thereby decreasing the energy input at breakdown. Therefore, before the base flow tests were performed on a variable duty cycle, it was speculated that a similar behavior would likely be evident for the base flow actuators. Five runs were performed with the actuators firing at 20 kHz in a “quad-flapping” mode \((m = \pm 4, \text{ forcing mode } 4)\) at 1 A. A single no-control run was performed before and after the five control runs to determine the baseline base pressure ratio and to ensure the mean RR flow was symmetric. The mean and standard deviation of the base pressure ratio for the seven runs are shown in Figure 61. The top figure shows the mean base pressure ratio for each case. The different colored curves represent the three base pressure tap locations. No-control runs are shown at 0% duty cycle. The average base pressure ratio for the two no-control runs is very consistent showing an average percent difference at the three tap locations of only 0.08%. With increasing duty cycle, the mean area-weighted base pressure ratio exhibits a monotonic decrease with increasing duty cycle for all tap locations. The maximum decrease of about -3.5% occurred at the maximum duty cycle tested of 20% as shown in Figure 62. Although not specifically tested again, the predicted percent change of the base pressure ratio for a 10% duty cycle (as used in the bulk of the other experiments) is consistent with the data from Figure 60. The standard deviation of the base pressure ratio for the three tap locations is also shown in Figure 61. The standard deviations are fairly consistent for all runs with and without control and amount to about 1.0-1.5% of the mean base pressure ratio.

The trend of increased flow modification for increased duty cycle is contrary to the observations of Hahn et al.\(^\text{93}\) It is not clear currently why the increased duty cycle caused the increased alteration or why the observations are at odds with previous experience. Two possible explanations for the observed differences are that there is either a fundamental difference in the fluid dynamic instabilities being excited between the two flows or that there are
some significant differences about the actuator operational parameters between the previous and current experiments. For example, in the OSU experiments, the actuators were operated with a current of ¼ A (versus 1 A), the operating pressure was ambient (versus ~12.8 kPa (~1.85 psia)), and the operating frequency was 3.5 kHz (versus 20 kHz). It is possible that the higher current, lower pressure, and/or higher operating frequency could modify the performance of the actuators significantly enough that the duty cycle trend is reversed. For example, if the breakdown voltage was no longer substantially modified by increased duty cycle at the lower operating pressure and higher current and frequency, then it is possible that greater duty cycles would increase the total energy input and the corresponding fluidic effect in the current experiments.

Figure 61. Base pressure ratio (top) mean and (bottom) standard deviation versus plasma actuator duty cycle at three different tap locations.
Figure 62. Percent difference of area-weighted base pressure ratio relative to no-control versus plasma actuator duty cycle.

To that end, the possibility of comparing constant energy inputs per discharge for an array of duty cycles was considered. To accomplish this task, the previous duty cycle experiments would be repeated with decreasing electric arc power inputs for increasing duty cycles (on-times) such that constant energy inputs per pulse would be maintained for the set of tests. In order to decrease the power input in a pulse (excluding the breakdown power input), the arc current would need to be reduced. The arc voltage is not directly tunable, but is determined intrinsically by the plasma. Therefore, an iterative process would need to be undertaken in order to determine the current that results in the appropriate gas voltage to create the desired power dissipation. This process is further confounded by the non-linear current-voltage relationship for the electric arc as witnessed in Figure 25 and the fact that the current is only modifiable by changing the ballast resistors on the DC driving voltage. Only two resistance values for the ballast resistors were available and the DC driving voltage has a minimum constraint in order to ensure breakdown. Modification of the resistance can also change the voltage ramp-up time constant, which was a point of concern when attempting to design experiments to isolate a single effect. Furthermore, the breakdown power input, a significant portion of the power input, was not able to be adequately measured due to the high level of EMI at breakdown and the bandwidth limitations of the voltage and current probes relative to the fast plasma formation. Further experiments along these lines were ultimately not pursued on account of these concerns.

In the end, the tests were not needed in order to determine if constant energy input into the plasma could negate the effects noticed for changes in duty cycle. It was later noticed that the ¼ A experiments actually possessed a larger plasma-on input power than the 1 A experiments. Even though the current was reduced by a factor of four, the voltage was increased by about a factor of 8 for the lower current experiments, similar to Figure 25. Since the ¼ A and 1 A axisymmetric mode \((m = 0)\) data were acquired for the same duty cycle (on-time), the comparison of the two sets of results could be used as a direct comparison of the influence of plasma input energy.
The lower-power 1 A data showed a larger effect on base pressure and a larger shear layer disturbance in the PIV (discussed below). Therefore, it can be concluded that increased performance of the actuators at higher duty cycles cannot be justified solely by increased power/energy input into the steady-state portion of the plasma. There is clearly more complicated dynamics at work that cause the observed duty cycle trends.

4.5.2 PIV Measurements

PIV data were also acquired for the eight-actuator base for the same frequency and mode combinations as discussed in the base pressure measurements section above. The two measurement sets (PIV and base pressure) were acquired during the same interval of time during the same runs, but were not time-synchronized. The field-of-view of the imaging technique was expanded relative to the results shown for the four-actuator preliminary actuator geometry study so as to include the rear stagnation point. Each realization reached from about 4 mm off of the base (~R/8) to about 95 mm downstream of the base (~3R). The images in Figure 40 and Figure 41 were taken from these data. The smaller field-of-view was originally used in the actuator geometry comparisons to evaluate the near-field of the region where the actuation occurred. In contrast, the purpose of the eight-actuator measurements was to investigate the influences of the multitude of actuators on the overall base flow field. Therefore, it was important to include the entire RR in these comparisons. The appearance of the shear layer disturbances is somewhat reduced for these images as a result of the enlarged field-of-view.

A no-control data set was acquired before and after every batch of control sets for comparison’s sake. It was confirmed that the RR flow field was symmetric before PIV control data was obtained. Example speed contour plots with and without control are shown in Figure 63. Flow is from left to right with a model of the base to scale on the left of each image. The spatial coordinates and speed field are non-dimensionalized by the base radius and freestream velocity, respectively. The selected control-on case forced a helical mode (m = 1) at 20 kHz, 10% duty cycle, and 1A and had a 50 μs phase delay (from the discharge of the top actuator). A slight ripple is caused in the two shear layers (difficult to see in this zoomed-out view), and the RR flow is asymmetric (displaced downward). Statistically significant changes in the RR length or maximum reverse velocity were not noticed for any of the cases besides the displacement of the maximum reverse velocity away from the axis of symmetry.

The ripples in the shear layer can be seen better in the left image of Figure 64, which displays the transverse, or radial, velocity field for the same conditions as Figure 63. The ripples are offset between the top and bottom shear layers by a 180° phase delay, or half the period (T/2 = 20 μs), as a result of the helical mode of forcing. This example control-on case was selected for display as it demonstrated one of the largest percent changes in base pressure (~ -2%). In general, the cases that demonstrated the largest changes in base pressure also exhibited an asymmetric RR. RR asymmetry was most common at the middle range frequencies (7.5-30 kHz), but was still common at the high-frequency test cases. Below about 5 kHz, it was a rare occurrence. The asymmetry was downward more often than upward, but did occasionally manifest upward. It is not clear what the fundamental cause of the induced asymmetry is and why it manifests downward more often given that the actuator locations are symmetric. It is possible that slight differences in actuator manufacturing, assembly, or operational parameters, or minor tunnel asymmetries, caused asymmetric shear layer stimulation, but the differences between the physical
actuator geometries and their light emission while operational are minimal. Voltage and current behavior have also been checked for consistency between different channels. The symmetry of the RR does appear to be a very sensitive parameter, though.

Figure 63. Base flow speed contour plots for (left) no-control and (right) helical mode forcing at 20 kHz, 4 μs on-time (10% duty cycle), 1A, and 50 μs phase delay (from discharge of top actuator).

Figure 64. (left) Base flow transverse velocity contour plots for helical mode forcing at 20 kHz, 4 μs on-time (10% duty cycle), 1A, and 50 μs phase delay (from discharge of top actuator) and (right) contour plot of difference between control and no-control transverse velocity field for quad-flapping mode forcing at 850 Hz, 25 μs on-time (2% duty cycle), and 1A with a 50 μs phase delay (from discharge of the top and bottom actuators).
It was noticed (as seen in Figure 64) that generally the disturbances were smaller and less intense in the bottom shear layer. Conversely, the cases that have an upward RR on average appear to show a slightly larger stimulation in the bottom shear layer than in the top. Electric arc / actuator variability is viewed as the most likely candidate for the cause of the differences besides the inherent sensitivity of the reverse flow and shear layer itself.

In order to evaluate the influences of the actuators better, several analytical techniques were developed. Similar to the processing technique used in the schlieren image analysis, contour plots of the differences between the control and no-control flow fields were evaluated. Figure 64 shows one such case. The difference is again non-dimensionalized by the freestream velocity. Specifically, the image shows the difference between the transverse velocity component fields for the quad-flapping mode \((m = \pm 4)\) forcing at 850 Hz, 25 \(\mu\)s on-time (2% duty cycle), and 1A with a 50 \(\mu\)s phase delay from discharge of the top and bottom actuators. Only one disturbance would be expected to be visible at this low frequency. The figure shows some random differences further downstream, but highlights the induced velocity of the two disturbances better than the raw velocity fields. A higher than normal outward velocity is induced on the outside edge of the upper shear layer and a higher than normal inward velocity is trailing it on the inside edge of the shear layer. The velocity change is about 6% of the freestream velocity, or about 30 m/s, at a maximum for this case. The disturbance also appears to generate a weak shock or disturbance in the supersonic outer stream, which may be similar to the wave-like disturbance noticed in the schlieren images. The transverse velocity modification in the supersonic flow is only about 2% of the freestream, or about 10 m/s, at a maximum on both sides of the flow. Other statistically significant differences are not consistently observed.

The influences on turbulence statistics were also investigated, but observations similar to the actuator geometry study were made. In essence, the turbulent statistics appear to vary more due to the RR asymmetry than due to the actuators themselves. With the variable degree of RR asymmetry depending on case and run, it is impossible to discern other underlying effects due to the actuators.

The full test matrix of frequency and mode combinations was evaluated for its flow control potential. Disturbances were noted in the shear layer at all frequencies and modes. A visual comparison of the disturbances in the shear layer immediately after separation for 40, 67, and 100 kHz actuation in the axisymmetric mode is presented in Figure 65. The images compare transverse velocity contour plots at the three highest frequencies investigated. The duty cycle and current were 10% and 1A, respectively. In each image, flow is from bottom to top. The RR is to the left (red region) and the freestream is to the right (red region). The expansion wave moves up and to the right and the shear layer moves up and to the left. Decreasing disturbance intensity and spatial extent is observed for increasing frequency, which could be caused by decreasing momentum exchange per pulse for higher frequencies. However, disturbances are clearly evident at all these higher frequencies. It is interesting to note that the same on-time (1.5 \(\mu\)s) was used for both the 67 and 100 kHz cases, and only a 0.5 \(\mu\)s increase in on-time occurs for 40 kHz operation. Therefore, the evident differences are not due to shorter on-times, especially when comparing the two highest frequency cases. While the effects at 100 kHz are clearly smaller than at 40 kHz, they are also occur more often and may therefore have a similar effect on the flow in general. As mentioned previously, base pressure was not able to be acquired for continuous operation above 40 kHz as the switches were limited to burst mode at these high frequencies.
Detailed analysis of the velocity profiles of both control and no-control cases was undertaken in order to better evaluate and compare the induced differences of the control technique on the shear layer. Plots of the streamwise and transverse velocity along a lateral slice through the shear layer disturbance 13 mm ($X/R \sim 0.41$) downstream were evaluated. Unfortunately, since the disturbances are in a high velocity gradient region, the absolute changes were challenging to discern. The contour plot appears well suited for detailing subtle changes in a high-velocity-gradient field.

Therefore, the shear layer was evaluated using another method that better highlights the small disturbances in regions of large velocity gradient by rotating the shear layer reference frame and velocities. First, the reference point (0, 0) of the base flow field was moved to the top base edge [(0, 1)$\rightarrow$(0, 0) in non-dimensional coordinates]. Then, an estimate of the top shear layer angle was made by determining the radial coordinate that corresponded to an axial velocity of $0.5V_{inf}$ in the shear layer at both 8 mm ($X/R \sim 0.25$) and 48 mm ($X/R \sim 1.51$) downstream of the base. In essence, the two points constituted the end points of the straight portion of the shear layer in the available data. $X/R = 0.25$ was selected as the starting point because it was one of the first points measured with high certainty in the shear layer (i.e., without possible edge effects) that was still upstream of the disturbances for the given delay time. $X/R = 1.51$ was selected as the downstream boundary because it was just upstream of where the shear layer was turned back to the freestream direction by recompression shocks. The slope of the line connecting these two spatial points was computed, and the spatial coordinates and velocity fields were rotated by the corresponding angle so that a horizontal shear layer was formed. With this transformation, a shear-layer-parallel and shear-layer-normal coordinate reference frame was created with shear-layer-parallel and shear-layer-normal velocity components. Figure 66 shows one such example for forcing of a double flapping mode ($\pm 2$) at 25 kHz, 10% duty cycle, and 1A with a 50 $\mu$s phase delay. $X$ and $R$ now represent the shear-layer parallel and shear-layer-normal directions as measured from the base corner separation point. This plot and successive plots are shown with dimensional values to better highlight the size of the disturbances and the magnitude of the velocity changes. For non-dimensionalization purposes, the average freestream velocity was computed to be 573 m/s and the base radius is 31.75 mm.
Figure 66. Speed contour plot of top shear layer rotated horizontally; forced with double-flapping mode at 25 kHz, 10% duty cycle, and 1A with a 50 μs phase delay.

Once in the rotated reference frame, the velocity field was recomputed for a new grid with 0.1 mm resolution instead of the ~0.4 mm resolution of the PIV data. Then, the shear-layer-normal location where the shear-layer parallel velocity reached 10%, 50%, and 90% of $V_{inf}$ was determined for all points between 8 mm and 48 mm from the base edge. The profiles formed from these traces are plotted over the contour plot in Figure 66. The black three traces represent the control-on profile, while the white three traces represent the no-control data. Again, a displacement of the velocity contours is evident both on the top and bottom sides of the shear layer.

A similar analysis was used on several control-on cases as well as their no-control counterparts. The results are shown in the left image of Figure 67 for the same cases as shown in the right image. In the legend, the control cases are designated by an abbreviation of the forcing mode followed by the actuation frequency. See Table 6 for definitions of the abbreviations. In the left image of Figure 67, only the 10% and 90% profiles are shown. The physical separation of these two markers in the shear-layer-normal direction is defined herein as the shear layer thickness. The right image of Figure 67 displays the shear layer thickness versus the shear-layer-parallel coordinate for the same four cases as in the left image. The no-control case is observed to grow fairly linearly at a rate of 0.106 (mm/mm). The estimate of the growth rate is obtained by using least-squares linear regression.

The forcing at 12.5, 15, and 20 kHz in the flapping mode produces a local thickening of the shear layer of similar magnitude for all three frequencies for the phase-locked disturbance. The thickness is reduced almost back to the no-control shear layer thickness further downstream, but remains slightly thicker for the control cases. At 15 and 20 kHz forcing frequency specifically, secondary disturbances should still be in the portion of the shear layer under investigation, but secondary bulges in shear layer thickness are not evident. Therefore, it appears that the magnitude of localized increase in shear layer thickness for disturbances further downstream is reduced substantially relative to the first, phase-locked disturbance.
Away from the localized disturbance, the actuation does appear to increase the shear layer thickness slightly. Using a least-squares-fit on the shear layers downstream of the initial disturbance (18 mm < X < 48 mm), the estimated growth rates are 0.101, 0.097, 0.100, and 0.106 for the no-control, 12.5 kHz, 15 kHz, and 20 kHz cases, respectively. Relative to the no-control case, the changes in shear layer growth rate are -4.1%, -1.0%, and +5.6% in order of increasing frequency. It is not believed that the changes to shear layer growth rate are statistically significant. It is believed that random variation in shear layer thickness and in the computation of the shear layer thickness is causing the observed changes given the typical spread of the data. In contrast, when comparing the full linear regression equation for all four cases, instead of just the growth rate (slope), the estimated shear layer thicknesses for the control cases are consistently between 1-5% thicker than the no-control case. In other words, the forcing appears to increase the shear layer thickness slightly, but does not appear to alter the shear layer growth rate substantially. The other frequency and mode combinations that were investigated showed a similar change in shear layer thickness and growth rate.

An estimate of the convective velocity (discussed below) was subtracted from the shear-layer-parallel velocity component. In the convective reference frame, a rotational structure was not apparent in the ensemble-averaged velocity field. For several of the strongest actuation cases, the vorticity of the flow field was also computed. No peaks in vorticity were observed at the location of the disturbances, which seemingly suggests that the disturbance is primarily a deflection of the local velocity field contour lines and not a large-scale rotational structure.

![Figure 67](image_url)

Figure 67. (left) 10- and 90-% freestream velocity location profiles for the shear-layer-parallel velocity component of the top shear layer; determined with and without control (50 µs phase delay from actuator firing) and (right) shear layer thickness (difference in R of the plots in the left figure) as measured normal to the shear layer direction versus distance along the shear layer as measured from the base corner.

One additional analysis was also performed on the shear layer. Similar to the method used to calculate the shear layer rotation angle, a line was defined through the rotated shear layer velocity field from the determination of two points. The two points were calculated by determining the shear-layer-normal location where the shear-layer-parallel velocity crossed 90% of $V_{inf}$ at 8 mm and 48 mm downstream of the base edge separation point as measured
in the shear-layer-parallel direction. This can be visualized by and is very similar to the top no-control line in the left image of Figure 67. This method uses a straight line, though, that connects the two end points. The velocity components are then calculated along this line through bilinear interpolation. The velocity profiles along a straight line in space contained within the shear layer can then be plotted to analyze the effects of the various mode and frequency combinations.

For example, the effect of three different forcing modes at 100 kHz (1 A, 10% duty cycle) on the shear-layer-parallel velocity component is shown on the left in Figure 68. In comparison to the no-control data set, a sinusoidal ripple is forced in the shear layer with a maximum peak-to-trough velocity change of about 10 m/s that appears very similar for all three modes of forcing. The oscillations appear to become less coherent further downstream as the disturbances appear to break up and dissipate. However, this velocity component is higher for all three modes of forcing than the no-control case for essentially the entire region examined.

