PLASMA ACTUATORS FOR BLUFF BODY FLOW CONTROL

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Abstract

The aerodynamic plasma actuators have shown to be efficient flow control devices in various applications. In this study the results of flow control experiments utilizing single dielectric barrier discharge plasma actuators to control flow separation and unsteady vortex shedding from a circular cylinder in cross-flow are reported. This work is motivated by the need to reduce landing gear noise for commercial transport aircraft via an effective streamlining created by the actuators. The experiments are performed at Re_D = 30,000. Using either steady or unsteady actuation, Karman shedding is totally eliminated, turbulence levels in the wake decrease significantly and near-field sound pressure levels are reduced by 13.3 dB. Unsteady actuation at an excitation frequency of St_D = 1 is found to be most effective. The unsteady actuation also has the advantage that total suppression of shedding is achieved for a duty cycle of only 25%. However, since unsteady actuation is associated with an unsteady body force and produces a tone at the actuation frequency, steady actuation is more suitable for noise control applications. In addition, plasma actuator optimization study is performed to improve the flow control efficiency and to reach higher Reynolds number. This part of the research is intended to maximize the body force produced by plasma discharge (steady and unsteady) which is a function of various parameters such as dielectric material, size of electrodes, their overlap, frequency, voltage, etc. Detailed experiments are performed in a controlled environment with no-external-flow condition with several different dielectric materials of various thicknesses. Plasma induced velocity (using glass Pitot probe), body force (using high precision weighing scale), and power dissipation are measured at various voltages and frequencies. Optimal voltage waveform and frequency has been found which resulted in time averaged maximum induced velocity and body force. This has resulted in an order of magnitude improvement of the actuator effect.
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NOMENCLATURE

\( D \) = cylinder diameter

\( \text{Re}_D \) = Reynolds number based on cylinder diameter

\( St_D \) = Strouhal number based on cylinder diameter

\( U_\infty \) = free stream velocity

\( \vec{f}_b \) = body force (per unit volume) vector

\( \rho_c \) = charge density

\( \vec{E} \) = Electric field vector

\( V \) = Voltage

\( f_s \) = vortex shedding frequency
CHAPTER 1: INTRODUCTION

1.1 Motivation and objectives

In the present study single dielectric barrier discharge (SDBD) plasma actuators are used to control flow separation and associated unsteady vortex shedding from a circular cylinder in cross-flow. The proof-of-concept flow control experiments reported here serve to demonstrate the ability of SDBD plasma actuators to effectively streamline bluff body flows. Although applicable to a wide variety of engineering systems, the research described in this paper is focused at landing gear noise reduction for commercial transport aircraft.

Expected growth of civil air traffic around major airports is making the problem of reducing aircraft noise on take-off and landing more urgent and challenging. The jet noise component of overall aircraft noise has been significantly reduced by the utilization of engines with high bypass ratio. In landing approach, when engines are throttled down, airframe noise now represents a primary noise source. This has spawned considerable interest in understanding the physical mechanisms responsible for airframe noise production and how they can be controlled. A combination of experimental and computational airframe noise research has identified key sources of airframe noise that appear generic to the current generation of commercial transport aircraft. These include: (1) landing gear noise associated with flow past landing gear struts, uncovered wheel wells, and undercarriage elements, (2) high-lift system noise associated with trailing flaps, leading edge slats and the associated brackets and rigging. Although the detailed physical mechanisms of noise production from these sources may differ and are still a focus of active investigation, it is clear
that a common feature of each is a region of unsteady, separated flow. Consequently, any flow control strategy, either active or passive, that eliminates or minimizes such flow separations will likely have a significant effect on reducing the associated airframe noise. Hence, it is not surprising to find that separation control is at the core of many noise control strategies currently under investigation for commercial transport aircraft. For example, passive flow control in the form of fairings that are designed to reduce flow separation over landing gear elements has been studied, as noted in [5,6]. However, their use is limited by practical considerations like the need to allow easy access for gear maintenance and the ability to stow the gear in cruise. Certainly their added weight is also a consideration. Active blowing or suction strategies must deal with the increased part count and maintenance costs associated with complex bleed air ducting systems. Obviously it would be quite an expensive proposition to retrofit such active flow control systems to the existing fleet of commercial transport aircraft.

Flyover tests have shown that landing gear noise represents a primary source of airframe noise (Michel et al [1]). As noted by Lazos [2], the inherent bluff body characteristics of landing gear give rise to large-scale flow separation that results in noise production through unsteady wake flow and large-scale vortex instability and deformation. Large-scale, unsteady Reynolds-averaged Navier-Stokes simulations of the flow field over a landing gear assembly have been performed by Li, Khorrami and Malik [3]. These simulations capture the unsteady vortex shedding that occurs from the oleo and struts as well the from the landing gear box and rear wheels. This study also serves to demonstrate the extreme complexity of the unsteady separated flow over the gear. A full aeroacoustic analysis of a landing gear assembly was recently reported by Lockard, Khorrami and Li [4]. Data from an unsteady Reynolds Averaged Navier-Stokes simulation of the flow over a landing gear assembly was used as input to the Ffowcs Williams-Hawking equation (Ffowcs Williams, J. E.
and Hawking, D. L) [7] in order to predict the noise at far-field observer locations. These computations demonstrate the potential of large-scale numerical simulations in the identification of acoustic sources in complex landing gear geometries.