Knowing the time between pulses, the convective velocity was estimated using a spatial FFT of the oscillations of the signal. The results of the spatial FFT for the first 30 mm of the four profiles are shown in the right image of Figure 68. The signal for the three control cases noticeably deviates from the no-control case between a wave number of 0.2/mm and 0.3/mm. All three control-on cases have a peak in the FFT at 0.234/mm. By taking the reciprocal of this value, it is determined that the wavelength from disturbance-to-disturbance is 4.27 mm. If the disturbance is convected 4.27 mm every 10 μs, then the convective velocity is about 430 ± 20 m/s. The uncertainty estimate is formed from consideration of the resolution of the FFT and experimentation with other forcing frequencies. The spatial FFT is useful at frequencies at or above 40 kHz. Below this threshold, the discharges are too infrequent to be effectively forced and tracked with a Fourier transform. The convective velocity
was also determined from separate PIV sets of the same condition at different delay times. While observed to be less precise, the latter method generally estimated the convective velocity within the range just quoted.

Calculation and comparison of the FFT magnitude at 100 kHz forcing for 10 mm segments of the $0.9V_{inf}$ velocity profile provided an estimate of the signal attenuation with distance traversed downstream. When comparing the first 10 mm ($8 \text{mm} < X < 18 \text{mm}$) of data to the second 10 mm ($18 \text{mm} < X < 28 \text{mm}$), the FFT magnitude declined almost 50%. This implies, as is fairly evident from the left image of Figure 68, that the oscillation magnitude of the sinusoidal variation degenerates with distance quite rapidly, which is consistent with past experimental observations for this flow. Kastengren noted that for an axisymmetric wake, naturally-formed structures in the shear layer could be tracked for about 10 μs on average. Therefore, the forced structures in the shear layer from the plasma actuators exhibit a longer coherence time that is on the order of 40 μs, although care must be exercised in this comparison because the methods used to track the structures in the two studies were different.

The same technique as that used to generate the left image of Figure 68 was used to compare the shear-layer-normal velocity along the $0.9V_{inf}$ line in the shear layer. The shear-layer-normal velocity was evaluated between 8 and 48 mm downstream as measured along the shear layer from the base edge. Figure 69 compares several traces of these plots for parametric changes in frequency (top-right), mode (top-left, bottom-left, and bottom-right), and current (bottom-right). The base pressure percent differences shown in Figure 60 were used as a guide to select the traces used in the plots of Figure 69. The top-right and bottom-left figures, for example, display only cases that exhibited the largest base pressure changes of all the tested cases. On the other hand, the bottom-right figure compares cases that show progressively smaller changes in base pressure (from the largest change to one of the least at the same frequency). The cases for this image were selected so as to include both $\frac{1}{4}$ A and 1 A axisymmetric cases in order to simultaneously evaluate the influence of different currents on the shear layer disturbance amplitude. Unless otherwise noted, all data sets are for 1A discharges with 10% duty cycle and a 50 μs phase delay.

The top-left image in Figure 69 compares the influences of three different modes (A, F, and H) at 100 kHz actuation. The three cases are the same data sets as used to generate the left image of Figure 68. No base pressure comparisons can be made because the actuators were not operated continuously at this high frequency. However, similar to the speed plot in Figure 68, several successive sinusoidal disturbances are visualized along the $0.9V_{inf}$ line. The maximum peak-to-through variation is about 5 m/s at this frequency. Although a slight offset is observed for the three cases, no significant differences in disturbance amplitude or coherence in the shear layer is observed for the three different modes.

The top-right image of Figure 69 compares changes in frequency for the double helical forcing mode. The frequencies that are compared to the no-control case are 15, 25, and 30 kHz. Substantial differences between the control and no-control cases are observed in the plots. Significant differences are even noticed between the three control-on cases. The disturbance caused by the phase-locked discharge is located at approximately the same location ($X \sim 16 \text{ mm}$) for all frequencies as would be expected for a phase-locked ensemble. The amplitude of the disturbance for all cases is roughly the same, and has a peak-to-trough amplitude of about 10-12 m/s. Secondary
disturbances can also be seen further down along the shear layer. A small timing/spatial separation can be seen for the secondary disturbance of the 25 and 30 kHz cases. The amplitude has significantly diminished downstream in the 30 to 40 μs (or ~15 mm) between successive discharges. The peak-to-trough amplitude is similar for both of the higher frequency cases and is estimated at about 5-7 m/s, which is a decrease of ~50%. The lowest frequency case (15 kHz) has twice the period between discharges as the highest frequency case (30 kHz). The 15 kHz case should, therefore, have phase-locked disturbances to the 30 kHz case for every other pulse. As expected, no disturbance is noticed for the 15 kHz case at the location of the secondary disturbance for the 30 kHz case, but two similar magnitude disturbances are noted for both the 15 kHz and 30 kHz cases further downstream (at about 43 mm downstream). The third disturbance for the 25 kHz case is apparently just beyond the region of interrogation as it is not observed in the plot. Significant differences between the two disturbances for the 15 and 30 kHz cases at the most downstream location are not evident, but the lower frequency disturbance does appear to be slightly larger spatially than the higher frequency disturbance, possibly owing to the longer on-time (twice as long) for the lower frequency case. It is also possible that the differences are caused by increased momentum exchange per pulse at the lower frequencies due to the longer recharge time as was noticed in the quiescent experiments.

The bottom two images of Figure 69 compare only cases with 20 kHz forcing. The left image compares several of the cases that induced the largest change in base pressure. The right image compares several cases with decreasing induced change in base pressure. The case with the largest change in base pressure (F, 20 kHz) is repeated for both plots. In the left image, a surprising amount of similarity in signals in noticed for the F and QF cases. For the two modes, the phase-locked disturbance has similar magnitudes as the DH mode discussed previously. Downstream of the initial disturbance, the signal closely resembles the no-control case. Between about 32 and 42 mm downstream the second disturbance is noted which causes deviations from the no-control case again. After, the two signals appear to overlap the no-control case again. It is not surprising that these two cases cause similar changes in base pressure. The helical mode forcing exhibits some differences, though. It appears slightly offset spatially from the other two modes. The initial disturbance is still sharp and of a similar magnitude as the two flapping cases, but it lacks the typical sinusoidal variations about the no-control case that the other modes exhibit. Instead, it seems to exhibit oscillations only above the mean that are smoother in variation. The second disturbance appears weaker and more diffuse. It is not clear why this might be and if it has any correlation to the helical mode of forcing itself, but it does not appear to have an effect on the induced change in base pressure.

The bottom-right image of Figure 69, as mentioned previously, compares cases with changes in forcing mode and/or current that exhibit decreasing change in base pressure. Besides a small offset, the oscillations of the F and A modes at 1 A appear quite similar. The secondary disturbance, between 35 and 40 mm downstream, for the A case appears to be of slightly smaller amplitude than for the F case (maybe 4 m/s instead of 8 m/s). The ¼ A case, however, has a noticeably reduced disturbance amplitude relative to the other two cases at both the first and second disturbance locations. Almost no disturbance is evident at the second location. This set of plots appears to show a fairly clear trend of decreased base pressure changes correlating to decreased disturbance amplitude. Moreover, the ability of the disturbance to stay well organized further down the shear layer also appears to be significant. The
majority of cases displayed similar disturbance magnitudes at multiple locations. The cases with decreased base pressure changes seem to cause weaker disturbances that dissipate earlier.

Figure 69. Shear-layer-normal velocity profiles with and without control (50 μs phase delay from actuator firing) along a line formed between two points; the equation of the line was determined from the spatial location where the shear-layer-parallel velocity reached 90% of the freestream velocity as evaluated at 8 mm and 48 mm downstream of the base edge (measured along the top shear layer) for (top-left) forcing mode variation at 100 kHz actuation, (top-right) frequency variation in double helical mode, (bottom-left) forcing mode variation at 20 kHz actuation, (bottom-right) forcing mode/current variation at 20 kHz actuation [span of modes at 20 kHz from largest to smallest change in base pressure].

As discussed in the base pressure measurements section, the effect of duty cycle changes at a constant frequency, mode of forcing, and current was also explored. The left image in Figure 70 presents a comparison of three cases with different duty cycles. The legend highlights that all cases are for QF at 20 kHz. A current of 1A and QF forcing mode were used in order to maximize the effect on the base pressure. The additional designation in the legend is the on-time used for the discharge. The 2, 6, and 10 μs on-times correlate to 4, 12, and 20 percent duty cycle for 20 kHz actuation. As was noted in the base pressure section, increasing duty cycle correlated monotonically to decreased base pressure. The changes were the largest for 20% duty cycle. The 20% duty cycle
actually caused the largest percent change in base pressure (-3.5%) of all cases evaluated. In comparison, the 4% and 12% duty cycle case caused about -0.75% and -2% changes in base pressure, respectively. With regard to the image that compares the shear-layer-normal velocity along the 0.9\textit{V}_{inf} line (Figure 70), increased strength of the initial disturbance shows a clear correlation with the increased percent change of base pressure. Therefore, it appears that increased duty cycle causes increased shear layer disturbance, which causes decreased base pressure. Further downstream, at the secondary disturbance, the amplitude trends are less clear. None of the cases seems to exhibit substantial differences from each other.

Given the increased percent change in base pressure for increasing duty cycle (or on-time), one might suppose that it is simply due to the increased energy input into the flow by the actuators for longer on-times. However, as mentioned above in the base pressure section, the electric power input between the electrodes is actually higher for the lower current ¼ A case as a result of the higher electrode potential difference. Therefore, upon further inspection, it does not appear that the power input while the discharge is active has a substantial correlation to the forcing magnitude and base pressure changes, at least for the parameters evaluated herein. Both increasing current and duty cycle (on-time) appear to have a positive effect on the base pressure change, though.

For that reason, the effect of a constant product of current and on-time on the flow field disturbances was evaluated in order to separate the more significant effect. The tests were performed in QF mode again. The frequency was 850 Hz. Significant base pressure changes were not observed at this low of a frequency. The right image of Figure 70 compares two cases with a constant current/on-time product of 25 mJ/kV. The first case has a current of ¼ A and an on-time of 100 μs (10% duty cycle). The second case has a current of 1 A and an on-time of 25 μs (2.5% duty cycle). Comparison of the two plots shows that the lower duty cycle/higher current actuation produced a stronger influence on the shear layer than the higher duty cycle/lower current actuation. So, apparently, the effect of current is more substantial than that of on-time/duty cycle at least for these test parameters.

Figure 70. Shear-layer-normal velocity profile for the top shear layer with and without control (50 μs phase delay from actuator firing) along a line formed between two points; the equation of the line was determined from the spatial location where the shear-layer-parallel velocity reached 90% of the freestream velocity as evaluated at 8 mm and 48 mm downstream of the base edge (left) for duty cycle variation in quad flapping mode at 20 kHz and (right) for a constant product of current and on-time (25 mJ/kV) at 850 Hz; also included in the right image is a trace for the largest current/on-time product attempted (100 mJ/kV).
The last curve in the right image of Figure 70 shows the highest current/on-time product tested (100 mJ/kV). It compares reasonably well to the other 1A discharge case with the shorter on-time/duty cycle, but the disturbance is slightly weaker. Therefore, there appears to be a diminishing return on investment for higher on-times (or duty cycles) with respect to the strength of the disturbance at least at these operational parameters.

In order to investigate the influence of the actuators in a plane between actuators, the sting was rotated half the angle between actuators (~22.5°). PIV data were acquired in this plane also for several of the most influential cases. Axisymmetric and helical modes were forced. Unfortunately, no significant differences were observed between the no-control and control data sets in this plane. It is unlikely that the disturbances have been able to propagate azimuthally so rapidly. This finding suggests that the effect of the arcs is very localized and does not likely have significant influences around the entire circumference. Therefore, it seems that to more effectively force global base flow and shear layer instabilities, which could cause more significant full-flow-field changes, more closely spaced LAFPA actuators around the circumference of the base are required.

4.5.3 Base Pressure / PIV Correlation

Each set of base pressure measurements was acquired with a corresponding set of PIV vector fields. When the correlation between the ensemble-averaged PIV fields and the base pressure measurements was investigated, it was noticed that oftentimes the greatest reductions of base pressure would correlate to a strongly asymmetric RR as mentioned above. With a flapping mode \((m = \pm 1)\), an investigation was conducted to determine if the asymmetric RR could be forced to vary back and forth using the actuators. Through phase-locked PIV, it was determined that the asymmetry did not switch back and forth rapidly enough to be significantly affected by the plasma actuators. Further analysis supports this observation. Given that a single RR mode is observed in instantaneous PIV images acquired over a 2 μs time span, it seems likely that the asymmetry is a full-field occurrence that oscillates on a time scale greater than microseconds.

The radial high-speed base pressure measurements of Janssen et al.\(^43\) also suggest that the RR changes likely occur nearly simultaneously rather than convectively. In the experiments, the peak cross correlation coefficient for radially-spaced high-speed pressure transducer measurements was determined to be at zero time delay. Since the RR undergoes pressure fluctuations at different locations on the surface nearly simultaneously, it is reasonable to hypothesize that the RR experiences full-field, or “global” (not to be confused with global used with regard to instabilities), changes and that large scale disturbances in the shear layer are not convected to the base through the recirculating flow or are not strong enough to cause significant base pressure fluctuations. Convected large-scale structures would likely yield a non-zero time delay between differing base pressure measurement locations.

Given the correlation between PIV fields and base pressure, an analysis was performed on the base pressure changes for different RR asymmetries. It was observed that a “downward” crossflow corresponds to a lower average base pressure. As mentioned earlier, the base pressure taps for these experiments were located 22.5° out of the laser plane on the top half of the base. From the PIV data, it was clear that the “downward” recirculation shifted
the ensemble-averaged forward stagnation point on the base to below the center of the base. It was therefore rationalized that the translation of the streamlines and “high-pressure” stagnation point to lower on the base could reduce the pressure on the top of the base where the base pressure taps were. Several experiments and additional analysis were performed in order to estimate the proportion of base pressure change that may be due to the asymmetric RR since there was little room within the sting for additional taps.

First, the nozzle was raised relative to the sting by a fraction of a mm (~0.25-0.50 mm, ~0.010-0.020") in order to force the sting to be slightly off-center. The area-weighted base pressure ratio (as calculated from base pressure measurements on the top portion of the base) was increased and the “upward” mode was noticeably dominant in the PIV, consistent with predictions. Then, the nozzle was dropped by a similar amount and the reverse was noticed in the PIV and base pressure measurements.

From the tests described above, it is apparent that a slight height difference between the top and bottom sides of the nozzle exit can cause the RR to favor a particular direction. It appears that decreasing the nozzle opening on the bottom will act to drive the RR towards the top (to prefer the “upward” mode). While it is not clear what the cause of this underlying connection is, two possible explanations include that the RR is made asymmetric by disturbing the shear layer stability and/or by creating small freestream static pressure or Mach number differences azimuthally around the base. For example, if the area ratio on opposite sides of the nozzle differs, the smaller of the two nozzle openings would have a higher freestream pressure and a lower freestream Mach number. The freestream pressure differential may then contribute to, or be an underlying driver of, the RR crossflow. While it cannot be definitively ascertained that pressure differential has any influence on the symmetry of the RR, it can be said that this explanation is consistent with the observations of experimentation with adjusting the nozzle opening in different directions. Further experimentation is necessary to be able to explain the underlying cause of the RR asymmetry.

The centering process, used to ensure the mean base pressure distribution and base surface flow visualizations are radially symmetric, would also serve to eliminate (or at least minimize) the nozzle azimuthal pressure differences by ensuring that the sting is concentrically located within the nozzle. Through nozzle centering, the base pressure radial distribution is also made symmetric. Therefore, the fact that the base pressure distributions can exhibit asymmetries when not centered is already well-established. However, to the author’s knowledge, the base pressure asymmetries have not previously been correlated to the RR flow field asymmetries so specifically. Furthermore, the ability to purposefully force the asymmetry even for a physically-centered sting has not been reported in the literature. The electric arc plasma actuators appear to be able to stimulate the shear layer such that an asymmetric RR and base pressure distribution can be forced. Unfortunately, the estimated torque produced on the sting due to the asymmetric base pressure distribution (higher pressure on one side than the other) is small (ϑ(0.01 N-m) or ϑ(0.1 in-lb)) and unlikely to cause any significant in-flight control force for steering purposes.

To further explore the influences of the actuators on base pressure and RR asymmetries, a single inclined-cavity electric arc plasma actuator was forced at the top of the base in the laser plane (channel 1 at 12 o’clock on the base) similar to the experiments performed during the actuator configuration study. During the latter studies, the base pressure and PIV data were not acquired simultaneously and so their correlation was not previously
investigated. The single actuator at the top of the base forced the “downward” RR mode to become dominant and the base pressure ratio was reduced by about 1% relative to the no-control case. Then, the opposite actuator (channel 5 at 6 o’clock on the base) was forced at the same conditions and the base pressure ratio was increased by a similar amount. Therefore, depending on the state of the RR, as much as 1% of the changes in Figure 60 could be due to the modulation of the mean RR flow away from the base pressure taps. A 1% base pressure change being induced by the asymmetric RR could account for all of the base pressure changes for some of the cases but not all of them. Several of the cases resulted in a 2-3.5% reduction in base pressure ratio, which exceeds the estimated effect of the asymmetric RR. Furthermore, some control cases have been observed to have a symmetric, or even an “upward”, RR crossflow on average in the PIV results and still result in a reduction in base pressure ratio of 1-2%. This confirms that, despite the observed effects of the RR asymmetries, the general trend of the overall base pressure ratio with electric arc control is to reduce the base pressure ratio, at least to a forcing frequency of about 25 kHz.

Normally when the nozzle is well-centered, a surface flow separation ring concentric to the base circumference forms in surface flow visualizations at \( r/R = 0.85 \pm 0.04 \). When the RR flow is asymmetric, as caused either by electric arc actuators, asymmetric surface disturbances, or an off-center nozzle, the separation ring is displaced in the direction of the crossflow and is no longer concentric to the base. The crossflow acts to wick away fluid accumulation on the surface (in the direction of the crossflow). A larger accumulation of oil forms on the side that provides the crossflow. The oil “pool” is likely caused by a low-pressure region there that is a result of the displacement of the forward stagnation point away from this location and towards the opposite side. In summary, the average asymmetry of the RR flow field and of the base pressure distribution can be determined just from observing the symmetry and oil accumulation pattern of the base separation ring.

In addition to the off-center and asymmetric forcing experiments, additional analysis was performed on past data acquired by Reedy et al.\(^44\) In these experiments, a total of 14 base pressure taps was used to investigate the base pressure distribution without control along two different radii of the base. Seven taps were used per radius, and the radii were separated by 120°. More information can be found on the experimental setup in the article by Reedy et al.

Comparison of the time-correlated base pressure ratio from the inner and outer taps along the two radii is made in Figure 71. By comparing the two tap locations (inner and outer) on opposite radii, a strong anti-correlation is apparent for inner and outer locations on opposing radii. More specifically, a correlation coefficient of -0.87 and -0.84 is computed for the inner and outer tap locations on opposing radii, respectively. In other words, the pressure changes on opposite sides of the base are inversely-related, or when one side is high, the other is low and vice versa. Furthermore, the correlation coefficient between neighboring taps on the same radius is always 0.99 or larger. This result is similar to what was noticed by Janssen et al.\(^43\) for neighboring high-frequency base pressure measurement locations. As mentioned previously, the peak correlation coefficient between neighboring taps was observed at zero time delay. It appears that neighboring taps on the same radius are strongly correlated both at high- and low-frequencies.