Many of the components that form the landing gear take the form of bluff bodies in cross-flow. Passive flow control in the form of fairings designed to reduce flow separation over landing gear elements have been studied experimentally. These investigations show that a faired landing gear generates considerably less noise than the corresponding unmodified gear. However, their use is limited by practical considerations like the need to allow easy access for gear maintenance and the ability to stow the gear in cruise. Certainly their added weight is also a consideration. Similarly, active blowing or suction strategies must deal with the increased part count and maintenance costs associated with complex bleed air ducting systems.

The Center for Flow Physics and Control at the University of Notre Dame is involved in the development and use of SDBD plasma actuators in several applications of active aerodynamic separation control. These include retreating blade stall on helicopter rotors, helicopter fuselage separation control, flow separation control on low-pressure turbine blades in turbojet engines, lift augmentation of airfoils via a “plasma flap”, wing leading edge separation control, and fuselage drag reduction. These studies have demonstrated that plasma actuators are well suited to flow separation control in a wide variety of aerodynamic applications. Since, as described above, airframe noise originates from regions of unsteady separated flow, the use of plasma actuators to actively reduce airframe noise appears promising.

Motivated by potential landing gear noise control applications, a primary objective of this study is to demonstrate the use of plasma actuator technology for bluff body flow control and for the reduction of radiated noise. In particular, we demonstrate the use of surface mounted SDBD plasma
actuators to create a “plasma fairing” that effectively streamlines a circular cylinder in cross-flow by active means. The cylinder in cross-flow is chosen for study since it represents a generic flow geometry that is similar in all essential aspects to a landing gear strut. By minimizing the unsteady flow separation from the cylinder and associated large-scale wake vorticity, the radiated aerodynamic noise is also influenced.

The ultimate goal of this research is to extend the results of the plasma flow control for a circular cylinder, including the acoustic noise reduction, to more realistic landing gear geometries and to Reynolds numbers typical for landing approach. We envision a scenario in which small gear components are positioned aft of larger elements (hence reducing high frequency noise) and the large elements are effectively streamlined by the plasma fairing.

To achieve the efficient plasma flow control at velocities typical of commercial transport landing approach we are developing DBD plasma actuators with sufficient authority. The important part of the present study is the plasma actuator optimization. Optimization parameters are experimentally demonstrated plasma induced velocity and thrust.

1.2 Single Dielectric Barrier Discharge Plasma Actuators

A single dielectric barrier discharge forms the basis for the plasma actuators used in this investigation (e.g. Fridman & Kennedy [8]). This type of plasma discharge has the unique property that it can sustain a large volume discharge at atmospheric pressure without arcing since it is self-limiting. The basic characteristics of SDBD plasma actuators are described in Enloe et al. [9,10].

As shown in Figure 1.1, a plasma actuator consists of two electrodes that are separated by a dielectric barrier material. The two electrodes are given a slight overlap. When a high voltage a.c. input is supplied to the electrodes the dielectric barrier discharge ignites. The photograph of the
discharge is shown in Figure 1.2. The physical structure of SDBD is studied in Gibalov and Pietsch [11]. The charge multiplication and air ionization mechanism is similar to the corona discharge process described in Raizer [12]. Ionization generally starts at the edge of the electrode that is exposed to the air where the intensity of the electric field has its largest value. When the magnitude of this electric field is high enough electron avalanches followed by streamer formation are produced. Streamers are thin ionized channels between the electrodes with a life time of the order of 10ns. They begin at the exposed electrode edge and terminate at the dielectric surface. Due to their relatively high conductivity the streamers efficiently transfer an electric charge from the exposed electrode to the plasma volume near the dielectric surface. Since this volume charge has the same sign with the exposed electrode charge, the electrostatic force attracts it to the dielectric surface above the covered electrode and repels it from exposed electrode. Due to the numerous collisions, charged particles (electrons, positive and negative ions) transfer their momentum to the non-ionized ambient air. Thus, the formation of the plasma is accompanied by a coupling of directed momentum to the surrounding air. In this electrode geometry the air is accelerated along the dielectric surface from the edge of exposed electrode toward the far end of the covered electrode. The buildup of surface charge on the dielectric opposes the applied voltage and gives the plasma discharge its self-limiting character. That is, the plasma is extinguished unless the magnitude of the applied voltage continuously increases. The charge transfer process repeats two times in opposite polarity during an a.c. cycle but the body force always has the same direction. The formation of the plasma gives rise to a body force on the ambient air. It is the resulting coupling of directed momentum to the surrounding air that forms the basis for flow control strategies. Although the direction of charge transfer varies during the two halves of the a.c cycle, the body force always has the same direction. Of importance is the fact that the body force and induced velocity can be tailored through the design
of the electrode arrangement, which controls the spatial electric field. For example, Post [13] has demonstrated electrode arrangements that could produce wall jets, spanwise vortices or streamwise vortices, when placed on the wall in a boundary layer.