For the outer taps in particular, the base pressure is infrequently observed at the mean value (horizontal lines represent mean pressure), and usually has a large slope when passing the mean value, suggesting that the mean
value is likely an unstable configuration. While it cannot be confirmed currently, it is likely that the bulk of the large base pressure fluctuations are driven by, or at least connected to, the bimodal RR behavior described earlier in the baseline no-control PIV results section. In other words, the base pressure oscillates in much the same way as the RR flow. At any instant in time, the RR crossflow is most likely in the direction of the high pressure tap as it was observed to displace the streamlines toward that side. Essentially, the coupling between the mean base pressure and the RR asymmetry that was noticed for off-center runs, or when employing flow control, is probably occurring on an instantaneous basis also. The actuators appear to have the ability to stabilize the normally unstable RR so that its crossflow is orientated in a particular direction.

A similar effect was observed herein for surface disturbances during preliminary experiments. It was observed that an asymmetric RR was caused by the “chamfered” actuator geometry even with all of the actuators disabled. The disturbance caused by the chamfer would trigger the crossflow to be directed away from the beveled edge. In the axial-radial plane containing the actuator, the RR appeared asymmetric, like the right image of Figure 55. Mineral oil accumulated on the base near the “chamfered” actuator geometry, consistent with past observations for RR asymmetries. The irregularity was first noticed when the axial-radial plane containing the “chamfered” actuator was normal to the plane of PIV investigation. The RR appeared symmetric, but had a reduced maximum reverse velocity of 19% of the freestream velocity, instead of the usual value closer to 27%. When the sting was rotated to investigate the cause of the anomaly, the asymmetric RR and mineral oil accumulation rotated with it. When the chamfered geometry was filled in with putty, the RR in the axial-radial plane containing the actuator became symmetric again, and the maximum measured reverse velocity returned to the historically-documented and anticipated value. Also, the mineral oil accumulations dissipated. Therefore, it appears that a base edge surface depression could cause the RR to be asymmetric, similar to the electric arc actuators. These preliminary investigations may also provide insight into how the mean RR flow behaves three-dimensionally since they provided data in a plane normal to the primary direction of the crossflow. As mentioned above, in this plane, the RR appeared symmetric on average with a reduced magnitude of reverse velocity.

If it is correct to assume that the cyclical base pressure variations are caused by the bimodal flow regimes of the RR, then Figure 71 also provides some clues about the frequency with which the RR asymmetry switches back and forth. FFTs of the four signals are shown in Figure 72. In accordance with Nyquist’s theorem, the maximum frequency resolvable without aliasing is estimated at 2.5 Hz as a result of the 5 Hz sampling rate and 5 Hz pressure line response rate estimate. The peak FFT characteristic frequencies for all signal traces are between 0.4-0.5 Hz, implying that the dominant oscillations occur on average about once every two seconds. The fact that the changes occur on the order of seconds suggests that the RR instability is a very low frequency oscillation ($St_D = 8(5x10^5)$). Investigations using the flapping mode of forcing, discussed above, suggested that the RR asymmetry could not be forced on a μs time scale by the plasma actuators, which would be consistent with the low frequency argument. Additionally, the fact that the entire RR flow appears to exist in one mode at a time in instantaneous PIV realizations suggests that the frequency of change is relatively low. Occasionally, the average of 20-40 no-control PIV realizations will still appear off-center as several successive instantaneous vector fields will have similarly directed crossflow, but the mean flow will finally appear centered for 100 or more realizations. The large number of
PIV realizations necessary to reach converged RR flow averages also suggests that the changes occur on the order of single digit Hz. The large number of averages necessary for convergence of the means is a result of the fact that the average flow field is a combination of two significantly different flow modes in the RR. Lastly, past investigators working on the axisymmetric base flow have reported that during real-time acquisition of the base pressure measurements the pressure distribution across a diameter of the base appears to oscillate back and forth between a positive and negative slope.

![Figure 71](image1.png)

**Figure 71.** Comparison of base pressure ratio versus time for inner and outer taps along two different base radii that are separated by 120°.

![Figure 72](image2.png)

**Figure 72.** FFT of base pressure ratio traces (shown in Figure 71) for inner and outer taps along two different base radii that are separated by 120°.
Several centering runs were also analyzed using data from Reedy et al.\textsuperscript{44} The mean and standard deviation of the base pressure ratio at the 14 base pressure taps for four centering runs are shown in Figure 73. The runs are listed in order of acquisition, and order of improving centering, from top to bottom in the legend. The most off-center run condition (blue curve) shows a strong positive slope, which likely implies a cross flow moving in the positive \( r/R \) direction and that the stagnation streamline is displaced in the positive \( r \) direction. If correct, this also demonstrates how the pressure distribution can be skewed on opposing sides based on asymmetric RRs and how it could exhibit strong anti-correlations between opposite sides.

![Figure 73. Base pressure ratio (top) mean and (bottom) standard deviation along two different base radii that are separated by 120° for varying degrees of centering.](image_url)
The standard deviations of the measurements are shown in the bottom image of Figure 73. Regardless of the actual measured base pressure ratio (top figure), the standard deviation of the centered cases (bottom figure) is highly consistent across the entire diameter, but the standard deviation of the off-centered run is about half that of the other three cases. In other words, a well-centered and highly-symmetric flow field is more variable, or unstable, than a poorly-centered flow field. It is theorized that the off-centered case does not oscillate between RR modes as much and, therefore, exhibits less variation in base pressure also.

This hypothesis is consistent with trends observed by Reedy et al.44 and Sandberg et al.58 Reedy et al. noted that the addition of splitter plates to the axisymmetric base, which divided the base into sub-regions, caused the base pressure ratio RMS to be reduced. The physical separation of the RR would prevent the bimodal RR behavior, which without the switching of the RR could reduce the standard deviation of the base pressure measurements similar to the “off-center” case in Figure 73. Furthermore, the peak in base pressure reported in both studies near the center of the base for reduced domain sizes would be consistent with a symmetric RR with the stagnation point at the center of the flow.

In effect, the relatively flat and symmetric base pressure distribution noted by past experimenters appears to be due to the alternation of a non-flat and asymmetric base pressure distribution, such that it is fairly flat on average. For example, the black curve in the top portion of Figure 73 (“Average of Off-Center”) is computed by taking the average of the base pressure ratio from opposite-sided taps (taps 1 and 14, 2 and 13, etc.) for the “Off-Center” runs. The trace is relatively flat and a nearly exact match for the “Centered” case, which supports the argument for the underlying cause of the flat base pressure distribution.

On the other hand, the “Off-Center” case can be reproduced from the centered data in a related, but opposite, analysis. If, in the time-based data, only instants in time are averaged that represent the peak pressure oscillations (e.g., $P_b/P_\infty > 0.58$ for “Outer Tap-2” in Figure 71), then a pressure distribution that resembles the “Off-Center” trace in the top portion of Figure 73 is obtained. This further supports the argument that the base pressure is oscillating back and forth between two asymmetrical configurations, just like the RR flow field (in a simplified 2-D sense, most likely helically in a 3-D sense).

Essentially, the flapping, or possibly the helical variation, of the flow ($m = \pm 1$ or 1 of the flow, not to be confused with the forcing mode $m = \pm 1$) appears to be responsible for the fairly flat base pressure, which provides a fundamental constraint to the application of symmetry to this axisymmetric geometry. The axisymmetric geometry may appear to be an ideal test case to simplify through symmetry, but the asymmetric flow patterns observed place limitations on the applicability of symmetry to this geometry. This recommendation is consistent with the observations of Sandberg and Fasel58 for reduced computational domains. They noticed that the symmetric base pressure distribution of larger domains (half-cylinder) was altered significantly as they transitioned to smaller and smaller domains (1/8 and 1/16 cylinder).

Lastly, the observations discussed above may be for an off-center no-control base flow, but similar base pressure trends are noticed real-time for the centered base flow and for the plasma-controlled base flow. Therefore, it is conjectured that the observations are significant to understanding the plasma actuator control authority.
CHAPTER 5 – SUMMARY AND CONCLUSIONS

The current project was undertaken to evaluate the effects of electric arc plasma actuators on high-speed separated flows. Two underlying goals motivated these experiments. The first goal was to provide a flow control technique that will result in enhanced flight performance for supersonic flight vehicles by altering the near-wake characteristics. The second goal was to gain a broader and more sophisticated understanding of these complex, supersonic, massively-separated, compressible, and turbulent flow fields. To that end, the aim is to provide experimental results that will grant a greater fundamental comprehension of the primary fluid dynamic mechanisms at work in supersonic axisymmetric base flows.

The attainment of the proposed objectives was facilitated through energy deposition from multiple electric-arc plasma discharges near the base corner separation point. The control authority of electric arc plasma actuators on a supersonic axisymmetric base flow was evaluated for several actuator geometries, frequencies, forcing modes, duty cycles/on-times, and currents. This open-loop active flow-control methodology allowed investigation of the influence of stimulating axisymmetric, anti-symmetric/helical, and lower-order azimuthal instability modes. A description of the recently constructed electric arc plasma actuator setup is also included herein, as well as the details on a characterization study of these actuators and their fluid dynamic effects on quiescent ambient air. The characterization study provides data for computational model comparison and validation that can lead to greater understanding of the fundamental fluidic effects of the actuator.

The array of measurement techniques performed in this study is not only valuable for the sake of quantifying the properties of the flow field altered by the active control method, but also for comparison with future computational modeling efforts by collaborating research partners. In general, these flow-control experiments, and the measurements used to quantify them, provide considerable further understanding of these massively separated base flows and the potential to control them under realistic flight conditions.

5.1 Research Summary

Initially, several diagnostic methods were used to characterize the plasma produced by a localized arc filament plasma actuator system in quiescent ambient conditions. These diagnostics included: intensified emission imaging, current and voltage traces, and PIV. Analysis of the data from the diagnostics suggested several conclusions on how variations in plasma properties, such as voltage, current, plasma on-time, and plasma frequency affect the overall velocity field evolution and electromagnetic emission. Velocity measurements obtained from PIV show a maximum induced velocity field from the plasma actuators of approximately 40 m/s for the baseline case operated at 1 kHz pulsing frequency, 0.25 A plasma current, and 20 µs plasma on-time. Results indicate increasing maximum induced velocities with decreasing actuation frequency, which suggests that increased fluidic coupling is caused by increased refill time and/or increased breakdown voltage, as the breakdown voltage also increases with decreasing frequency. The 1 A discharge appears quite strong, but interestingly is delayed in its evolution relative to the other cases.
It is even proposed in these experiments that the arc may at times be switching into a glow discharge mode. While the PIV results shown and discussed herein have been conditionally averaged to only include low-voltage (arc-type) discharges, a comparison was made with the potential for the high-voltage mode to induce a fluidic effect. Interestingly, the results are quite similar between the two different modes. Of all the frequencies, on-times, currents, and potential plasma types that were investigated, it is perhaps most illuminating that all of the maximum induced velocities are within a reasonable proximity to one another. For example, a four-fold increase in current yielded little change in the evolution of the velocity field even though it discharged more than twice as much power. Additionally, a 10-fold increase in frequency yielded only a two-fold decrease in maximum fluid velocity. This suggests that the induced velocity field from the plasma is likely not particularly sensitive to the actuation parameters investigated.

Preliminary investigations of actuator geometry in the supersonic base flow determined that the two base cavity geometries (i.e., inclined cavity and normal cavity) could produce significant disturbances in the shear layer. The disturbances were able to be tracked in time with phase-locked schlieren imaging and PIV. Surface-mounted actuator geometries and an afterbody normal cavity geometry did not produce substantial and/or traceable modifications to the base flow. The influence of the afterbody normal cavity was likely reduced relative to the base cavity geometries due to the influences of the centered expansion at the base corner. The significant difference in fluidic effect on the base flow with and without a cavity is in opposition to that noticed by past researchers for high-speed jets. In their studies, the presence of the cavity was insignificant on the forcing effect of the actuators. However, the significant influence of the cavity is in agreement with the numerical results reported by Kleinman et al.

The disturbances that were produced by the base cavity geometries appeared able to destabilize the shear layer, leading to an asymmetric recirculation region. The supersonic streamlines were also deflected by the actuator producing a wave-like structure in the supersonic stream. Although the two base cavity actuator geometries produced similar influences, the inclined base cavity was ultimately selected for replication into an eight-actuator base due to slightly stronger actuation at high frequencies and increased structural durability.

The flow control experiments with the eight-actuator, single-geometry (inclined cavity) base showed moderate influences on the axisymmetric shear layer. At 10% duty cycle, the peak percent change of base pressure was about -2.5%. Similar changes were noted for all modes and a range of frequencies from about 10-30 kHz, although the axisymmetric mode was the only mode of forcing that generally speaking underperformed the others. The differences between all modes were small, though. The helical and flapping modes probably produced the strongest effects with regard to base pressure, but again the differences were small.

The most substantial changes to the shear layer and base pressure were noted for the highest current and duty cycle tests. The area-weighted base pressure linearly decreased with increasing duty cycles between 4% and 20%. The maximum base pressure reduction at 20% duty cycle was -3.5%. The percent change in base pressure per percent increase in duty cycle was -0.18. This trend is contrary to observations of Hahn et al. for high-speed jets. In their study, they noticed that increased control authority occurred for decreased duty cycle. The authors theorized that the trend was due to the increased energy input during breakdown for shorter duty cycles. It is not clear why the
two trends disagree, but it is possibly influenced by the fact that the tests were conducted at differing operating pressures (12.8 kPa versus 101 kPa), currents (1 A versus ¼ A), and operating frequencies (20 kHz versus 3.5 kHz).

A maximum reduction in base pressure of -3.5% was realized for forcing in a quad-flapping mode \((m = \pm 4)\) at 20 kHz, 1A, and 20% duty cycle. Given the small variation in base pressure in the 10% duty cycle tests (for different forcing modes in the frequency range of 10-30 kHz), it is likely that similar magnitudes of base pressure change would be realized at 1 A and 20% duty cycle (in this frequency range for the rest of the forcing modes). It is believed that the most sensitive range of frequency is a result of the optimum balance between forcing frequently enough to cause substantial effects on the time-averaged flow and not forcing too frequently that the actuator momentum exchange with the surrounding fluid is decreased.

It is interesting to note that the most sensitive range of frequencies also corresponds with recommendations from Dahan et al.\(^ {115} \) and Hasan et al.\(^ {116,117} \) for low-speed 2-D rearward-facing step experiments and those of Sivasubramanian et al.\(^ {60} \) for numerical simulations (at the experimental test conditions used herein). Dahan, Hasan, and their colleagues argued that for turbulent separation the shear layer instability mode scales better with the approach boundary layer momentum thickness, \(\theta\). For the current experimental investigations, this corresponds to a frequency estimate of 25 kHz ± 5 kHz.

Similarly, Sivasubramanian and colleagues found computationally that the most unstable streamwise wavelength for the axisymmetric mode at \(Re_D = 30,000\) corresponded to \(St_D = 0.83\) \((f \approx 7.5 kHz)\). However, the most unstable streamwise wavelength shifted to higher frequencies for higher \(Re_D\), which motivated their studies at \(St_D\) between 0.83-5.0. This range of \(St_D\) corresponds to frequencies between 7.5 kHz and 45 kHz for the current experiments, which overlaps well with the range of frequencies found to be most influential herein. Although the details of the forcing were different than in the current experiments, Sivasubramanian found that the axisymmetric forcing they used decreased the base pressure by several percent (~8-10%) at the lower frequencies tested and increased the base pressure by several percent (~5%) at the highest frequency tested. While primarily decreases in base pressure were observed for the current experiments, the general trend with increasing frequency near the maximum frequency tested was to increase the base pressure, and there were two cases at high frequency for which the base pressure was above the baseline. It is possible, but uncertain, that positive changes in base pressure may be realized at higher frequencies beyond what is currently attainable with the LAFPAs.

Of course, it is important to also consider that the amplitude of the forcing effect from the plasma actuators likely decreases with frequency, but was held constant in the numerical simulations by Sivasubramanian and colleagues. A goal of these experiments was to determine the most sensitive frequency for forcing the base flow instability mechanisms. However, it is important to highlight that it cannot be assumed that all frequencies were forced with the same amplitude. Therefore, the influence of frequency on the base pressure cannot be completely separated from the variation of actuator control authority with frequency.

Analysis of the shear layer velocity profiles acquired through PIV showed a local thickening of the shear layer in the region of the disturbance caused by the actuator. A slight increase in thickness was also observed away from the disturbance. Disturbances were able to be tracked at all frequencies and translated along the shear layer at a convective velocity of 430 ± 20 m/s. A fairly clear trend of decreased base pressure changes correlating to
decreasing velocity disturbance amplitude was noted. Moreover, the ability of the disturbance to stay well organized further down the shear layer also appears to be a significant factor in the actuators’ effect on base pressure. Consistent with these observations, it appears that increased duty cycle causes increased shear layer disturbance amplitudes, which resulted in the observed linear decrease in base pressure with duty cycle.

Additionally, the development of the PIV technique for the supersonic axisymmetric base flow facility has enabled substantial insight to be gained into the effects of the actuators on the ensemble-averaged flow field and on the variability of the instantaneous flow field with and without control. A sensitive bimodal recirculation region behavior was found in the no-control flow field that the plasma actuators could apparently force. The flow field and turbulence statistics in each mode were substantially different from each other. Through analysis of past no-control base pressure measurements, it is believed that the bimodal behavior fluctuates back and forth at a characteristic frequency between 0.4 and 0.5 Hz ($St_D = \theta(5 \times 10^{-5})$). The flat time-averaged base pressure distribution is believed to be a superposition or averaging effect of a normally non-flat instantaneous base pressure distribution. Also, the standard deviation of the base pressure measurements is reduced when in one recirculation region mode as compared to when it is fluctuating back and forth between recirculation region modes.

5.2 Suggestions for Future Work

The most apparent recommendations for future experimental flow control work with LAFPAs would be to investigate the influence of higher currents and duty cycles. Two currents of ¼ A and 1 A were used in these experiments. The 1 A discharges were found to be substantially more influential than the ¼ A discharges. However, it is unclear if the underlying differences were caused solely by the changes in current or if part of the observed difference could be attributed to the apparent change in plasma type (i.e., arc discharge to glow discharge transition). While the changes to the induced velocity field between the two discharge modes in the quiescent experiments was minimal, further experimentation at higher currents could help ascertain if the observed changes in flow field disturbance with current are more attributable to the change in current itself or to the change in discharge mode.

Through additional experimentation, it was confirmed that the high-voltage power supplies could output as much as 4 A of current for short durations. In the present experiments, however, 4 A of current were discharged in parallel to four separate actuators. Therefore, it could be valuable to evaluate the influences when the entire 4 A are routed to a single actuator (by connecting the ballast resistors in parallel). Given the current experimental setup, multiple actuators would not be able to be forced, but the evaluation of even a single 4 A disturbance with PIV could help determine if the magnitude of change in the shear layer is increased with a 4 A discharge. If the magnitude of change is revealed to be more substantial at 4 A, an improvement in actuator control authority could likely be derived by modifying all channels to operate at higher currents. If, however, the change with additional current input is modest, then it is likely that the presently observed trends are due more to discharge mode than current itself.

Of course, the proposed experiments investigating the influences of changing current are potentially just one aspect of understanding the underlying cause of the observed change with current. In addition to the possible
differences caused by the transition of discharge mode, it is also possible that the higher gas temperatures, the modified RC time constant from the decreased ballast resistance in the circuit, and/or the increased breakdown energy input are contributing factors to the observed influences. For example, breakdown energy input is believed to be a primary driver behind the actuators’ control authority for high-speed jets, as the power input during breakdown is believed to be as much as an order of magnitude higher than that during sustained plasma discharge.⁹³

Furthermore, the range of duty cycles investigated showed a linearly decreasing effect on base pressure with only a slight drop-off of the slope of the trend at the highest duty cycle (20%). Extension of this plot to higher duty cycles would be valuable to determine if and when the changes with increased duty cycle plateau and/or if always-on actuators would be preferred. If, however, a peak change is observed for a particular duty cycle, then the test matrix performed herein for 10% duty cycle could be re-evaluated to better delineate the influences of the other parameters. Again, the power supply and ballast resistors are currently the limiting aspect of driving the duty cycle higher than about 25%, although backup power supplies could be used to power all channels at higher currents and duty cycles.

As mentioned above, it is possible, as suggested by the recent computations of Sivasubramanian et al.⁶⁰, that positive changes to the base pressure could be obtained for even higher frequencies than currently used. If changes to the high-voltage switches can be made to drive the actuators at higher frequencies continuously (rather than in burst mode), evaluation of this possibility could be made. The greatest influence is still likely to be realized by tuning the frequency to excite natural instability mechanisms already present in the flow.

Additionally, the numerical simulations of Sivasubramanian et al. were made using axisymmetric forcing. However, the actuators used in these experiments only cover about 16% of the base circumference, and so cannot produce fully axisymmetric forcing. Expansion of either the number of actuators or the extent of their circumferential coverage could be valuable in increasing the fluidic effect. While the expansion of the number of actuators may be restricted for this base flow configuration due to limited internal sting space and cost of expansion, the extent of the actuators’ coverage could possibly be increased by increasing the electrode spacing. The spacing was originally set for validation testing at atmospheric pressure. With the decrease in pressure in the base flow facility, the arcs could be formed over a greater distance, which would help to make the forcing more continuous around the periphery, like the true axisymmetric forcing mode.

In future experiments, it is recommended that the base pressure is monitored on 2-3 separate radii to evaluate the symmetry and uniformity of the distribution. Monitoring along multiple radii would eliminate the need to make assumptions about the pressure distribution symmetry when comparing area-weighted base pressures.

The increased variability of the base pressure measurements with active plasma arcs in comparison to the no-control case should also be further evaluated. It is not clear why these data, or the magnitude of the disturbance in the shear layer of the PIV, can vary fairly substantially from run-to-run even with the same plasma characteristics. One possible check could be to further evaluate the influence of EMI on the measurement devices. Although the pressure scanner is disconnected electrically from the arcs through the plastic pressure tubing, it is possible that the plasmas or high-voltage electronics could have an influence on its accuracy that might contribute an artificial variation to the base pressure measurements. Discharging the arcs outside of the facility, or inside the facility in an
inconspicuous location, while running the tunnel and acquiring base pressure measurements could help shed light on and possibly account for the influence of this proposed effect. EMI cannot possibly explain the differences in shear layer disturbance in the PIV data, however.

Ideally, this research endeavor will be followed by additional computational and experimental work focusing on the active control of base flows. Additional active control and plasma-based flow control techniques and configurations, such as the SparkJet, could be explored as there is a potential for alternative configurations to show more substantial results. The additional techniques are important for facilitating understanding of the sensitivity of axisymmetric base flows to active control and to help determine if more ideal control techniques exist outside the investigated test space.

Since the most significant disturbance to the base flow from the plasma appeared to be caused by the zero-net-mass-flux synthetic jet forcing, the SparkJet, or pulsed plasma jet, with its higher currents and ejection velocities is a strong candidate for causing increased shear layer disturbance. It is a particularly strong candidate for forcing the base flow if it can be operated at similar frequencies as herein without substantial drop-off of the peak jet velocities.

One additional recommendation may be to perform active, always-on jet forcing along the edge of the base flow separation point. Base bleed at the center of the base recirculation region has been performed previously in this facility, but bleeding air or the placement of jet forcing at different locations and angles around the circumference of the base could provide an increased understanding of the sensitivity of the shear layer and recirculation region to differing jet configurations/patterns. The air jets could be throttled to different flow rates, momentums, or velocities in order to evaluate the effects on the supersonic base flow. Additional benefits of this proposal include the elimination of high-voltage, measurement-limiting arc EMI and light emission, the need to phase-lock the measurements, and the variability of the forcing amplitude with frequency. Since the jets would be always on, the duty cycle would effectively be increased by a factor of ten from the primary test matrix to a value of unity.

An additional significant revelation of this research effort appears to be the illumination of the asymmetric recirculation pattern on an instantaneous basis. The added capability of performing PIV in the facility has opened up new options for the exploration of both previously investigated and new flow control techniques. Experimentally, the addition of more advanced techniques, such as stereoscopic PIV or high-speed PIV, could be beneficial. The stereoscopic PIV technique could be particularly useful in illuminating the three-dimensionality of the recirculation region asymmetry. The high-speed PIV method could provide confirmation and insight into the frequencies of oscillation of the base flow field and recirculation region. Specifically, the source of the 850 Hz dominant base pressure frequency is computationally suggested to be pulsations of the rear stagnation point. Although it has yet to be confirmed or refuted experimentally, this could possibly be evaluated with implementation of high-speed PIV and careful selection of the acquisition rate.

In general, with the development and implementation of the new PIV optical diagnostic in the base flow, the goal of attaining a broader and more sophisticated understanding of these complex, supersonic, massively-separated, compressible, and turbulent flow fields has been attained. Future base flow computational work now has a new benchmark for comparison with both the instantaneous flow field realizations and the ensemble-averaged
flow field data. Hopefully, subsequent computational efforts can benefit from these data through code validation/comparison. Then, in return, evaluation of the active control test space can be completed to motivate and further guide future experimental work.
REFERENCES


APPENDIX A – PRELIMINARY ACTUATOR SELECTION STUDY

1. Introduction

The focus of this section is to present a description of a study of plasma/boundary layer interactions performed in a Mach 4 facility. The intended objective of this initiative was an extension of our previous research on plasma influences on axisymmetric jets\(^1\) and was conducted to determine the most effective actuator in this particular supersonic actuation configuration. Although independently motivated and funded from the base flow work, some of the indications on actuator effectiveness shaped and motivated the actuator selection and design for the base flow work, and so, are presented here for completeness.

There were three types of plasmas / plasma actuators under consideration for their prospective influences: a capacitively-coupled radio frequency (RF) discharge that pulses at a frequency of 13.56 MHz, a pulsed plasma from an arc discharge lasting approximately 200 µs full-width, half-maximum (FWHM), and a laser-induced optical breakdown, which has a significantly shorter duration (~10 µs FWHM). Thus, in addition to the type of plasma, the effectiveness of varying discharge times is explored in this study. The arc discharge and optically-induced plasmas are actuated in single pulses. The capacitively-coupled radio frequency discharge has time scales much shorter than the core flow and turbulent boundary layer, and it is only able to operate at a relatively low power of 50 W before the glow-type discharge breaks down into an arc at the wind tunnel test section static pressures of 8.62 kPa (1.25 psia).

The potential of each actuator and its effect on the Mach 4 supersonic boundary layer are evaluated through photographs, schlieren imaging, and high-frequency pressure measurements at 40 mm (1.57”) and 60 mm (2.36”) downstream of the discharge. The pressure measurements were low-pass filtered at 80 kHz. This array of measurement techniques is not only valuable to quantify characteristics of the flow field altered by the plasma, such as downstream pressure distribution and the presence of vortical structures in the boundary layer, but also provides valuable quantitative information for comparison with future computational modeling efforts.

2. Wind Tunnel Description

A Mach 4 supersonic wind tunnel was used to facilitate the study of the effects of various types of plasmas and perturbations on boundary layers in a high-speed flow. The tunnel has a 12.7 cm x 12.7 cm (5” x 5”) square test section with optical access on all four sides and a current capability to produce Mach 4 flow. The system has been designed modularly enough to accommodate flow speeds as low as Mach 2.0. For the nominal Mach 4.0 flow, the system is capable of five minutes of run time on a full charge of the storage tanks. The complete tank refill pump time is roughly five and a half hours with the use of a four-stage CompAir Mako compressor. Besides the quality of the flow, safety and economic considerations were of primary concern in the design of the tunnel. Pitot probe measurements, schlieren imaging, and a laser-based flow visualization technique, boundary layer condensation imaging, have been used to investigate the properties of the wind tunnel flow. The general wind tunnel schematic is shown in Figure A.1. The nozzle installed in the tunnel with the side wall removed is shown in Figure A.2. The nozzle used for these experiments was the second iteration of the facility nozzle design. Two images of the total wind tunnel assembly are shown in Figure A.3. More details on the tunnel can be found in Ref. 2.
Figure A.1. Wind tunnel schematic.

Figure A.2. Wind tunnel with side wall removed to expose nozzle contour.

Figure A.3. Images of the assembled Mach 4 wind tunnel: (top) view looking downstream from stagnation chamber; (bottom) view looking upstream from diffuser.
In order to examine the quality of the flow in the test section, several experimental evaluation methods were implemented. The Mach number was initially estimated through pressure measurements and use of isentropic flow relations. Schlieren imaging was implemented in order to assess the presence of shock waves, expansion fans, or Mach waves in the flow. The schlieren imaging technique was also exploited as an additional measurement technique for the test section Mach number. A Pitot probe and translational stage were used to measure the variation of Mach number within the core and boundary layer flows. Finally, a laser sheet flow visualization technique was used to image the boundary layer and estimate its thickness. Table A.1 summarizes some of the main wind tunnel parameters.

### Table A.1. Summary of significant wind tunnel parameters.

<table>
<thead>
<tr>
<th>Mach number</th>
<th>Test section size</th>
<th>Boundary layer thickness - 95%</th>
<th>Reynolds number (based on δ)</th>
<th>Stagnation pressure</th>
<th>Stagnation temperature</th>
<th>Test section velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Square bottom top</td>
<td>cm/in cm/in cm/in</td>
<td>million</td>
<td>MPa/psig</td>
<td>K</td>
<td>m/s</td>
</tr>
<tr>
<td>4.12±0.07</td>
<td>12.7 / 5.0</td>
<td>2.15/0.84</td>
<td>1.74/0.68</td>
<td>1.21 / 175</td>
<td>280</td>
<td>697</td>
</tr>
</tbody>
</table>

3. **Experimental Setup and Diagnostic Techniques**

The RF discharge, DC arc discharge, and laser-induced breakdown plasma results were evaluated using three methods: visible light/emission photographs, instantaneous and conditionally averaged schlieren imaging, and downstream surface static pressure measurements of the perturbed boundary layer. These data were acquired at various powers for the RF discharge and different delay times for the DC arc and laser-induced breakdown.

The RF discharge emission measurements/photographs as well as all setup images were obtained with a Nikon D70 camera. All other photographs (DC arc discharge and laser-induced breakdown) were obtained with a Cooke Corporation PCO.1600 camera and Nikon Nikkor lens because of the timing requirements. The DC arc discharge emission photographs required the incorporation of a neutral density filter, and the laser-induced breakdown photographs and PMT measurements required the use of a 532 nm holographic notch filter.

Timing was controlled by Quantum Composers 9514 and 9518 signal generators. A Thor Labs DET210 Photodiode was used to detect the initiation of visible emission from the plasma for triggering purposes. The visible emission initiation was used as the starting time for all images obtained with a delay time. Specific waveforms and pulse duration data were acquired by a Hamamatsu HC120-05 PMT detector. Waveform shape, timing traces, and high-frequency pressure transducer measurements were obtained with an Agilent Infiniium oscilloscope. Figure 10 of the main text shows a schematic of the emission photography acquisition method. The photodiode triggers the camera at a delay controlled by a signal generator. Then, the camera data are sent to the computer for storage. Confirmation of the appropriate signal delay times is made using the Agilent Infiniium oscilloscope.

The schlieren imaging was acquired using a typical z-type configuration as shown in Figure 9 of the main text. Three different schlieren light sources were used in three different schlieren setups in order to probe the boundary layer / plasma interaction. The first setup used a Thorlabs, Inc. model number MRMLED blue light-
emitting diode (LED) light source, which pulses at a dominant wavelength of 455 nm and has a maximum power setting of 700 mW. An iris is positioned directly in front of the LED to make the source effectively a point source, which helps to make the image clearer. The second setup used a Thorlabs, Inc. model number M660L1 red LED light source, which pulses at a dominant wavelength of 660 nm and has a maximum power setting of 850 mW. The last setup uses a Strobotac General Radio stroboscope model number 1538-A. The stroboscope pulsed white light at 10 Hertz for approximately 1.5 microseconds per pulse in order to provide a more instantaneous schlieren image. Regardless of the source, the light is then collimated and sent through the test section by a 29.2 cm (11.5”) diameter parabolic mirror with a focal length of 2.54 meters (100”). An identical mirror then focuses the light back to a point that is positioned halfway across a knife-edge. A New Focus model 9852 50-mm circular classic center-mount mirror is used in both setups to turn the light in the streamwise direction before it reaches the knife-edge. A C-mounted Nikon Nikkor camera lens was used to focus the image. Then, the PCO.1600 camera was used to capture the images and send them to a computer for storage. The schlieren image timing is accomplished by basically the same schematic as the emission photography timing method with the addition of a schlieren light source. The light source is triggered by the same signal generator that triggers the camera shutter.

High-frequency pressure measurements were acquired at 40 and 60 mm downstream of the discharge by Endevco model number 8530C-15 high-frequency, piezoresistive pressure transducers. The pressure transducers have a pressure range from 0-103 kPa (0-15 psia) and have a natural frequency of 180 kHz. The pressure transducer signals were conditioned by an Endevco 102/109 pressure transducer conditioner (amplifier and power supply), Tucker Labs Krohn-Hite model 3347 low-pass filter, and Agilent Infinium oscilloscope (1.5 GHz, 8 GSa/s). The low-pass filter was set to a maximum allowed frequency of 80 kHz as the anticipated maximum fluid dynamic frequencies were in the range of 20 to 40 kHz. The transducers were calibrated using atmospheric pressure and the wind tunnel test section pressure during run conditions for a two-point calibration. The high-frequency pressure acquisition schematic is shown in Figure A.4. The photodiode triggers the successive recording of the appropriate pressure traces on the oscilloscope.

Figure A.4. Schematic of high-frequency pressure transducer acquisition technique.
4. **Methods of Plasma Generation**

**Figure A.5** displays a photograph of the RF discharge electrode configuration, a model of the Teflon insert used for the DC arc discharge experiments, and a schematic of the laser-induced breakdown setup including the insert used in generating the plasma in the wind tunnel.

**A. RF Plasma**

The RF plasma used in this effort is a non-equilibrium, non-thermal γ-discharge. The RF discharge is similar to a DC glow discharge, but the oscillating electric field provides more effective ionization than a DC field due to the exponential dependence of ionization rate on electric field magnitude. The RF plasma is self sustained by secondary electron emission from energetic ion collision with the cathode. It has smaller current densities than an arc discharge but influences a larger volume. The voltage drop across this type of plasma is also larger than that of an arc discharge. The glow discharge occurs due to the Townsend mechanism, where an electric field causes an electron avalanche that is self sustaining by freeing electrons from the metallic surface.

Originally, an attempt was made to ignite the RF plasma using the same pin electrode configuration that is used in the DC arc discharge experiments, but this effort was unsuccessful because there was not enough capacitance between the two pins. So this configuration was abandoned in favor of the more successful plate configuration in **Figure A.5** (left). The electrodes were fashioned from 3.18 mm (1/8") thick copper plates that were affixed within the Teflon mount on the bottom test section window blank. The electrodes extended through the Teflon insert and were bent at a 90-degree angle towards each other in order to form the capacitive plates/smooth surface shown in **Figure A.5**. The plates were sealed to the Teflon insert using Loctite 59630 superflex red high temperature RTV. They extended outside of the other side of the Teflon insert for attachment to the copper flashing used to transfer the signal/current. The plates themselves were each 1.82 cm (.715") by 6.71 mm (.264") and were separated by a gap of 2.24 mm (.088"). One plate was grounded to a true earth ground while the other was connected to the high-voltage RF output. The electrodes were observed to heat up quite quickly, which was detrimental to the integrity of the Teflon and RTV. In future endeavors, Litz wire or laminated plies of copper may reduce the heating effect by reducing eddy current losses.
B. DC Arc Discharge

The DC arc discharge operates on single pulses by charging and discharging a flash capacitor with a capacitance of 650 μF to approximately 300 V. After the discharge, an average voltage \( V \) of 75 V is left across the capacitor after the plasma collapses. Using the equation for the energy \( E \) stored in a capacitor with capacitance \( C \):

\[
E = \frac{1}{2} CV^2,
\]

(A.1)

the total discharged energy can be computed to be approximately 27.4 J. If discharged over roughly 250 μs duration, the implied average power is approximately 100 kW while the plasma is on. Conversely, the total flow power based on the enthalpy flow rate is around 900 kW.

The plasma is created by three 1.59 mm (1/16") diameter, pin-type electrodes made from 1.5% lanthanated tungsten. The three electrodes are designated as high-voltage, high-current, and ground. The high-voltage/ground electrodes serve as the plasma initiators, while the high-current/ground electrodes sustain the plasma with the large amount of energy (in the form of current) stored in the capacitor. The arc discharge circuit operates through the incorporation of an oscillator circuit and a transformer. The two, in tandem, produce a relatively high-voltage (approximately 300 V), which passes through a diode to charge a capacitor. When the trigger switch is shorted on the arc discharge circuit, a small fraction of the capacitor’s stored energy passes through another transformer with a higher turn ratio to produce high-voltage (kV range). This voltage is high enough to break down the air between the high-voltage electrode and the grounded electrode. Once the air is dissociated into a plasma, the high-current electrode readily discharges the rest of the stored charge from the capacitor to the ground electrode producing a high-energy arc. This method of sustaining the arc is safer and more economical than storing a large amount of energy at high voltage. A model of the Teflon insert is included in Figure A.5 (center) with the approximate path of the electrode holes highlighted in the drawing. Each electrode angles slightly in towards each other to achieve sub-millimeter proximity of all three electrodes at the surface.