Figure 1.1: Schematic of the SDBD plasma actuator.

Figure 1.2: Plasma discharge (top view).

For the electrode geometry shown in Figure 1.1, air is accelerated along the dielectric surface from the edge of exposed electrode toward the far end of the covered electrode, thereby giving rise to a wall jet effect. It will be shown that an array of this type of SDBD plasma actuators mounted on the surface of a cylinder gives rise to a plasma fairing effect in which the cylinder in cross-flow is effectively streamlined.
The advantages of plasma actuators for separation control are numerous and include (1) excellent actuator authority even at Reynolds number of the order of $10^6$, (2) excellent dynamic response, (3) low required energy input (although the applied voltage is large, current draw is small), (4) very robust, (5) inexpensive, (6) capable of both steady and unsteady actuation with a wide range of unsteady actuation strategies implemented in software, (7) can be easily retrofitted to the current generation of commercial transport aircraft, and (8) since the effect of the localized plasma is to create a body force on the surrounding fluid, the effect of the plasma actuator is easily incorporated into numerical simulations by means of a simple body force term. This is in contrast to suction or blowing, for example, where the local fluid physics of the actuation must be explicitly and realistically included in the simulations. In this manner, numerical simulations can be used to effectively explore optimum noise control strategies using the plasma actuators.

The electrostatic plasma body force vector given by

$$\vec{f}_b = \rho \vec{E}$$ \hfill (1.1)\n
can be calculated if the electric field and the charge density distribution are known. An approach to solve this electrostatic problem is developed by Enloe et al [9,10]. The body force vectors are tailored through the design of the electrode geometry and dielectric material that control the spatial electric field. For example, the electrode arrangement used in the experiments reported in this study was designed to provide locally tangential blowing. The body force per unit volume produced by the SDBD plasma actuators may be increased by: (1) increasing the actuator applied voltage and optimizing the voltage waveform. It has been demonstrated that the thrust (which corresponds to the total body force) generated by the actuators varies as voltage to the $7/2$ power. Below in this study, it is found that, after the voltage is increased up to a certain value, the body force stops growing with the voltage. It was also found that plasma actuator performance depends significantly on the applied
voltage waveform. Enloe et al [10] experimentally found that the positive sawtooth waveform was the best, in terms of maximizing the body force. Forte et al [14] conducted LDV study of plasma actuator induced velocity and found that the negative half cycle of the sinusoidal voltage induced more velocity than the positive one. (2) Increase the number of actuators in series. This investigation was conducted by Post [13] and Forte et al [14]. It has been demonstrated that the thrust due to actuators in series sums approximately linearly and the induced velocity increases greatly. The utility of adding additional actuators is clear by comparing the results of this study which utilizes four actuators with those of Thomas et al [16] which utilized only two. The Reynolds number range for effective flow control more than doubled with the addition of two actuators. (3) Explore the use of more effective dielectric materials for construction of the actuators. Many of the current designs of the SDBD plasma actuator have utilized a polyimide (Kapton®), PTFE (Teflon) or Macor ceramic for the dielectric layer. Based on an equivalent circuit model of the SDBD actuator by Orlov and Corke [61], improvements in the dielectric strength (dielectric breakdown voltage) and dielectric constant of the barrier layer would significantly enhance the actuator performance.

1.3 Flow around circular cylinder

In order to experimentally demonstrate the bluff body flow control using the plasma fairing concept, attention is given to the application of four SDBD plasma actuators for the control of unsteady separation from a cylinder model in a cross-flow.

Since cylinder bodies are the main parts of the landing gear strut shown in Figure 1.4, a circular cylinder model in a cross-flow was employed to investigate the control of unsteady separation using plasma fairing concept. This section provides background material on the vortex shedding and flow control behind circular cylinders.
Flow around a circular cylinder is one of the fundamental problems of aerodynamics. It has been studied extensively because of its widespread engineering applications and associated problems of vibration induced by flow, wake turbulence, acoustic noise, and drag forces on bodies. A comprehensive review of cylinder flow is given in Williamson [18] and Zdravkovich [19].

A variety of flow regimes exists in the flow due to the presence of the cylinder. Far upstream, the flow is essentially uniform. Close to the cylinder, the flow slows down and forms a stagnation region near the windward leading edge of the cylinder. The flow accelerates from the stagnation point, and a boundary layer starts to develop on the cylinder in the presence of a favorable pressure gradient. If the Reynolds number is high enough the flow separates from the surface at the top and bottom sides of the cylinder (Figure 1.3) due to an adverse pressure gradient. The separated boundary layers continue to develop downstream as free shear layers on each side of the cylinder and eventually form vortices behind the cylinder. The structure of the boundary and shear layers and vortex structure depends strongly on the Reynolds number.
At very low Reynolds numbers, below $Re = 4$, the flow is fully laminar and firmly attached to the surface of the cylinder all around its circumference. When the Reynolds number increases up to $Re = 4...5$ the flow separates behind the cylinder, and steady “attached” separation bubbles form symmetric vortex pairs. The separated shear layers meet at the end of the near-wake and form a “free stagnation point” [19].

The strength of vortices and the length of the recirculation region increase as the Reynolds number increases. At $Re = 45...65$, a staggered array of laminar vortices is formed. The Reynolds number at which this regular shedding starts is known as the critical Reynolds number; the flow
pattern is described as a von Karman vortex street. The frequency of the shedding in the vortex street can be scaled using the Strouhal relation

\[ f_s = \frac{S_{tD} U_\infty}{D}, \]  

(1.2)

where \( f_s \) is the vortex shedding frequency, \( U_\infty \) is the velocity of flow around the cylinder of diameter \( D \), and \( S_{tD} \) is the Strouhal number, a nondimensional number that depends on Reynolds number. The Strouhal number remains almost constant over a wide range of Reynolds numbers. The main features of the flow pattern in the vortex street remains essentially the same for \( 45 \ldots 65 < Re < 4 \times 10^5 \), except for the transitions at various downstream regions, with the increase in the Reynolds number. The vortex street is laminar for \( 30 \ldots 48 < Re < 350 \ldots 400 \). With the increase in the Reynolds number, the laminar wake becomes unstable. The transition from the laminar to turbulent flow gradually moves upstream from the far wake to the near wake for \( 180 \ldots 200 < Re < 350 \ldots 400 \). At the end of this regime, the transition occurs in the vortex during its formation. Three-dimensionality in the flow develops around \( Re = 180 \ldots 194 \), and streamwise vortices appear along the span of the cylinder. Depending on Reynolds number, these vortices can be of two types, mode A and mode B, as described in Williamson [20]. In the Reynolds number range of \( 350 \ldots 400 < Re < 1000 \) the free shear layers start to oscillate and the length of the formation region increases. The Kelvin-Helmholtz instability of the shear layer appears at \( Re = 1000 \ldots 2000 \) when the transition waves roll-up into the small discrete vortices along the separated shear layer. Bloor [53] found that the frequencies of the shear-layer vortices in the wake vary roughly as \( Re^{3/2} \). The transition to turbulence in the shear layers occurs from \( 1000 < Re < 1 \times 10^5 \ldots 2 \times 10^5 \). This state is known as subcritical. The formation length decreases in this regime. When the Reynolds number increases beyond \( Re = 1 \times 10^5 \ldots 2 \times 10^5 \) the transition in the boundary layers occurs at the separation
line. This state of the flow is known as the critical state. Above \( Re = 3.5 \times 10^5 \ldots 6 \times 10^5 \), the transition in the boundary layers takes place somewhere between the stagnation and separation lines. This is known as supercritical regime. The upper end of this regime is difficult to estimate because the transition region shifts towards the stagnation line asymptotically with the increase in the Reynolds number [19].

Vortex shedding behind the circular cylinder occurs because of the instabilities in the flow. Recently, the onset of the vortex street has been explained by the presence of an absolute instability in the near wake region of the cylinder. A comprehensive review of absolute and convective instabilities in shear flows is given in a paper by Huerre and Monkewitz [23]. The local instability characteristics of a parallel flow are determined by the behavior of an impulse response. A flow is absolutely unstable if the localized disturbances spread upstream and downstream and contaminate the entire parallel flow. By contrast, a flow is convectively unstable if the disturbances are swept away from the source. At the Reynolds number well below the critical Reynolds number, the wake trail is convectively unstable. Triantafyllou et al. [26] demonstrated this by investigating stability characteristics of the velocity profiles obtained by Kovasznay [22] at \( Re = 34 \). When the Reynolds number is increased, the convective instability changes into the absolute instability in the region close to the near wake. The nature of the local instability after this region, as explained by Chomaz et al. [27], changes from absolute to convective at a certain downstream transition location. According to Koch [28], this transition allows the feedback of the temporally-growing vorticity waves that propagate upstream and downstream and also the global oscillations of the separated flow to develop. Koch also suggested that this hydrodynamic resonance is the key to the frequency selection of the vortex shedding. By investigating various velocity profiles, Triantafyllou et al. [26] showed that the flow at \( Re_{critical} \approx 56 \) and at the higher \( Re = 140,000 \) is, in fact, absolutely unstable in
the formation region behind the cylinder, and the flow is convectively unstable downstream of this region.