C. Laser-Induced Optical Breakdown

The process of plasma attainment for a laser-induced breakdown is described in detail by Adelgren.\(^4\) It initiates by a focused laser beam that achieves a minimum required radiation flux density. Once achieved, the discharge is similar to the electric arc discharge described above. A multi-photon ionization causes the excitation and release of several electrons. These electrons collide with other molecules to cause a cascade of electron releases. The plasma then becomes increasingly opaque to the laser light, which causes increased photon energy absorption especially along the laser axis in the direction of the incident light. The energy deposition causes a detonation wave to form. Once the laser pulse ceases, the plasma relaxes and a vortex ring is left in its wake due to the asymmetric plasma formation.

A Newport-Spectra Physics Quanta-Ray Model GCR 250-10 PIV Series Nd:YAG 532 nm laser is used to achieve the breakdown with an energy level of 300 mJ per pulse over a six nanosecond discharge time. A Thor Labs DET210 Photodiode was used to detect the initiation of laser light scattered from the beam as it travels through air. The schlieren setup used the red LED light source described previously. Figure A.5 (right) and Figure A.6 show a schematic and a photograph, respectively, of the laser-induced breakdown setup including the insert used in
generating the plasma in the wind tunnel. The laser beam is initiated downstream and travels beneath the tunnel parallel to the direction of flow until it is reflected vertically by a mirror. It then passes through an anti-reflection coated, 100 mm lens that is mounted into the bottom of the aluminum insert to focus the laser light down to a point in the boundary layer. The focused, coherent light then initiates the breakdown. The two pressure transducer ports are also visible, 40 mm (1.57”) and 60 mm (2.36”) downstream.

Figure A.6. Photograph of the laser-induced breakdown insert used in generating the plasma in the wind tunnel. A lens is mounted into the aluminum insert to focus the laser light down to a point in the boundary layer. The two pressure transducer ports are also visible downstream.

5. Results and Discussion

A. RF Plasma Discharge

The RF discharge plasma results were evaluated using two methods: visible light/emission photographs and instantaneous and conditionally averaged schlieren imaging. These data were acquired at various discharge power levels. No timing was used in the acquisition of the data because the RF signal cycle times of 74 ns are significantly shorter than the fluid time scales. Photographs of the RF discharge from the copper plate in the Mach 4 wind tunnel are shown in Figure A.7. The flow is from right to left for Figure A.7 and all subsequent figures. The powers represented by each image, from left to right, are 30 W, 40 W, and 50 W. The reflected power was maintained to no more than 1 W. Attempts were made to maximize the bias voltage, and it was always at least 5 V. It is apparent that as the power increases the plasma spreads out and emanates from a larger portion of the plates. Also, as evidenced by the decreasing background intensity, the luminosity of the larger discharge powers is more intense. A pink to purple glow/emission supports the presence of the plasma across the two plates, while a more intense, nearly white emission emanates from the gap between the two electrodes. The white emission likely represents a higher temperature discharge, which was further validated by increased charring of the RTV and Teflon in this region.

Figure A.7. Photographs of the RF discharge from the copper plate in the Mach 4 wind tunnel. The plasma input power is 30 W, 40 W, and 50 W (from left to right) with no more than 1 W reflected power. The flow is from right to left.
A baseline (plasma-off) schlieren image for the RF discharge experiment is presented in Figure A.8. The schlieren image was acquired with a one-microsecond shutter time, spark light source, and vertical knife edge to highlight horizontal density gradients. A sequence of weak waves is obvious in this image emanating from the gap between the electrode plates and the junctures between the copper plates and the Teflon electrode mount. The boundary layer is evident by the increased turbulence near the wall that appears in the schlieren image as an increase in the light and dark variations.

Schlieren images of the RF discharge in the Mach 4 wind tunnel are presented in Figure A.9. The two images presented are for 30 and 40 Watt discharge powers. Schlieren imaging is not presented for the 50 W discharge because it was unstable and would break into an arc that reset the system before acquisition was possible. Other than the plasma, the schlieren images were obtained at the same flow conditions as the baseline image. Similar features are evident in the two images with the plasma-on as in the baseline (plasma-off) condition. No noticeable and significant feature differences can be seen between the three images.

Figure A.10 shows average schlieren images of the RF discharge off and on in the Mach 4 wind tunnel. The plasma-on condition was acquired at 40 Watts discharge power. The schlieren was obtained with a vertical knife edge and the blue LED light source using a 100 microsecond shutter to acquire an average image. There is no perceivable or significant difference between the two images, which suggests that the RF discharge does not have a significant effect on the flow in the configuration attempted and at the power levels used. As a result, no high-frequency pressure transducer measurements were obtained for the RF discharge. It is possible that improvements could be made to the electrode configuration in the future so that higher powers could be effectively coupled into the flow.
Figure A.9. Schlieren images of RF discharge in Mach 4 wind tunnel obtained at 30 and 40 Watt discharge powers from left to right; obtained with a vertical knife edge.

Figure A.10. Average schlieren images of RF discharge in Mach 4 wind tunnel obtained with plasma off and plasma on at 40 Watt discharge power; obtained with a vertical knife edge.

B. DC Arc Discharge

The DC arc discharge plasma results were evaluated using three methods: visible light/emission photographs, instantaneous and conditionally averaged schlieren imaging, and downstream surface static pressure measurements of the perturbed boundary layer. These data were acquired at various delay times. The start point for the delay times for each run was triggered by a photodiode. The photodiode was used as an alternative to signal generator triggering because it was noticed that there were significant variations in the time between the signal generator trigger and the initiation of the plasma. Figure A.11 shows the four traces as acquired on the oscilloscope. The trigger initiates the plasma with a one hundred microsecond pulse. The photodiode signal is then used to trigger the camera shutter for two microseconds at the specified delay time (150 microseconds in this instance). It should be noted that the photodiode was only used to trigger the camera. The trailing edge of its waveform may not be correct as a higher than recommended termination impedance was used for the photodiode signal because of overall weak signal strength at the lower recommended termination impedance setting. The PMT was therefore used to acquire the actual waveform with matched termination impedance at an appropriate signal intensity. The unmatched impedance is the reason that the photodiode signal decreases slower than the PMT signal. The full width-half maximum of the PMT signal is 175 microseconds. The signal ramp-up time is around 65 microseconds, and the photodiode trigger was set at 75 mV. The full width-10% maximum is 436 microseconds as might be expected from the long tail. Without the flow on, the spark occurs at atmospheric pressure and, consequently, the spark is less intense but occurs for a greater duration. The full width-half maximum is around one millisecond with the full width-10% maximum extending beyond two milliseconds (not shown in figure).
Photographs of the plasma were obtained and superposed on a background image of the wind tunnel for perspective. Four of these images are presented in Figure A.12. The images represent 50, 100, 150, and 200 microsecond delays from initial light emission as detected by the photodiode. It should be noted that the background intensity is enhanced by several orders of magnitude in order to have both the plasma and the background at approximately the same intensity in one image. Again, the flow is from right to left in all images. The images show an unsteady plasma interface that seems to convect upward by buoyant forces and causes the boundary layer to separate immediately downstream of the discharge. The boundary layer reattaches shortly thereafter. The plasma has almost completely dissipated after 200 microseconds. The luminescent plasma is drawn downstream and continues to be visible over 2.5 cm (1”) downstream of the electrodes. The conditional average of five independent images was processed for the same delay times as above (not shown). Similar features are evident as in the instantaneous images with the exception that the unsteady fluctuations of the plasma boundary are averaged out.

The baseline (plasma-off) schlieren images for the DC arc discharge experiments were acquired with a 2-microsecond shutter, blue LED light source, and vertical knife edge to highlight horizontal density gradients. No signs of strong gradients are evident in the images. Very slight Mach waves are visible emanating from the leading edge of the Teflon insert and the electrode gap. Schlieren images with the arc discharge actuator active are presented in Figure A.13 for 5, 25, 50, 100, 200, and 400 microsecond delays. The formation of a bow shock is evident that bends around the plasma and extends downstream. Also apparent is the emission and heated plume of the plasma that convects downstream with an unsteady interface with the flow. Originally, the heated plume is entrained downstream at approximately the same speed that the tip of the shock front extends downstream. Towards the end of
the image sequence (400-microsecond delay), the plasma has almost completely extinguished and the shock is starting to dissipate as well.

![Photographs of DC arc discharge with wind tunnel background image superposed for perspective. The photographs are obtained with 50, 100, 150, and 200 microsecond delays.](image)

Fifteen independent instantaneous (2-microsecond shutter) images were acquired for 50 and 100 microsecond delay times and conditionally averaged. The results are presented in Figure A.14. Similar fluid dynamic features are apparent except that the unsteady interface is, for the most part, averaged out of the image. The heated region appears to have the most effect around 100 microseconds delay as the effects are seen over 7.62 cm (3’’) downstream. The plasma appears to dissipate and retract somewhat by 150 microseconds delay (not shown). The core speed is around 700 meters per second; so, for a delay time of 100 microseconds, the plasma would be expected to convect approximately 7 cm (2.76”), which seems consistent with the observed displacement in the schlieren image. The slight under prediction even when using the core flow speed may be due to the fact that the delay time is measured from the photodiode actuation, which requires a certain minimum signal to trigger the camera shutter. Therefore, by the time the trigger has been achieved, the plasma may have convected downstream somewhat already. It may also be influenced by the increased speed of sound as a result of the high temperature plasma so that the local plasma fluid speed is higher than that of the surrounding fluid.

In Figure A.15, two sets of pressure traces are provided for a DC arc discharge in a Mach 4 flow. The successive graphs are for the 40 and 60 mm transducers, respectively. One independent trace is presented with the average of five independent traces plotted over the top. For the phase-averaged trace, the plots were shifted based on the position of the consistently distinct peak due to slight variations in the triggering of the plasma. Therefore, the
zero on the plot does not necessarily correspond with any significant ignition point or the timing used in the schlieren images above. The peak amplitude of the signal fluctuation is as much as 29% of the mean pressure amplitude. Oscillations are present in the traces that arrive before the high pressure wave and are likely either electromagnetic interference or radiative heating. As these oscillations die out, the shock wave and successive expansion waves arrive sequentially at the 40 mm transducer followed by the 60 mm transducer. The time difference between the two transducers indicates a convective velocity of 541 m/s for the DC arc discharge. Before the pulses, the single-shot signals are composed of oscillations that appear to reduce in frequency after they are affected by the DC arc discharge. This produces a small but distinguishable pressure drop and likely represents the passing of a high-temperature plume. Large amplitude oscillations appear for a longer interval at the 60 mm location, and while the low-frequency oscillation is still apparent, it has diminished in amplitude. These observed influences led to the development of the localized arc filament plasma actuator system for the base flow studies.

Figure A.13. Schlieren images of DC arc discharge in Mach 4 wind tunnel obtained at 5, 25, 50, 100, 200, and 400 microsecond delays.

Figure A.14. Conditional averages of 15 independent instantaneous (2 μs shutter) images of a DC arc discharge in the Mach 4 wind tunnel for 50 and 100 microsecond delay times.
C. Laser-Induced Breakdown

The laser-induced breakdown plasma results were evaluated using the same three methods as for the DC arc discharge plasma: visible light/emission photographs, instantaneous and conditionally averaged schlieren imaging, and downstream surface static pressure measurements of the perturbed boundary layer. These data were acquired at various intervals from the detection of the laser beam by the photodiode. Figure A.16 shows the four traces as acquired on the oscilloscope by the Hamamatsu PMT. The average full width-half maximum and ramp-up times of the PMT signal for the flow-off case are around 9.1 and 4.0 microseconds, respectively. The average full width-half maximum and ramp-up times of the PMT signal with the Mach 4 flow on are 8.3 and 2.1 microseconds, respectively. The full width-10% maximum is 20.7 and 18.7 microseconds for the flow-off and flow-on cases, respectively, further suggesting a fairly short tail relative to the DC arc discharge. With the flow on, the discharge has a significantly larger standard deviation in intensity as is alluded to by the larger difference between the single and average trace with the flow on as compared to the flow-off case. In other words, there was greater repeatability and consistency over many discharges for the flow-off cases than for the flow-on.

Photographs of the plasma were obtained and superposed to a background image of the wind tunnel for perspective. All of the images were taken with the flow moving from right to left. Six of these images are presented in Figure A.17 for an equal intensity range. The discharge only lasts for six nanoseconds so the plasma duration is much shorter than for the arc discharge. For this reason, the images are presented for both flow-off and flow-on (left to right) for only 2, 5, and 10 microsecond delays (top to bottom). It should be noted that the background intensity is enhanced by several orders of magnitude in order to have both the plasma and the background at approximately the same intensity in one image. Both the initial focused laser beam (which bleeds through due to its high intensity) and emission from the plasma are observed. After the emission has been allowed to convect downstream for 10 μs, the image shows a significant reduction in the plasma emission as it interacts in the boundary layer and travels further downstream. The 5-microsecond instantaneous image clearly shows stronger emission higher in the boundary layer and even marks the high shear region near the wall as the line of plasma is stretched. The images also show that the intensity is much higher but shorter in duration for the flow-off case as compared to the flow-on case. With the flow on, the plasma does not appear to have developed significantly at two microseconds, but has reached a peak by five microseconds.

A similar sequence of 35 images has been conditionally averaged. Similar features are evident as in the instantaneous images with the exception that the unsteady fluctuations of the plasma boundary are averaged out. With the flow on, the turbulent boundary layer velocity profile can be seen slightly in the instantaneous and averaged, five microsecond delay images. However, with the background superposed, it is more difficult to discern so the averaged, five microsecond delay image is shown again on the right in Figure A.16 without the background to better illustrate the velocity profile. The wind tunnel surface can be located approximately by the reflection that is cast from it. The plasma is convected downstream at the local boundary layer velocity, which gives an approximate velocity profile from the leading edge of the convected plasma. Such a technique of viewing the boundary layer, if the plasma is found to have only minimal effects on the flow, has the potential to serve as a boundary layer imaging and investigation technique.
Figure A.15. Pressure fluctuations as measured 40 and 60 mm downstream of a DC arc discharge in a Mach 4 flow.

Averaged, flow-off schlieren images for the laser-induced breakdown discharge experiments are presented in Figure A.18 for 10 and 100 microsecond delays. The schlieren images were acquired with a 2 microsecond shutter, red LED light source, binning by two, and vertical knife edge to highlight horizontal density gradients. A blast wave trailed by an expansion fan is obvious throughout the sequence of images. The heated plume is seen developing in the wake of the focused laser discharge.
Figure A.16. (left) Oscilloscope traces for single and average traces with flow on and off for the laser-induced breakdown and (right) Average emission photograph of laser-induced breakdown in a Mach 4 flow at a 5 microseconds delay without the wind tunnel background image superposed; flow is from right to left. Notice the approximate turbulent boundary layer profile mirrored from the surface of the wind tunnel.

Figure A.17. Emission photography of laser-induced breakdown with wind tunnel background image superposed for perspective. The photographs are obtained with the flow off and on and at 2, 5, and 10 microsecond delays.
Figure A.18. Schlieren photography of laser-induced breakdown with no flow. The photographs are obtained at 10 and 100 microsecond delays.

Instantaneous schlieren images of the laser-induced breakdown in a Mach 4 flow are presented in Figure A.19 for 5, 25, 50, and 100 microsecond delays. Initially, no signs of strong gradients are evident in the image. Very slight Mach waves are visible emanating from the leading edge of the Teflon insert. Upon discharge initiation, the formation of a bow shock is evident in front of the discharge that bends around the plasma. The emission and heated plume of the plasma is evident at 5 microseconds. The laser light is not significantly evident in any of the images because of the 532 nm notch filter that was used to occlude the specific laser wavelength. A light and dark region is seen convecting downstream. The region moves with an approximate convective velocity of 545 meters per second. The upstream portion of the blast wave or bow shock is also convected downstream once the laser-induced plasma dissipates. An apparent dark expansion region also exists directly downstream of the moving wave. Towards the end of the image sequence (100 microsecond delay), the visible effects of the plasma have almost completely disappeared and the shock is starting to dissipate as well.

Figure A.19. Instantaneous schlieren photography of laser-induced breakdown in a Mach 4 flow. The photographs are obtained at 5, 25, 50, and 100 microsecond delays.

Thirty-five independent, instantaneous (2 microsecond shutter) images were acquired for 5, 10, 20, and 100 microsecond delays and conditionally averaged to produce the resultant images of Figure A.20. The effects of the
laser-induced breakdown can be seen more clearly in the averaged images. At five microseconds, the intense emission from the light core can be seen with a strong expansion extending in both directions that is terminated by a strong shock. The upstream shock is the strongest in intensity, while downstream, the density change is smeared over a larger area. The expansion in the vertical direction is not as obvious because of the use of a vertical knife edge. At 10 microseconds, the wave has expanded slightly and begun to convect downstream. The emission has disappeared and a blast wave surrounding the plasma is observed which is deformed by the velocity gradients in the boundary layer. The upstream shock appears more well-defined than the downstream one. At 15 microseconds (not shown) and without the thermal heating effects of the laser, the higher-pressure bubble begins to collapse back on itself. At 20 microseconds, the light and dark regions begin to coalesce and the boundary between the two regions starts to become less distinct. At 30 microseconds (not shown), the disturbance has expanded slightly and the higher temperature region continues to grow and be stretched in the boundary layer. These trends continue as the structure convects downstream. The light and dark regions continue to coalesce and convect downstream at an approximate convective velocity of 545 m/s. The upstream portion of the blast wave, or bow shock, along with an apparent dark expansion region is also convected downstream and into the core flow once the laser-induced plasma dissipates. The downstream weaker disturbance appears to be maintained until almost 100 μs, and is deformed by the boundary layer velocity gradient as time progresses. It convects at approximately 825 m/s, which is significantly higher than the freestream value of 700 m/s. This is likely because of the added momentum imparted to the downstream disturbance in the direction of the flow by the energy deposition and expansion process. Near 100 μs delay, the visible effects of the plasma have almost completely disappeared and the shock is starting to dissipate as well. The process becomes less consistent spatially due to the varying turbulent velocities, and the averaged images begin to smear. In this case, the instantaneous images can be more illuminating. In the instantaneous images, the downstream weaker disturbance appears to be maintained until almost 100 microseconds and is deformed by the boundary layer velocity gradient as time progresses.