The relation between the local absolute instability and the self-excited global oscillations of the entire wake has been investigated by Provansal et al. [29] and Chomaz et al. [27]. By investigating the wake of a circular cylinder by LDA, Provansal et al. have shown that the vortex shedding at low Reynolds numbers is indeed a self-excited limit-cycle oscillation of the near wake, resulting from a time-amplified global instability. Provansal et al. in their investigation used a Stuart-Lindau nonlinear model equation for the amplitude of the wake oscillation. Monkewitz [30] has further investigated the presence of global modes and suggested that the von Karman mode is the first global mode to become unstable; however, a wake flow may possess multiple global modes. Chomaz et al. [27] have also demonstrated, using a Ginzburg-Landau model, that the self-sustained resonances may appear via a Hopf bifurcation when the system exhibits a sufficiently large region of the local absolute instability. In addition, as demonstrated by Hammond and Redekopp [24], modification of bluff body base flow by application of base suction renders the flow more absolutely unstable but decreases the spatial extent of the region of absolute instability. This has a net favorable effect on reducing global modes which are responsible for vortex shedding. In contrast, Hanneman and Oertel [25] demonstrated that base bleed renders the flow less absolutely unstable.

The high-speed mode of vortex shedding occurs in the transition-in-shear-layer (subcritical) state, in the range $350\ldots400 < Re < 1\times10^5\ldots2\times10^5$. This mode has two distinct stages: formation and shedding. Prandtl [31] proposed that the vortices are formed behind the cylinder by the spiral roll-up of the free shear layer in an almost-fixed location; the free shear layer feeds the circulation into the growing vortices. For the shedding stage, Gerrard [32] suggested that when the developing vortex becomes sufficiently strong it draws the other shear layer across the wake. The interaction of
the oppositely-signed vorticity from the other shear layer cuts off the circulation and stops the growth of the vortex; this causes the vortex to shed into the wake. The vortex street is formed by the alternate shedding of the fully-grown vortices. Cantwell and Coles [33] investigated this mode of the vortex shedding at \( Re = 140,000 \). They measured the velocity field behind a cylinder by a “flying cross-wire”.

In present study, the Reynolds number is about 30,000 which corresponds to subcritical regime. The boundary layer is laminar up to the separation line. Karman vortex shedding occurs at Strouhal number 0.21. The free shear layers give birth to vortices, due to the Kelvin-Helmholtz instability, and cause further transition to turbulence. Thus, the flow is in a subcritical regime.

1.4 Overview of flow control around circular cylinder

The problem of control of vortex shedding behind circular cylinder is of a great technical interest. Plenty of researchers have investigated different approaches to controlling this vortex shedding; their objectives have been directed at suppressing the vortex shedding, separation control, and lock-in or synchronization of the shedding. The ability to control the vortex shedding can be used to reduce drag, increase lift, suppress noise, decrease vibration, and increase mixing or heat transfer. The method of control depends on the objective as well as the Reynolds number of the flow. In order to control the vortex shedding, researchers have considered both active and passive control schemes in their investigations. Many investigators have also used feedback in their control loops [34].

An emphasis of many control approaches has been based on the suppression of vortex shedding. The recent advancement in identifying the absolute instability as the cause of the vortex shedding has provided an opportunity to control the vortex shedding by the suppression of the
absolute instability. Roshko [35] observed changes in the flow at \( Re = 1.45 \times 10^4 \) when a splitter plate was inserted behind a cylinder; when the length of the plate was longer than five diameters, the vortex shedding disappeared. Using numerical methods Kwon and Choi [36] demonstrated that the vortex shedding behind the circular cylinder completely disappeared when the length of a splitter plate was larger than a critical length; in the range of \( 80 < Re < 160 \), this critical length was proportional to the Reynolds number. According to Monkewitz, the splitter plate imposes zero transverse velocity along the wake centerline and hence suppresses the absolutely unstable sinuous mode of the vortex shedding. Oertel [37] also suggested that the splitter plate prevents the formation of the von Karman vortex street when it extends beyond the area of the absolute instability.

Another well-known method for the suppression of the vortex shedding behind the bluff bodies consists in bleeding fluid from the base [38,39]. Recently, Schumm et al. [40] and Delaunay and Kaitksis [41] advanced the theory that the base bleed suppresses the mechanism for the absolute instability, thereby suppressing the vortex shedding. Schumm et al. demonstrated, using flow visualization, a total suppression of the vortex shedding at \( Re = 68 \) using base bleed; moreover, by calculating the coefficient of the instability equations, they established that the bleed suppressed the absolute instability. Delaunay and Kaitksis found, by direct numerical simulation and global stability analysis, that blowing can stabilize the wake and reduce vortex shedding at \( Re = 30 \ldots 90 \). Park et al. [42] reported a computational study of the feedback control of the flow behind a cylinder. The feedback sensors were located in the wake, and the actuators were a pair of blowing/suction slots at \( \pm 110 \) degree from the forward stagnation points. They achieved complete suppression of the vortex shedding behind the cylinder at \( Re = 60 \).

Schumm et al. [54], in an experimental investigation, used transverse oscillation of a cylinder to suppress the vortex shedding at \( Re = 56 \); they used a forcing frequency of about 1.8 times
the natural vortex shedding frequency and relatively small cylinder oscillations. In their investigation, they also proved that the suppression of the vortex shedding by the transverse oscillation of the cylinder is, in fact, the suppression of the absolute instability. Tao et al. [43] also reported the suppression of vortex shedding at $Re = 41...50$ using feedback control and transverse oscillation of the cylinder.

Many other techniques have also been used to suppress the vortex shedding or global oscillation of the flow behind the cylinders with a possible connection to the suppression of the local absolute instability. In an effort to suppress the vortex shedding, Strykowski and Sreenivasan [44] placed a second, much smaller ($1/8...1/20$ of main cylinder’s diameter), cylinder in the near wake of the main cylinder. They found that the vortex shedding could be effectively suppressed over a limited Reynolds number range of $40...100$ by the proper placement of the control cylinder. They further demonstrated, through numerical methods, that the natural vortex shedding is associated with the absolute instability and the suppression of the vortex shedding by the control cylinder corresponds to a globally damped wake. They suggested a possible connection between the reduction of the absolute instability and the suppression of vortex shedding. In another experimental investigation, Schumm et al. [40] also used wake heating to suppress the vortex shedding at $Re = 57...83$.

The vortex shedding behind a circular cylinder can also be suppressed by the unsteady pulsing of the wake. The pulsating jet adds net momentum to the flow by the second-order streaming effect, without adding any mass to the flow. Williams and Amato [45] demonstrated the suppression of the vortex shedding (at $Re = 370$) by producing unsteady pulsing at the trailing edge or base of the cylinder through a small slit, spanning the length of the cylinder. They found that the
region of re-circulating flow decreased behind the cylinder as the forcing was increased. This indicates that the unsteady pulsing may also have suppressed the local absolute instability.

The vortex shedding behind the cylinder can also be suppressed by exciting the whole flow around the cylinders. Ffowcs-Williams and Zhao [46] reported the suppression of vortex shedding by feedback control for $Re = 100$ using acoustic forcing. They used a hot-wire sensor in the wake and excited the flow by sound from a single loudspeaker placed outside the wind tunnel. Roussopoulos [47] carried out similar experiments to that of Ffowcs-Williams and Zhao and concluded that the feedback control was able to stabilize the wake at Reynolds numbers about 20% higher than the $Re_{critical} = 48.4$. In his experiment, he also showed that the ‘active’ control of the vortex shedding described by Ffowcs-Williams and Zhao was really an active method of preventing a sensor from detecting vortex shedding and that their control strategy did not suppress vortex shedding at $Re = 400$.

The rotational oscillation of the cylinder has also been used to suppress the vortex shedding from the cylinder. Taneda [48] studied the effects of rotational oscillations at $Re = 30…300$, and showed that at very-high oscillation frequencies and magnitudes the vortex shedding process could be nearly eliminated. Recently, Fujisawa et al. [49] reported the attenuation of vortex shedding and reduction in aerodynamic forces using feedback control. They used feedback from a hot-wire sensor and rotational oscillation of the cylinder to control the vortex shedding at $Re = 6,700$. Homescu et al. [50] reported similar results for their computational investigation of the flow behind a circular cylinder at the $Re = 100$ and 1000; they too attempted to suppress vortex shedding by rotationally-oscillating the cylinder using optimal control.

Siegel et al. [51] investigated in direct numerical simulation the effect of feedback flow control on the wake of a circular cylinder at a Reynolds number of 100. The control approach uses a
low-dimensional model based on proper orthogonal decomposition (POD). Actuation is implemented as displacement of the cylinder normal to the flow. A drag reduction of 15% of the drag was achieved, and the unsteady lift force was lowered by 90%.

Kim and Choi [52] applied a distributed (i.e., spatially varying) forcing to flow over a circular cylinder for drag reduction. The distributed forcing is realized by a blowing and suction from the slots located at upper and lower surfaces of the cylinder. The forcing profile from each slot is sinusoidal in the spanwise direction but is steady in time. The Reynolds numbers considered are from 40 to 3900 covering various regimes of flow over a circular cylinder. For all the Reynolds numbers larger than 47, the present in-phase distributed forcing attenuates or annihilates the Kármán vortex shedding and thus significantly reduces the mean drag and the drag and lift fluctuations. It is shown that the in-phase forcing produces the phase mismatch along the spanwise direction in the vortex shedding, weakens the strength of vortical structures in the wake, and thus reduces the drag. Unlike the in-phase forcing, the out-of-phase distributed forcing does not reduce the drag at low Reynolds numbers, but it reduces the mean drag and the drag and lift fluctuations at a high Reynolds number of 3900 by affecting the evolution of the separating shear layer, although the amount of drag reduction is smaller than that by the in-phase forcing.

Despite huge amount of studies, suppression of global instability and vortex shedding has been typically accomplished only at relatively low Reynolds numbers (up to 10000), which is out of range of technical interest, especially for commercial aviation applications.