Figure A.20. Averaged schlieren photography of laser-induced breakdown in a Mach 4 flow. The photographs are obtained at 5, 10, 20, and 100 microsecond delays.
The pressure traces for the laser-induced breakdown experiments are shown below in an AC form with the average DC pressure amplitude removed. In Figure A.21, the pressure transducers capture the arrival of a shock-expansion wave pair from a laser-induced breakdown that occurs at ambient pressure with no induced flow. The maximum pressure amplitude is about 2-3% of atmospheric pressure. Judging from its arrival time, the shock appears to be traveling at a speed of 400 meters per second, or just above the ambient speed of sound indicating that it is a fairly weak wave. From the schlieren imaging, the later peak could not feasibly be the arrival of a reflected wave from the top surface of the wind tunnel and therefore, must be an artifact of the heated plume. It should also be mentioned that the range of the pressure transducers is from zero to 103.4 kPa (zero to 15 psia), and because this set of experiments was conducted at atmospheric pressure (with the flow off) the pressure transducer located at 60 mm may have been saturated, or at its maximum pressure, or may have a defect, such that it does not detect the arrival of the shock wave. This discrepancy is not noticed on the alternate transducer trace.

![Figure A.21. Pressure fluctuation in kPa as measured 40 and 60 mm downstream of a laser-induced breakdown with no induced flow.](image)

In Figure A.22, two sets of traces are provided for a laser-induced breakdown in a Mach 4 flow. The successive graphs are for the 40 and 60 mm transducers, respectively. One independent trace is presented with the average of five independent traces plotted over the top. With the smaller DC pressure amplitude, the peak amplitude of the AC signal is as much as 30% of the DC pressure amplitude. An artificial anomaly is present in the traces that is first detected less than one microsecond after the laser discharge but peaks at 13 microseconds at the 40 mm location. The implied travel speed would be unphysical for the fluid flow and is likely caused by the plasma formation or initial thermal radiation. As this oscillation dies out, the shock wave and successive expansion waves arrive sequentially at the 40 mm transducer followed by the 60 mm transducer. The lag between the two signals suggests a convective velocity of 715 m/s. The peak at 56 μs for the 40 mm transducer is believed to be associated with the passage of the first downstream shock. At both locations, the shock structure is followed by a lower
pressure series of oscillations, likely expansion waves, but could also be influenced by ringing of the transducer after the shock passes. As a qualitative observation, the signal is primarily composed of “medium-sized” oscillations before the laser pulse. However, after the waves pass by, the 40 mm transducer seems to record a low-frequency pressure drop that may be the passing of a large-scale turbulent structure. No obvious evidence is present to suggest that the medium-frequency oscillations are dissipated during the laser-induced breakdown traces, likely owing to the short duration of influence. Large amplitude oscillations appear for a longer interval at the 60 mm location, and while the low-frequency oscillation is still apparent, it has diminished in amplitude. Further study is needed with larger data sets for signal analysis to confirm if these observations are real.

Figure A.22. Pressure fluctuation in kPa as measured 40 and 60 mm downstream of a laser-induced breakdown in a Mach 4 flow.
6. Conclusion of Plasma Comparison Study

Preliminary results of a plasma/boundary layer interaction study were presented to determine if significant fluid dynamic interactions and mechanisms are present. The aim was to increase understanding of supersonic boundary layer / plasma interaction and to provide a partial justification for why localized arc filament plasma actuators were selected as the actuator of choice for the base flow studies.

Three types of plasmas / plasma actuators were evaluated for their prospective influences: a capacitively-coupled RF discharge that pulses at a frequency of 13.56 MHz, a pulsed plasma from an arc discharge, and a laser-induced optical breakdown. The potential of each actuator and its effect on a Mach 4 supersonic boundary layer are evaluated through emission photography, schlieren imaging, and high-frequency pressure measurements at 40 mm (1.57”) and 60 mm (2.36”) downstream of the discharge. No noticeable fluid dynamic effects were seen from the RF discharge most likely due to its similarity to the dielectric barrier discharges (DBDs) and their weak effect on high-speed flows. The DC arc discharge was found to produce a bow shock from the leading edge of the discharge similar to a tab or transverse jet. The plasma was also convected downstream and was noticeable in schlieren photography up to 7.62 cm (3”) downstream of the discharge. The DC discharge with its longer pulse duration was seen to have an overall disorganizing effect on the turbulent fluid structures. The dominant frequency originally was around 75 kHz, but was smoothed out over a wider range of frequencies with the plasma on. There was also a lower frequency signal that was noticeable after the discharge. The laser-induced breakdown produced a blast wave that collapsed shortly after the termination of the laser pulse. It is theorized that the shorter laser pulse, specifically the shorter ramp-on and ramp-off times, is what leads to the differences between influences in comparison to the DC discharge. After the blast wave collapses, a light and dark pair is noticed in the schlieren images. The light and dark pair, along with the tip of the shock front, convects downstream. The light and dark regions are hypothesized to be a counter-rotating large scale structure that acts to organize the small-scale structures and the frequency of oscillation of the fluid. The light and dark region in the laser-induced breakdown schlieren convects downstream with a speed of 545 m/s. More testing and analysis are necessary to confirm the accuracy of the proposed hypotheses.

From the results presented herein, the DC arc discharge (LAFPA-type) actuator exhibited the best potential for scalability when considering a multi-discharge flow control arrangement. It was clear from these experiments that RF-type discharges, like the glow discharges used in DBDs, would not produce a substantial enough influence on supersonic flow fields to be practical (at least for the tested configuration). The laser-induced breakdown also presented concerns in terms of the practicality and scalability of the energy deposition technique to multiple actuators. Furthermore, the repetition rate of the laser-induced breakdown was severely limited. While the DC arc discharge also exhibited some limitations with regard to EMI and the extent of the flow affected by the plasma, it was deemed the best candidate of the three for scaling to multiple actuators in order to further evaluate its potential for flow control on the supersonic base flow. The DC arc discharge used for the Mach 4 boundary layer experiments was a simple and inexpensive design, but lacked the robustness and repeatability desired for a multi-actuator flow control configuration. Based on the promising potential of the DC arc discharge to influence supersonic flows, additional effort and capital were invested to increase the robustness and repeatability of the
discharges through the construction of the current LAFPA power supply and control system used in the base flow experiments.
APPENDIX A -- REFERENCES


APPENDIX B – SAFETY AND OPERATIONAL PROCEDURES

The below procedures are included to ensure safe and reliable operation of the high-voltage plasma actuator system. The operation and safety protocols were adapted from general lab and electrical safety guidelines, manufacturer recommendations, and guidelines set forth in the equipments’ user manuals. The safety protocol was adapted from the American Heart Association’s CPR course’s emergency response procedure. The most important check to make before working on the cart is to ensure that the HV PS’s HV switch and front panel circuit breaker are off. An additional measure of safety can be provided if the electrical disconnects on the wall are turned off, too. The electrical disconnects are disconnected when the throw lever is down. They can also be locked-out so that no one else can enable them while someone is working on the carts. This is especially important if working on a setup out of direct view of the disconnects. The three-phase plugs do not need to be unplugged from the wall outlet before working on the circuit. It may even be advisable to leave the plug in place as the ground connection is still maintained even when the disconnect is in the “open” position. Before running the cart, be sure to double check for a sound and robust ground connection and that all HV wires are isolated from ground and other LV electrical equipment/wires. The unit can still operate if the circuits are shorted after the resistors, but the PS will trip if its output is shorted directly out of the unit. Also, always be aware of the voltage and current settings on the front of the HV PS.

LAFPA - Operation Protocol
Checklist for Setup, Operation, and Shut Down
Version 4 (March 6, 2012)

SETUP
1. Two people must be in the lab at all times the HV is on.
2. Plug in and turn on the surge protectors.
3. Ensure all cooling fans are operating normally.
4. Check all electrical connections. Ensure solid connections, adequate spacing, and no shorts.
5. Prepare facility / wind tunnel. Ensure facility is grounded and that the cart is grounded to the wall receptacle ground and a good earth ground.
6. Confirm anode and cathode are connected electrically and that ground/power lines are not grounding out on tables, other wires, etc. Ensure all BNC and low-voltage lines are clear of high voltage wires.
7. Turn on 5 V (15 V and 85 V, if necessary) power supplies. Ensure appropriate voltage setting (~5.6 – 6 V), stability of voltage signal, and that the current is adequate to maintain signal. Check jumper between (-) and (gnd).
8. Confirm all appropriate signal connections on the PCB / circuit board box.
9. Turn on function generator. Set desired frequency and duty cycle.
10. Ensure coolant level is adequate and that both valves are fully open (valve handle in line with coolant lines). Then, power on the cooling tower. Slowly close the bypass coolant line ball valve until a flow rate of 1 GPM (3.8 liters per minute) is achieved. The pressure should be around 5 psi (34.5 kPa). Do not allow the pressure to surpass 10 psi (68.9 kPa). Check for leaks. Fix any leaks before proceeding. Do not allow the temperature of the coolant to exceed 100 deg. F. (311 K) (Note: opening both valves initially is preferred rather than leaving them in their previous position because of pressure spikes that can occur during startup.) Note coolant level.
11. Before turning on HV, double check connections, grounds, and leaks. Use a probe to check for continuity for any new configuration.
12. Make sure all shields and guards are in place. Hang the two rubber mats (front and back, with eyelets) from their respective bolts. Be sure to affix the mat to both the top and bottom bolts.
13. Remove discharging ground wires from resistor clips.

**START UP**

14. Make sure all circuit modifications are complete. Unlock/untag the Lock out-Tag out (LOTO) setup from the power disconnect and energize 3-phase power to HV DC PS by throwing switch upward. Do not touch the middle level of the cart after unlocking the LOTO setup.

15. Turn on HV DC PS by flipping the PS’s breaker. Ensure positive polarity. Set voltage and current to appropriate settings. Ensure current limit exceeds desired max.

   - If new electronic configuration, turn the voltage setting to zero and the current setting to .01 A. Slowly, increase voltage being sure to use caution to isolate yourself.

16. Put on the appropriate HV personal protective equipment (HV gloves with leather protectors).

17. Initiate HV on HV DC PS with green push button.

18. Perform a ‘live’ continuity / overload check. Use only one hand to touch components/cart/PS/etc. Monitor for appropriate output signals using the Agilent 1/1000x HV probe.

19. Set facility for desired flow conditions.

20. Acquire required data set.

**SHUT DOWN**

21. Turn off plasma by turning off the HV on the HV DC PS with red push button.

22. Observe the voltage drain to ~0.03 kV on HV DC PS meter.

23. When finished testing or if HV circuit modifications need to be made, turn off the HV DC PS using the front panel breaker.

24. De-energize 3-phase power from wall electrical disconnect by throwing switch down. Be sure to lock out/tag out the disconnect.

25. **CAUTION:** ALLOW ADEQUATE TIME (~ 1 minute for LAFPA capacitor) FOR HV PS CAPACITOR TO DRAIN. CHECK WITH HV PROBE AND MULTIMETER BEFORE TOUCHING.

26. Hook discharging ground wires to resistor clips.

**END OF DAY / FINAL SHUTDOWN**

27. Make sure the HV is off first (including HV PS unit breaker and wall disconnect with lock out-tag out procedure; double check capacitor drainage and any points in question with the HV probe) and then turn off the rest of the power supplies, cooling tower, and surge protectors. Listen for cooling fans and check for any potential leaks that may have developed. Check final coolant level/mark if changed.

**General Plasma Safety Considerations**

1. Put on general personal protective equipment (i.e. safety glasses, etc.)

2. No jewelry, watches, or loose metal objects are allowed to be on your person while working on circuitry or running the actuators.

3. All operators need a safety briefing before beginning work. Once briefed the new operator should sign off that they have received such training.

4. Make sure power supply is off and capacitor is drained before touching hot or ground leads/electrodes.

5. Make sure all circuits are disconnected/turned off/discharged before working on them.

6. Ensure the wind tunnel/work bench is grounded. This can be confirmed with a continuity/resistance test. Redundancy in grounding is encouraged, but use star grounding to eliminate ground loops.

7. Only use one hand when working on any circuits. Put other hand in pocket or behind back.

8. Ensure high-voltage electrode is isolated from potential grounds.

9. Use the electrically insulated gloves and arc flash face shield when running the tunnel or directly probing the HV.

10. Give the DC PS capacitors time (> 10 minutes) to discharge before opening the cover to the PS generator for any reason.

11. Electrical safety gloves need to be periodically air tested for good integrity. They also need to be tested at a lab after six months of use (with a 12 month shelve life).
Safety-Spotter Protocol
Version 2 (March 7, 2012)

This safety protocol document is intended for personnel who act as safety-spotters in the laboratory, but are not necessarily trained for working on or operating high-voltage circuitry.

**General High-Voltage Safety Considerations**

1. Two people must be in the lab at all times the HV is on.
2. Know the emergency procedure (see below) to follow in case of an accident.
3. Know where power switches are located.
4. No jewelry, watches, or loose metal objects are allowed to be on your person while working on circuitry.
5. All personnel need a safety briefing before beginning work.
6. Electrically insulated gloves and arc flash face shield are available for use when directly probing the HV or contacting possible HV components.

**EMERGENCY PROCEDURE:**

In the event of a high-voltage emergency, use common sense to determine the best course of action. Below is a general procedural guideline.

1. Call 911 (9-911 from a campus phone) as soon as is safely possible.
2. Assess the situation and ensure the immediate area is safe.
3. Assume all wires and circuitry components are at high-voltage.
4. Turn off high voltage at power supply and/or de-energize 3-phase power from wall/electrical disconnect by throwing switch down, if accessible.
5. Even though power is off, some components (e.g. capacitors, etc.) may remain charged and at high voltage.
6. If the victim remains in contact with the electrical circuit, use caution.
   - Use electrically insulated gloves to isolate yourself and remove the victim from the circuit.
   - Use insulated rod to remove victim from power source.
7. Administer CPR, if necessary.
8. Administer other first aid, as necessary.
Safety and Electro-Magnetic Interference: Lessons Learned

The following safety and EMI recommendations are compiled to ensure safe and frustration-free operation of the LAFPA power supply cart in the future. First and foremost, a lock-out/tag-out procedure should always be observed for the electrical disconnects before working on the high-voltage electronics. Furthermore, the HV power should be off for at least a minute before making modifications to the circuit. This is to ensure that the high-voltage capacitors have fully been drained by their internal bleed resistors. The voltage should be allowed to drop to less than 20 V (0.020 kV). Confirmation of the appropriate voltages can be made on the front panel display or with the HV probe before making modifications to the circuit. When probing a live circuit, use caution. Only one hand should be used in order to minimize the risk of cardiac arrest from passing a current across one’s chest.

While the resistance of human skin varies wildly with conditions such as dryness, perspiration, damaged skin, etc., the human body exhibits a resistance of approximately single-digit kΩ. Thus, a 20 V differential will only produce a mA or so of current in the body, which is the generally accepted lower level of human sensation. However, a current as small as 50-60 mA can cause ventricular fibrillation. This is especially so for AC current. Generally, several hundred mA are necessary to produce the same effect for DC current. From this comparison, it is apparent that the gap between human sensation and lethality is very small. Add to this the fact that the presence of a dangerous voltage typically eludes human detection as it produces no sound, smell, or visual cues to alert an operator of such a hazard. As such, it is of critical importance to be aware of the dangers and anticipate the risks before ever touching a circuit. For this reason, the lab is equipped with the appropriate personal protective equipment, like high-voltage gloves and face shields. The high-voltage gloves should be periodically air-tested to ensure that there are not any cuts or tears in the glove material. The leather glove covers also help prevent such cuts or tears. Either way, the gloves should be recertified on a six month schedule (with a 12 month shelf life contingency). It is also a good idea to always keep the HV barriers in place when the system is operational and to work with a partner in the lab in the event of an accident.

As for the cart itself, the liquid cooling connections on the HV switches are only rated to 100 kPa (15 psig) and, as such, extra caution should be exercised in turning on the cooling tower to prevent over-pressurization that could result in nuisance leaks. The 5 V PS should be driven at no more than 6 V for the sake of the internal PCB components. Additionally, the HV PS has isolation between the LV and HV sides of the unit. If the unit will not turn on or power up, it is likely a fault of the incoming power connection or possibly a fuse on the LV circuit that can be replaced by the user. Use extra caution to ensure that the internal circuitry is discharged before working inside the HV PS. More information can be found in Appendix C or in the user manuals.

The electro-magnetic interference (EMI) of any plasma can be a serious impediment to data transmission and acquisition. It was, after all, plasma that caused radio blackout during re-entry of the Apollo missions. While significant improvements have been made in this field, a thorough understanding of plasma noise physics is still elusive. Several general statements can be made, though, that were a result of many hours of testing. Originally, long cables that isolated the user and sensitive electronic equipment were deemed a likely remedy to the EMI problems experienced. However, long cables and Faraday cages have not shown much promise in past experience with the LAFPA system. The majority of debilitating noise issues were generally tracked back to long BNC cables.
connecting different parts of the experiment. An expensive and timely effort to produce in-house quad-shield BNC cables yielded no positive improvements. The addition of ferrites (affectionately called “magic doughnuts”) occasionally would solve some problems when the system/computer would only experience the occasional noise issue, but typically would not fix more serious problems, like if the system crashed immediately after plasma initiation. When the LAFPA system was first built and tested, the entire computer OS would crash at first discharge of a single actuator. Currently, with eight actuators operating at 1 A and frequencies varying from 1-100 kHz, the worst problems experienced are generally a disabled mouse because of USB connection corruption. Some mice, USB cables, and computer systems seem to be better shielded than others, though.

A higher breakdown voltage seems to cause more noise. Therefore, operating at higher frequency, current, and/or lower pressure reduces noise by reducing the breakdown voltage. The majority of the noise is seemingly due to the initiation of the plasma rather than the sustained discharge portion of the plasma. While this fact cannot be directly observed, it was deduced from several observations. When the plasma would cause problems with the computer, it would usually do so immediately after the first discharge. Once the plasma has been maintained for a few seconds, the likelihood of a computer crash decreased rapidly. It was also noticed that the first breakdown would generally occur at a higher voltage than subsequent breakdowns due to residual ionization or increased electrode temperature. Whatever the reason for the reduction in breakdown voltage, the electronics were not as susceptible to those later discharges. Yet, from a voltage and current perspective, the only thing that changed between them was the magnitude of the initial breakdown voltage spike. Therefore, it was reasoned that the first breakdown that required a stronger electric field likely also generated more EMI than the later breakdowns. The observation of increased EMI from high-voltage breakdowns is consistent with the moment of highest light output intensity as well. This is likely because there is a correlation between the emission of both types of electro-magnetic radiation.

Significant improvements to noise susceptibility can be made by using star grounding principles. This practice encourages an experimenter to connect all points of ground to the same single ground line rather than making several various points of connection that can result in ground loops. Always be sure the single ground connection is a very sound connection, though, as this discourages redundant ground connections. It is also of a high value to keep HV lines as short as possible to minimize the electric field lines emitted from the wires as the current passes through them and to keep the inductance (i.e., circuit time constant) to a minimum as well.

Solid-body resistors help enormously over wire-wound resistors. Although not necessary currently for plasma experiments, a fiber optic transmitter and receiver circuit has been designed by Nachiket Kale that can replace long BNC cables to break-up ground loops and the noise transmitted on the outer ground sheath of BNC cables. A schematic of the circuits from his upcoming dissertation entitled “Active and Hybrid Flow Control in S-Ducts and Diffusers” is included (with permission) in Figure B.1. The unit is in its second design iteration, and each end of the circuit is powered by a 9V battery. Battery-powered operation was selected over AC outlet operation to de-couple potential ground loops and reduce the inherent EMI transferred from the power supply to the circuit.
The latest 4 channel fiber optic board can even transmit timing signals to the HV switches directly as the output from the fiber optic receiver has been designed to be compatible with the switches. In the ideal configuration, the transmitter receives a TTL signal over a short BNC cable from a pulse generator. The digital signal is converted to light that is then transferred through a fiber optic cable over long distances (up to 50 m with 1 mm diameter optical fiber) to the receiver circuit. The fiber optic output device can produce light pulses that range in frequency from continuous to 10 MBd (10$^7$ baud or pulses per second) at a wavelength of 650 nm. The receiver circuit converts the fiber optic light signal back to a 5 V TTL signal that, along with the ground and 5 V DC signals, is channeled directly to the switch inputs. In this way, the switches can be actuated at very high repetition rates (up to their maximum frequency of 100 kHz) over a fiber optic cable that has demonstrated a high level of EMI resistance. The two circuits are smaller than the standard PCB currently in use (5.97 cm x 3.18 cm and 4.70 cm x 3.18 cm vs. 24.8 cm x 10.2 cm), but are a little more complicated to use for other reasons, as there are extra connections and the batteries occasionally need to be replaced. In general, the design vastly improves noise problems, though, and should be considered if persistent issues are encountered.

In the end, closer equipment and shorter cables have shown to be more noise impervious than large spacing and longer cabling. Originally, experiments were conducted with spectrometers and cameras in the other room. Now, it is possible to obtain schlieren, PIV, or spectroscopy data with the camera only a few feet away from the plasma.

Figure B.1. Fiber optic transmitter and receiver circuit schematic for four (4) channel printed circuit board (PCB) used for LAFPA control; designed by Nachiket Kale and used with permission.
APPENDIX C – PLASMA ACTUATOR BASE APPARATUS DRAWINGS

The following images are presented to better illuminate the details of the design used in the various stages of testing. Figures C.1-3 show several views of the same four actuator geometries from differing perspectives. Figures C.4-7 show various angles of the four-actuator assembly with different components made transparent to better illustrate the internal configuration of the assembly. Figure C.8 presents an exploded view of the brass afterbody, BN inserts, aluminum base plate, stainless steel dowels, and steel retaining rod. Figures C.9-13 show two-dimensional dimensioned drawings used in the manufacture of the different components. These five figures also occasionally use perspective views or section views for clarity. The drawings, in order of appearance, are the eight-actuator aluminum base plate, eight-actuator BN inserts, four-actuator aluminum base plate, four-actuator BN inserts, and the all BN base plate that failed during preliminary testing.

Figure C.1. Transparent view of the various actuator configurations machined into the boron nitride base plate that is used in the electric arc base flow assembly. The four configurations shown, clockwise from top-left, are “normal cavity”, “flush”, “chamfered”, and “inclined cavity”.
Figure C.2. Transparent section view of the various actuator configurations machined into the boron nitride base plate that is used in the electric arc base flow assembly. The four configurations shown, clockwise from top-left, are “normal cavity”, “flush”, “chamfered”, and “inclined cavity”.

Figure C.3. Three-dimensional view of the various actuator configurations machined into the boron nitride base plate that is used in the electric arc base flow assembly. The four configurations shown, clockwise from top-left, are “chamfered”, “flush”, “normal cavity”, and “inclined cavity”.

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Figure C.4. Close-up image of the back side of the four-actuator electrode configuration study model looking through a transparent brass afterbody. The blue inserts are actually made of BN.

Figure C.5. Image of the four-actuator electric arc base flow assembly with transparent brass afterbody. Notice the electrode paths highlighted on the bottom insert and the retaining rod. The blue inserts are actually made of BN.
Figure C.6. Image of the base of the four-actuator electrode configuration study model with a transparent brass afterbody. The base pressure taps are highlighted. The blue inserts are actually made of BN.

Figure C.7. Image looking through a transparent Al base for the four-actuator electrode configuration study model. The transparent blue inserts are actually made of BN.
Figure C.8. Exploded view of the eight-actuator base flow control model highlighting axial retaining rod, brass afterbody, 8 BN inserts (transparent blue), mating dowel pins, and Al base plate.
Figure C.9. Two-dimensional dimensioned drawing of eight-actuator aluminum base plate.
Figure C.10. Two-dimensional dimensioned drawing of eight-actuator BN inserts.
Figure C.11. Two-dimensional dimensioned drawing of four-actuator aluminum base plate.
Figure C.12. Two-dimensional dimensioned drawing of four-actuator BN inserts.
Figure C.13. Two-dimensional dimensioned drawing of four-actuator all BN base plate.
1. **PIV Uncertainty Introduction**

Particle image velocimetry (PIV) is an established optical diagnostic technique that can effectively and efficiently measure the velocity of a fluid within a flow field. For the basic single-camera PIV arrangement, the method estimates the two components $u$ and $v$ of the velocity $\mathbf{u} = (u, v, w)$ in a plane from:

\[
\begin{align*}
    u(x, y, t) &= \frac{\Delta x(x, y, t)}{\Delta t} \\
    v(x, y, t) &= \frac{\Delta y(x, y, t)}{\Delta t}
\end{align*}
\]  

where $\Delta x$ and $\Delta y$ are the average displacements of markers located within an interrogation region over a time interval $\Delta t$.\(^1\) Broadly speaking, small tracking particles are introduced into a flow and are tracked statistically by correlation analysis between two images acquired at a short time delay apart. The particles can be solids suspended in gases or liquids, gaseous bubbles in liquids, liquid droplets in gases, or immiscible liquids.\(^1\) The particles are illuminated successively by a laser light sheet, and the scattered laser light is then imaged by a photodetector, such as a CCD. The images are subsequently transferred to a computer for analysis. An illustration of a typical planar PIV system and associated image analysis is shown in Fig. D.1. In an effort to contribute to the state-of-the-art of particle image velocimetry (PIV) uncertainty analysis, a concerted effort was undertaken to develop a general and practical method to estimate the uncertainty contributions from several different and independent sources. One key point of this analysis is that instead of reporting a single uncertainty value for the entire flow, the developed technique estimates the unique uncertainty at every interrogation region based on the local flow conditions. Then, the maximum, mean, or median uncertainty values can be reported. The technique was originally developed and reported on by Lazar et al.,\(^2\) and is implemented here for the supersonic base flow.

While many PIV techniques and systems have been developed, there has only been limited success in establishing a standard tool for evaluating the associated uncertainty because of the difficulty and situational dependency.\(^3\) The accuracy of velocity measurements obtained from PIV data is a composite of the ability of the seed particles to follow the flow and for the imaging system and analysis procedure to record and process a field of particle images.\(^4\) In quantifying the accuracy, a number of factors should be considered, such as the number of samples obtained, turbulence intensity of the flow, processing algorithm, reliability and accuracy of equipment used, and tracking particle size.\(^5\) To this end, the following procedure describes a practical method for uncertainty analysis of velocity measurements obtained by PIV. It is intended that the steps detailed here will provide a set of tools to evaluate the accuracy of PIV measurements for general flow fields. However, while this error/uncertainty analysis
analysis should be sufficient for most investigations, it falls short of encompassing all sources of uncertainty or error. It attempts to provide a guide on how to lower the uncertainty as much as possible a priori by following tips for acquiring good quality data. It also is intended as a guide on predicting the largest residual contributing sources of error or uncertainty for a given configuration. Subsequently, the technique intends to provide reasonable estimates of the remaining large sources of uncertainty that can feasibly be estimated, and to do so in a timely, and less tedious fashion than a full and more thorough analysis of all sources of uncertainty, regardless of their relative size of contribution. In some cases, additional sources of uncertainty not discussed here may need to be evaluated. The PIV uncertainties considered here will be limited to: equipment, particle dynamics, sampling, and processing algorithm of the image pairs. A flow chart outlining sources of variation and parameters that affect the overall uncertainty is presented in Fig. D.2.

Fig. D.2. PIV uncertainty tree diagram.

Mathematically, the uncertainty in a measurement can be estimated on the basis of the uncertainties of the variables that make up the measurement. In the case of PIV, these variables are the components used to construct and evaluate the particle images. Following a typical uncertainty analysis, a measurement \( V \) can be expressed as a function of the independent variables \( y_1, y_2, y_3, \ldots, y_n \).
\[ V = V(y_1, y_2, y_3, \ldots, y_n) \]  

Let \( w_V \) be the uncertainty in the measurement \( V \) and \( w_1, w_2, \ldots, w_n \) be the uncertainties in the independent variables \( (y_i) \). Assuming that the uncertainties in the independent variables are each given with the same probability, then the uncertainty in the measurement is expressed as:

\[
w_V = \sqrt{\left( \frac{\partial V}{\partial y_1} w_1 \right)^2 + \left( \frac{\partial V}{\partial y_2} w_2 \right)^2 + \ldots + \left( \frac{\partial V}{\partial y_n} w_n \right)^2}.
\]  

Equation (D.3) can be used to link together the uncertainties generated from several independent sources and to provide an estimate for the overall measurement uncertainty.

2. Sources of Uncertainty

A. Equipment

The equipment uncertainty was analyzed according to the procedure outlined in Ref. 2. In the procedure, the six contributors to the equipment uncertainty that are typically most significant are summarized and combined to form an estimate of the total equipment uncertainty. The root-sum-square (RSS) formula used to combine the uncertainties is:

\[
w_u = \sqrt{\left( \frac{\partial u}{\partial l} w_l \right)^2 + \left( \frac{\partial u}{\partial L} w_{L_1} \right)^2 + \left( \frac{\partial u}{\partial \lambda} w_{L_2} \right)^2 + \left( \frac{\partial u}{\partial \lambda} w_{L_3} \right)^2 + \left( \frac{\partial u}{\partial \Delta t} w_{L_4} \right)^2 + \left( \frac{\partial u}{\partial \Delta t} w_{L_5} \right)^2}.
\]  

where \( \bar{u} \) is the PIV velocity measurement in a pixel-time reference frame and \( \Delta t \) is the laser pulse time separation. Descriptions of other relevant variables in Eqn. (D.5) are summarized in Table D.1. Table D.1 also lists the values used in the calculation for the independent variables and major contributing uncertainty components. Each term (from left to right) in the two equations above represents in variable form the six equipment uncertainty sources highlighted at the bottom of Fig. D.2 (from left to right). They represent the uncertainty contributed from the (1) calibration scale physical length, (2) calibration scale image plane length, (3) image distortion due to aberrations, (4) distance from the calibration scale to the lens, (5) laser pulse timing, and (6) accuracy of the delay generator.

Velocity component uncertainty contour plots non-dimensionalized by freestream velocity are presented in Fig. D.3. In non-dimensional coordinates normalized by the local fluid (or more appropriately, particle) velocity (not shown here), the equipment uncertainty is spatially uniform and is about 0.6%. The maximum uncertainty when normalized by the freestream velocity is also approximately 0.6%. When equipment uncertainty is normalized by the constant freestream, it takes on a spatial dependence in accordance with the local particle displacement (Fig. 181)
In general, the equipment uncertainty at most locations not in the high-speed freestream is small (less than 0.2%).

Table D.1. Summary of equipment uncertainty parameters.

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Description</th>
<th>$y_i$</th>
<th>$w_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>$l$</td>
<td>Calibration scale physical length</td>
<td>50 mm</td>
<td>100 µm</td>
</tr>
<tr>
<td></td>
<td>$L_1$</td>
<td>Calibration scale image plane length</td>
<td>1074 pixels</td>
<td>1 pixel</td>
</tr>
<tr>
<td></td>
<td>$L_2$</td>
<td>Image distortion due to aberrations</td>
<td>1074 pixels</td>
<td>5.37 pixels</td>
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<tr>
<td></td>
<td>$\lambda$</td>
<td>Distance from calibration scale to lens</td>
<td>700 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>Timing</td>
<td>$t_1$</td>
<td>Laser pulse timing</td>
<td>2000 ns</td>
<td>1 ns</td>
</tr>
<tr>
<td></td>
<td>$t_2$</td>
<td>Accuracy of delay generator</td>
<td>2000 ns</td>
<td>1.5 ns</td>
</tr>
</tbody>
</table>

Fig. D.3. PIV equipment uncertainties as a percent of the freestream speed for the (left) streamwise and (right) transverse directions for the base flow velocity field.

B. Particle Dynamics

The particle dynamics uncertainty was also analyzed according to the procedure outlined in Ref. 2. In the procedure, Newton’s second law is used to equate the sum of all forces $F$ acting on a seed particle to the product of its mass ($m_p$) and acceleration ($a_p$). The sum of forces acting on the particle can be written as:

$$\sum F = F_{SD} + F_g + F_b + F_p + F_{vm} + F_B + F_{Ma} + F_S + F_{TH}$$

where the forces considered are the Stokes drag force ($F_{SD}$), gravity force ($F_g$), buoyancy force ($F_b$), pressure gradient force ($F_p$), virtual mass force ($F_{vm}$), Bassett force ($F_B$), Magnus force ($F_{Ma}$), Saffman force ($F_S$), and thermophoretic force ($F_{TH}$). Several simplifications are made to the above equation that are primarily a consequence
of typical seed particle densities being several orders of magnitude higher than the fluid density. With these simplifications, the above equation reduces to:

\[ \sum F \approx F_{SD} = m_p a_p. \]  \hspace{1cm} (D.7)

Furthermore, Ref. 2 enumerates several assumptions and simplifications used to then arrive at a closed-form estimate of the particle dynamics uncertainty. The particle dynamics uncertainty is estimated in terms of the particle slip, or fluid-particle velocity differential. The resultant equation for the particle slip, \( u_f - u_p \), is:

\[ u_f - u_p = \frac{1}{18} \frac{\rho_p d_p^2}{\mu_f} \left( \frac{\partial u_p}{\partial x_p} \frac{dx_p}{dt} + \frac{\partial u_p}{\partial y_p} \frac{dy_p}{dt} \right). \]  \hspace{1cm} (D.8)

where \( \mu_f \) is the fluid viscosity and \( \rho_p \) and \( d_p \) are the particle density and diameter, respectively. A particle diameter and density of 0.25 microns and 875 kg/m\(^2\), respectively, were used for the calculations. The subscripts \( f \) and \( p \) are used to denote fluid and particle properties, respectively. The viscosity of the fluid is estimated locally with Sutherland’s equation. The temperature field is computed for use in Sutherland’s law from adiabatic relations as the flow is nearly isoenergetic. The time derivative of the particle location is known as it is equal to the velocity measured by the PIV technique. The spatial derivative of the particle velocity was also estimated from the PIV data by computing the derivative with a second-order central difference method.

Contour plots of the particle dynamics uncertainty for each velocity component are shown in Fig. D.4. The average and maximum slip speed were computed to be about 0.5 m/s and 10 m/s, respectively. Non-dimensionalized by the freestream velocity, these values correlate to less than 0.1% and 2% uncertainty for the mean and maximum, respectively. Undoubtedly, some of the particle tracking behavior and dynamics are lost by performing this analysis on the average flow field (and not on the instantaneous). Therefore, the true slip velocity may be larger in highly turbulent regions. However, the analysis definitely highlights regions of increased uncertainty due to the effect of velocity gradients on particle tracking.

C. Sampling

In order to accurately measure mean and turbulence quantities by PIV, a sufficient number of image pairs is required. In practice, fluid measurements generally are reported as time-averaged velocity quantities at multiple points in space. In forming PIV measurements of this type, instantaneous data are ensemble-averaged in an identical spatial window over multiple images recorded at random or independent instances in time. In a turbulent flow, individual realizations can be assumed to be normally distributed, and statistical sampling theory can be used to obtain estimates of the uncertainty. It is essential to provide a confidence interval for the uncertainty estimates since it is of little value to provide uncertainty estimates so large that they encompass all possible measurement values. Instead, it is more useful to specify a sampling uncertainty and then also specify a certainty, or probability, that the actual measurement value will fall within the defined limits. Fortunately, this idea is an integral part of the definition of standard deviation, also known as root-mean-square deviation. Specifying the standard deviation for a normally distributed variable asserts a probability that a sample will fall within a range of one standard deviation from the mean for roughly 68% of the samples. This confidence level increases to 95% for a range spanning two
standard deviations from the mean. In general, the likelihood of sampling a velocity at a certain confidence level around the sample mean $\bar{V}$ for a sample of size $n$ and standard deviation $\sigma$ can be expressed as

$$\bar{V} \pm \frac{z_c \sigma}{\sqrt{n}}$$  \hspace{1cm} (D.9)

where $z_c$ is the confidence coefficient or critical value and can be determined from normal distribution tables. The term $\sigma$ in this expression is known as the fluctuating velocity or RMS deviation since it is representative of the fluctuations inherent in the flow at a given location. The standard deviation for a sample of the population can be expressed as

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (V_i - \bar{V})^2}{n - 1}}$$ \hspace{1cm} (D.10)

Furthermore, the standard deviation of the mean $\bar{\sigma}$, or standard error, can conveniently be expressed by

$$\bar{\sigma} = \frac{\sigma}{\sqrt{n}}$$ \hspace{1cm} (D.11)

which sets a range within which the true mean or any future sample mean would lie with a given confidence level or likelihood. With these formulas, one can adequately estimate the uncertainty of mean PIV velocity vector measurements due to sampling. However, many PIV processing programs already compute the root-mean-square (RMS) deviation velocity, which is equivalent to computing the standard deviation of the velocities at every interrogation spot. DPIVB and LaVision’s DaVis, for example, are two programs that can perform such an analysis. This feature was used on 170 vector fields (actually, $n$ was equal to 165; 5 vector fields were manually removed due to obviously erroneous data caused by sensor saturation) from the four-actuator data sets, and the results are displayed in Fig. D.5 for a confidence coefficient of one (68% confidence). The average sampling uncertainty computed for the 30,000 vector locations in the PIV velocity field is 0.85%; the median is 1.1%. The maximum sampling uncertainty is 2.3%. Put another way, the percent of the 30,000 locations with sampling uncertainty magnitudes (root-sum-square [RSS] of the streamwise and transverse components) over 1% and 2% of the freestream velocity is 46% and 0.15%, respectively.