1.5 The Plasma Fairing Concept

Although a faired landing gear generates considerably less noise than the corresponding unmodified gear, the need to access the gear for maintenance and stow the gear in cruise makes
passive separation control via fairings impractical. In the work presented here, it is envisioned that surface mounted SDBD plasma actuators are used to create a so-called “plasma fairing” that effectively streamlines the gear by active means.

Many of the components that form the landing gear take the form of bluff bodies in cross-flow. In this study proof-of-concept experiments are presented which serve to demonstrate the ability of plasma actuators to reduce bluff body flow separation that is a source of landing gear noise. Consideration is given to a simple, generic landing gear strut model instrumented with plasma actuators in order to reduce flow separation about the element. This effective streamlining of the landing gear element by the plasma actuators is termed a “plasma fairing”. An example is shown in Figure 1.4 where a generic landing gear strut is shown. Both upstream and downstream elements are covered with an array of plasma actuators (like that shown in Figure 1.1) which are capable of producing locally tangential blowing. The electrodes extend along the strut. A schematic of the flow in the cross cut plane A-A’ without the use of actuators is shown in Figure 1.4b. The flow is characterized by large-scale separation over the leading and trailing elements, the formation of unsteady large-scale vorticity in the wake that is subsequently distorted by the downstream strut element. This interaction, along with the pressure fluctuations at the surface of the upstream element due to Karman vortex shedding, gives rise to an effective dipole source for acoustic radiation. A schematic of the flow with the actuator array is shown in Figure 1.4c. As shown in the inset panel, the surface mounted electrodes are operated so as to accelerate fluid along the surface, giving rise to a local wall jet effect. This wall jet has a tendency to remain attached to a convex surface. This phenomenon is commonly referred as the Coanda effect. The Coanda effect of the wall jet blown from a flat nozzle tangentially to a circular cylinder surface is investigated in [15]. In both steady and unsteady mode the plasma actuator causes an intensive turbulent mixing in the initially laminar
boundary layer. This serves to transfer momentum from high velocity to low velocity layers making
the boundary layer much more stable and drastically delaying separation.

Figure 1.4: Schematic of plasma actuator array on a landing gear strut.
CHAPTER 2: FLOW CONTROL EXPERIMENTS

2.1 Experimental apparatus and flow field facility

In order to experimentally demonstrate the bluff body flow control using the plasma fairing concept, consideration is given to the application of four SDBD plasma actuators to the control of unsteady separation from a cylinder model in a cross-flow. This geometry is similar, in essential aspects, to the landing gear strut shown in Figure 1.4. This section describes the cylinder model and wind tunnel facilities used for the experiments. The most part of the results of this section is published in [17].

2.1.1 Wind tunnel facility

The flow control experiments were performed in one of the low-turbulence, subsonic, in-draft wind tunnels located at the Hessert Laboratory for Aerospace Research at the University of Notre Dame. The wind tunnel has an inlet with contraction ratio of 20:1. A series of 12 turbulence management screens at the front of the inlet give rise to tunnel freestream turbulence levels less than 0.1% (0.06% for frequencies above 10 Hz). Experiments are performed in a test section of 0.610m square cross-section and 1.82m in length. One sidewall has optical access for non-intrusive laser flow field diagnostics (particle image velocimetry).

2.1.2 Application of SDBD plasma actuators to a cylinder

Figure 2.1 presents a schematic of four dielectric barrier discharge plasma actuators mounted on a circular cylinder model. The cylinder model takes the form of a quartz glass cylinder (1) with an outer diameter \( D = 100 \text{ mm} \), wall thickness \( d = 2.5 \text{ mm} \), and dielectric constant of 3.7. The
cylinder diameter was driven by a “packing constraint” imposed by the need to mount four actuators on the cylinder. This constraint arises from a need to have a sufficient length of covered electrode so that full plasma formation can occur and by the recognition that multiple actuators must be placed sufficiently far apart so that plasma does not form on the upstream edge of a downstream exposed electrode. In the experiments reported here this gave rise to a cylinder diameter that produced a blockage ratio of 16.7%. Drag coefficient measurements were performed using a Pitot probe traverse in conjunction with an integral momentum balance \[16\]. This experiment will be presented below. After applying appropriate blockage corrections, the expected drag coefficient for the unactuated cylinder in cross-flow was obtained. Hence, the essential character of the cylinder flow is not altered by the blockage effect. Further, in this study it is the relative character of the actuated versus non-actuated flow that is of most interest and this will not be significantly influenced by this degree of blockage.