D. Image Analysis

The processing procedure used in analyzing PIV data is a critical step in the analysis process, as it couples with the image-acquisition process to determine the accuracy, reliability, and spatial-resolution of the measurements. Many processing procedures have been developed and applied to various flow fields, including the cross-correlation technique, four-step particle tracking, etc. However, while the effectiveness of the techniques has been analyzed by the developers, there is a need for a general approach to evaluate them for a broad range of studies, particularly the variety of pre- and post-processing algorithms and filtering procedures that are utilized. It would be of value to provide a methodology to evaluate the uncertainty for general flow fields investigated using PIV.
I. Technical Suggestions and Experimental Guidelines

Since the inception of the PIV technique and the subsequent advent of digital PIV and spurred on by rapid advances in digital camera and computer processing technology, much effort has recently been directed toward understanding and improving the processing algorithm used to transform the particle images into meaningful and quantitative velocity fields. Noteworthy initiatives include the optimization of various PIV parameters, such as particle image size, particle seeding density, window size, particle displacements, etc., reduction of mean bias and peak-locking errors, improvement of the accuracy of sub-pixel estimators, and the introduction of image deformation techniques to improve results in regions of strong velocity gradients. These categories will each be elaborated upon sequentially in the following paragraphs. While theory, experimentation, and computational models have all had significant influences on the field, the Monte Carlo method (synthetic PIV) has quite possibly been the most widely used technique of all. Generally, synthetic PIV has been used to establish ideal values and guidelines to minimize error during PIV acquisition and as a test bed for simulation or for comparing new ideas or novel techniques.

Fig. D.4. Slip velocities as percent of freestream for (left) streamwise and (right) transverse velocity components for the base flow velocity field.
It is generally accepted that increasing particle density is beneficial to the overall correlation accuracy as long as the particles do not begin to occlude each other or alter the fluid motion. Every particle that can be reasonably correlated with itself in the second image essentially adds to the ensemble average of the local velocity value. Raffel et al. showed that the optimal particle image size is between 2.0 and 2.5 pixels for cross-correlation techniques, as this value maximizes the signal-to-noise ratio for the sub-pixel interpolation schemes while minimizing peak-locking errors and allowing adequate particle numbers within the interrogation spot. The term peak-locking error is used to describe the tendency, most commonly introduced by the sub-pixel interpolation schemes, for particle image displacements to more frequently be computed as integer values. It can be caused by insufficiently large particles that do not allow the interpolation scheme to determine the displacement more accurately than to an integer value. It is generally well accepted that correlation noise, and thus error, scales with particle diameter. The uncertainty in particle displacement is typically less than 5-10% of the particle diameter. Thus, the dynamic velocity range can be maximized by an in-plane displacement of roughly one-quarter the interrogation window size (7-8 pixels for a 32x32 interrogation window). Furthermore, the out-of-plane motion should be limited so that particles have no more than the time to traverse a quarter of the laser sheet thickness in the duration between laser pulses. This is to limit out-of-plane loss of particles and to keep the particle image intensities from altering significantly, as a drop in intensity corresponds to a drop in correlation. Nobach and Bodenschatz reported that the intensity variations induced by out-of-plane particle velocities can contribute displacement errors on the order of 0.1 pixels. Currently, the dynamic velocity range for PIV is in the range of 100-200, which
generally constrains the lowest possible uncertainty to around 0.5% of the freestream velocity. Significant improvements to the dynamic velocity range could significantly improve the utility and reduce the uncertainty of the PIV technique.

Westerweel et al. established the benefit of window shifting to reduce RMS errors. To perform such a window-shifting technique, an original estimate of the integer pixel displacement is determined without a window shift and then a subsequent cross-correlation is computed with the shift. This reduces errors by increasing the likelihood of a particle match, thus making the correlation peak more detectable. While peak-locking errors are minimized by use of appropriately sized particles in the image plane and by using an appropriate sub-pixel interpolation scheme, more elaborate methods have been developed to correct for such errors. The mean bias error, which typically tends to underestimate the measured displacement as a result of an increased likelihood of loss of high-speed particle pairs, can be reduced or eliminated by various techniques such as zero-padding, using weighting functions, using different size interrogation windows, or even by such ideas as Gaussian window masks. On the topic of sub-pixel interpolation, a Gaussian curve fit method is used predominantly because of its simplicity and relatively high accuracy. However, if increased returns are desired in accuracy, improvements in the sub-pixel interpolator are imperative. Such improvements, like the more computationally intensive Whittaker (also cardinal or sinc) interpolation, were proposed and studied by Nobach et al., Roesgen, Westerweel, and Lourenco et al.

In addition to general guidelines on the primary parameters of PIV, higher-level techniques have been proposed for a variety of corrections to the processing algorithm. One such item for which a significant number of researchers have proposed correction techniques is windowing. Improved windowing techniques are of benefit, because the computationally efficient Fast-Fourier Transform (FFT) that is used in most cross-correlation algorithms is subject to certain Fourier-based errors, known as spectral leakage and wraparound aliasing. Putman et al. evaluated the error due to the partial image created by segmenting the image into interrogation regions; Scarano investigated the benefits of non-isotropic spatial resolution; and Eckstein et al. and Florio et al. studied various other advances in windowing techniques. General overviews on ways to reduce uncertainty in PIV are given by Beresh, Piirto et al., Roth et al., Fincham et al., and Hart.

One final topic that deserves further elaboration is the effect of velocity gradients on the PIV interrogation technique. Velocity gradients within the interrogation domain that cause variations in displacement that are less than the mean particle image diameter will usually have relatively small effects. However, a velocity gradient across an interrogation window will tend to bias the measured velocity attributed to the center of the window. The velocity sampled will not be representative of the velocity at the center of the interrogation spot. Since the displacement information is slightly different for each particle, the correlation peak will be reduced in intensity and more disperse. Meunier et al. showed that a single component of the error introduced by velocity gradients can reach one pixel in magnitude (for a single window shift technique). As a result, techniques implementing iterative shift and window deformation or image deformation/distortion have been introduced to try to accommodate for the dispersion of the correlation peak. Using initial estimates, the velocity derivative in the spot can be estimated and the window or image deformed to accommodate for the known particle displacement changes in a consistent way. These advanced techniques have shown the capability to reduce errors by an order of magnitude in
simulations, but have also been shown to slightly underperform such a significant reduction estimate in actual experiments.\textsuperscript{45} It was later noted that the errors around velocity gradients exacerbated errors further in turbulence statistics. As a result, the image deformation/distortion technique has been well accepted, and further developments of this technique and its introduction into commercial software subsequently followed.\textsuperscript{46-49}

II. Experimental Technique

As outlined above, current PIV processing techniques, or algorithms, are varied and complex in nature. Their differences are further emphasized by the various post-processing filters and interpolation techniques employed to improve accuracy, minimize particle loss, and remove spurious vectors. Therefore, in order to create a method to evaluate the different PIV processing techniques that is both practical and universal, a synthetic PIV program was created within a MATLAB environment that would allow end users to evaluate the performance of their unique algorithm for their unique flow conditions, including control and variation of particle density, particle translation, particle size, peak intensity, background noise, and spanwise velocity (normal to the laser sheet). The synthetic PIV program can also aid in evaluating the performance of various algorithm parameters such as interrogation spot size, overlap, filters, interpolation techniques, and interrogation spot deformation methods. As was mentioned previously, synthetic PIV has seen increased use in recent years to evaluate so-called standard images with a known feature, such as a certain velocity gradient, particle density, particle size, etc.\textsuperscript{350-52} However, the synthetic PIV program created in this work is designed to analyze not only a very specific, or standard, set of parameters, but also to be capable of performing synthetic PIV for a realistic velocity field for an actual flow involving complicated fluid dynamic structures such as vortices, bow shocks, shear layers, etc. By introducing this capability, users are able to evaluate initial PIV data to gain valuable insight into the performance of their PIV algorithm given their current parameters and the locations of highest uncertainty and therefore highest concern, or to gain an idea of the uncertainty introduced by their algorithm for the features of their respective flow.

The generation of synthetic PIV images follows a technique outlined by Raffel et al.\textsuperscript{15} First, particle images are generated in an 8-bit image through the use of a random number generator to specify the three-axis location of the center of each particle \((x_0, y_0, z_0)\) and the light intensity distribution emitted by each particle (approximation of the Airy function) of diameter \(d_p\) using the formula

\[
I(x, y) = I_0 \exp \left\{ -\frac{(x - x_0)^2 - (y - y_0)^2}{(\frac{1}{8}) d_p^2} \right\} \quad (D.12)
\]

This equation assumes that the particle intensity profile is roughly a Gaussian bell, and that roughly 95\% of the scattered light is found within the particle diameter. The synthetic images used randomly distributed particles to create an even particle distribution throughout the image. The synthetic images did not re-create the non-uniform particle distribution observed in the shear layer of the actual images. The intensity \(I_0\) can be related to the \(z\)-axis location of the particle relative to the light sheet, or spanwise axis, through the formula

\[
I_0(z) = I_{\text{max}} q \exp \left\{ -\frac{z^2}{(\frac{1}{8}) Z^2} \right\} \quad (D.13)
\]
where $I_{max}$ is the maximum possible peak intensity, $q$ is the particle’s light scattering efficiency, and $Z$ is the laser sheet thickness measured at the $e^{-2}$ intensity values. The peak intensity of the light sheet is assumed at $z = 0$. A top-hat laser intensity shape can be used for simplicity also. With this formulation for the peak intensity, a z-axis velocity can be introduced to represent loss and introduction of particles out-of-plane and, therefore, to simulate a more realistic introduction of noise due to non-ideal particle dynamics.

Image-processing techniques, such as bilinear interpolation, can then be used to smooth a predetermined velocity field, such as vectors from a previous PIV acquisition, back to the original camera resolution. In this experiment, vectors were assumed to be representative of the velocity at the center of the interrogation region. Extra care must be exercised to interpolate the velocity field back to its realistic state. For example, the edges must be taken into account, especially if overlap is used, as bilinear interpolation will evenly distribute the particles over the specified resolution. One additional item to note is that edge vector quantities are extrapolated out to match the simulated CCD resolution since there are no values to interpolate between outside of these values. Once the higher resolution velocity field has been established, the particles, based on their central point, can be translated in both directions by the velocity of the nearest pixel to each particle’s center. Finally, the intensity distributions can be re-created from the above formulas. Two example synthetic PIV images are shown below in Fig. D.6 for differing magnifications and for a particle diameter of three pixels (standard deviation of one pixel) and 5% noise (standard deviation of 1%). The performance of the technique was evaluated in greater detail in a work by Lazar et al.$^2$

![Example subregion of the synthetic PIV image used in this investigation for (left) far-field and (right) zoomed-in region.](image)

**III. Experimental Results**

Thirty synthetic PIV images were produced and processed by LaVision’s DaVis processing program for the base flow field mentioned and used earlier. The simulated velocity field was obtained from a previous PIV data set of 170 realizations, but only 165 realizations were ultimately used because of separated oil globules in 5 of the images that caused sensor saturation and obviously bad vector data. The PIV data were originally obtained at 1200x1600 pixel resolution. By evaluating this with 16x16 pixel interrogation spots with 50% overlap, a synthetic
mean velocity field of 150x200 vectors was obtained (DaVis buffers the edge to add one more vector than normal in each direction; however, all of the edge vectors are removed [i.e., set to 0]). Parameters of specific importance to the creation of the synthetic images were median, mean, and maximum displacements of 4.6, 10.1, and 25.4 pixels, respectively, three pixel diameter particles on average with a standard deviation of one and a minimum and maximum particle size of one and five pixels, respectively, 5% background, 1% noise, and a constant spanwise velocity that displaced the particles 16% of the laser sheet thickness. The DaVis program was set to limit the allowable vector range and required a minimum peak Q ratio. It iteratively replaced bad vectors with the 2nd, 3rd, 4th, or 5th highest peaks based upon the difference between the new value and the median of the neighboring vectors. The processing used 8 passes, 50% overlap, and no weighting function at the 64x64 and 32x32 levels and 2 passes, 50% overlap, and an adaptive PIV technique with Lanczos reconstruction at the 16x16 level. No zero padding was applied. It should be mentioned that the scenario represented by this synthetic PIV simulation is somewhat idealized and has neglected some potential sources of uncertainty, such as non-uniform particle seeding density and curvature effects. However, curvature effects are neglected by all two-image PIV systems so this is not a fault of this system alone. It should also be noted that this field is a mean field and is an idealized representation of the flow. The instantaneous exact flow field characterized by the mean flow velocities never actually exists in its perfectly averaged form. This is further exemplified in the percent root mean square figures, similar to Fig. D.5, for the synthetic PIV images. The RMS values for the synthetic images are much less than those values presented in Fig. D.5 for the true data as a result of losing the turbulent fluctuation data by taking the mean. Thus, this technique is not appropriate for estimating the sampling uncertainty.

For this very specific set of parameters, the reconstructed flow field is shown in Fig. D.7. A significant amount of similarity is seen between the original PIV data and the reconstructed synthetic data. The differences can be highlighted by calculating a percent difference relative to the freestream velocity between the reconstructed PIV and the original data. A map of the percent difference for the speed is shown in Fig. D.7 with the streamwise and transverse velocity component percent differences shown in Fig. D.8. The percent differences across almost the entire field are quite moderate with the mean and median of the absolute value being 0.5% and 0.2%, respectively. Unlike previous test cases, the predominant percent difference value, specifically away from strong gradient regions, is not negative as one might expect from mean bias theory. This may be due to the more advanced adaptive PIV techniques used in the commercial PIV code. The largest percent differences reside solely within the shear layer, and to a lesser extent, the centered expansion where the largest velocity gradients exist. The vast majority (86.5%) showed less than 1% deviation from their expected values with only 0.5% of the points having a deviation greater than 5%.

3. **Combined Uncertainty**

The resultant formula for the net, or total, uncertainty $\varepsilon_T$ from the four dominant sources is thus acquired by processing their individual components in the root-sum-square equation.

$$\varepsilon_T = \sqrt{\varepsilon_K^2 + \varepsilon_L^2 + \varepsilon_S^2 + \varepsilon_P^2}$$  (D.14)
The subscripts $E$, $L$, $S$, and $P$ stand for equipment, lag (particle), sampling, and processing, respectively. The uncertainties are processed using this equation and are shown in Fig. D.9. For this flow and PIV acquisition setup, the largest contributor to uncertainty in the freestream is the equipment. This is because equipment uncertainty affects all portions of the image equally rather than being primarily influenced by gradients or velocity fluctuations like the other sources of uncertainty. The higher freestream uncertainties are especially noticeable for the streamwise velocity component, as can be seen in the left image of Fig. D.9.

![Fig. D.7. (left) reconstructed (synthetic) base flow field (150x200 vector resolution) and (right) percent difference in speed due to the processing technique for the base flow velocity field.](image)

Figure D.10 shows two histogram plots that display the percent of total uncertainty magnitudes that fall within 0.1% intervals between zero to two percent uncertainty. The figure shows these histograms for the four primary sources of uncertainty along with the total uncertainty. The peak in equipment uncertainty for the streamwise velocity component histogram in Figure D.10 further highlights that equipment uncertainty is a primary contributing source for a significant number of points in this direction. The streamwise velocity component total uncertainty histogram trace has two peaks. One, at approximately 0.6%, is caused predominantly by the equipment uncertainty and the other, at approximately 1.0%, is caused primarily by the sampling uncertainty. The transverse component peak is also at about 0.6% and is primarily due to sampling uncertainty. The peaks rise to between 15-25% of the total number of points. In this way, the histograms highlight how the vast majority of uncertainty values lie below 1.5%. The source of uncertainty that contributed the most extreme values (largest magnitudes) is processing with peak values in the 10% range. The percent of total uncertainty values (root-sum-square of components) over 2% and 5% of the freestream is only 12% and 1.7%, respectively.
Fig. D.8. Percent difference (of freestream velocity) due to processing techniques for (left) streamwise and (right) transverse velocity components for the base flow velocity field.

Fig. D.9. Total (root-mean-square) percent uncertainty for combined equipment, particle lag, sampling, and processing uncertainties for (left) streamwise and (right) transverse velocity components for the base flow velocity field; shown as percent of freestream.
Fig. D.10. Histograms of the four independent sources of uncertainty shown with total percent uncertainty (relative to the freestream velocity) for the (left) streamwise and (right) transverse velocity components of the base flow velocity field.

The percent uncertainty for the streamwise and transverse velocities has also been plotted individually for the four sources considered for a transverse line (parallel to the base) extending through the shear layer and recirculation region at a location of $X/D=0.2$ (see Fig. D.9). By comparing the contributions from the four sources in Fig. D.11, various trends can be observed. Uncertainty due to image analysis and sampling uncertainty correlate well with each other and local maxima are observed in regions of high velocity gradients. While sampling uncertainty remains consistently high across the recirculation region, it drops nearly to zero in the inviscid supersonic portion of the flow. The equipment uncertainty exhibits almost the complete opposite trend for the reasons discussed previously. The particle lag appears to have the lowest overall uncertainty across the entire flow field as a result of the small particle size from the new Corona seeder and due to the general lack of strong gradients in the local fluid direction, especially at $X/D=0.2$.

Fig. D.11. Contributions to percent uncertainty for (a) streamwise and (b) transverse velocities from particle lag, equipment, image analysis, and sampling for a line parallel to the base at $X/D = +0.2$. 
4. Conclusions of PIV Uncertainty Analysis

An order-of-estimate PIV uncertainty analysis was performed on the base flow PIV data following the process outlined in Ref. 2. This technique evaluates the PIV data uncertainty to a reasonable accuracy, but makes several simplifications and neglects the typical RMS fluctuations encountered in PIV ensemble data. The equipment uncertainty was computed to be about 0.6% of the local velocity. The particle lag uncertainty was generally very small owing to recent improvements in particle size and seeding and the lack of strong gradients parallel to the flow in the mean flow field. A brief overview of sampling uncertainty with confidence levels was reviewed, followed by a background on suggestions and guidelines to allow PIV researchers to optimize their experiment and allow the processing algorithm to perform optimally. A brief review of processing techniques was cited, and a method to use Monte Carlo techniques to produce synthetic PIV images for the user’s specific flow was presented. The processing uncertainty was generally small outside of the shear layer, and sampling uncertainty reached its maximum in the recirculation region. The equipment and sampling uncertainty were the largest sources of uncertainty for the majority of points in the flow field. However, the majority of points (88%) had uncertainties of less than 2% demonstrating the high quality of the data and the significant advancements in seeding, processing algorithm, and other necessary equipment used in the current PIV experiments.
Appendix D - References