In the configuration shown in Figure 2.1 the cylinder wall serves as the dielectric barrier for the SDBD plasma. The ends of the cylinder terminate in Plexiglas endplates that prevent cylinder flow interaction with the tunnel sidewall boundary layers. As indicated, the outer, exposed electrodes (2) are mounted to the surface of the cylinder with their plasma generating edges located at ± 90 degrees and ± 135 degrees with respect to the approach flow direction. These surface electrodes are made of 1.6 mil thick copper foil tape of width 6.4 mm. This choice for the electrode location results from an idea that the best location for the first pair of plasma actuators is near the separation point \[59,60\]. The second pair of actuators is placed downstream to additionally accelerate the boundary layer and therefore to prolong Coanda effect. Note that the thickness of the electrodes is greatly exaggerated in Figure 2.1. The corresponding four inner electrodes (3) are mounted to the inner surface of the cylinder. They are each made of 1.6 mil thick lead foil tape of
25.4 mm width. Both inner and outer electrodes extend 0.508 meters in the spanwise direction. Seven layers of 5-mil-thick Kapton tape (4) cover the inner electrodes and serve to prevent inner discharge. Each inner and outer electrode pair has a small overlap equal to one half of the dielectric thickness which gives rise to a large local electric field gradient. Plasma (5) forms near the edge of the exposed electrode and extends a distance along the cylinder’s dielectric surface as depicted in Figure 2.1. As indicated in the figure, the actuators are each connected to a high voltage a.c. source that provides 8.1 kV rms sinusoidal excitation (≈11.4 kV amplitude) to the electrodes at a frequency of 10 kHz. This frequency is considerably higher than any relevant time scales associated with the flow. Hence the resulting body force on the ambient fluid may be considered effectively constant and the resulting actuation is termed “steady”. The case of unsteady actuation will be discussed in the next section. The power dissipation using the actuator in the steady mode is approximately 100 Watt for each actuator (power dissipation per unit length in spanwise direction is 200W/m for each actuator). It is measured by LeCroy LT262 oscilloscope which processes in real time current and voltage signals from the plasma actuator. The high voltage is measured by LeCroy PPE20kV DC high voltage probe. The current through the actuator is measured by two Pearson Electronics Model 2100 current meter.
Figure 2.1: Schematic of twin SDBD plasma actuators mounted on the cylinder model.

Shown in Figure 2.2 is the plasma generation circuit used in the flow control study. It should be noted that this circuit is similar to one used in the optimization study. A low amplitude, sinusoidal signal from a function generator (Stanford Research Systems DS335) is first supplied to two two-channel power amplifiers (Crown CE4000) forming four power amplification channels. The amplified voltage from each channel is then fed through a 1.2 Ohm 300 Watt resistor into the primary coil of a 1:180 transformer (Corona Magnetics) to increase the voltage level to 8.1 kV rms. The resistor limits the current through the primary coil. A switched capacitor set is connected in parallel to the primary coil of the transformer in order to adjust the resonant frequency of the system. The high voltage for the excitation of the plasma actuators is obtained from the secondary coil of the transformer. The resonance in contour formed by the capacitance of the plasma actuator
and the inductance of the transformer is used to reduce the amplifier load. Each of the four channels is used to feed one corresponding plasma actuator.

![Plasma actuator circuit schematic](image)

Figure 2.2: Plasma actuator circuit schematic.

To suppress a radio frequency electromagnetic noise, anti-noise filters, similar to one described in the optimization study, are used. Four filters are installed inside the cylinder model (one filter for each actuator). The filter consists of an inductor (12 turns, ferrite core, 31.1 mm OD, 19.1 mm ID, 15.9 mm H) and one high-voltage capacitor (15pF, 15kV DC max).

2.1.3 Steady and Unsteady Actuation

The single dielectric barrier discharge requires an a.c voltage for its sustenance. However, if the time scale associated with the a.c. signal driving plasma formation is sufficiently small in relation to any relevant time scales for the flow, the associated body force produced by the plasma may be considered effectively steady. Certainly, this is the case for the 10 kHz excitation used for the plasma generation in the present flow control study, since Karman vortex shedding frequency at given cylinder diameter and the freestream velocity used is approximately 8 Hz. However, unsteady actuation may also be applied and signals for steady versus unsteady actuation are contrasted in
Figure 2.3. Both utilize the same high frequency sinusoid. Referring to the figure, it is apparent that during time interval $T_1$ the plasma actuator is on only during the sub-interval $T_2$. Hence, the signal sent to the actuator has a characteristic frequency of $f = 1/T_1$ that can be much lower than that of the sinusoid and will comparable to some relevant frequency of the particular flow. In addition, an associated duty cycle $T_2/T_1$ may be defined. Obviously, the frequency and duty cycle may be independently controlled for a given flow control application. Two types of the unsteady actuation are used for given plasma actuator configuration. Symmetric, unsteady actuation involved firing all four actuators simultaneously. Asymmetric actuation involved firing the top and bottom pair of actuators in anti-phase.

![Steady and Unsteady Actuation Diagram](image)

Figure 2.3: Steady and unsteady actuation.

2.1.4 Actuator induced velocity field

Prior to characterizing the behavior of the “plasma faired” cylinder in the wind tunnel, the flow induced solely by the surface mounted plasma actuators was examined. In order to do this, a
second cylinder model with twin plasma actuators surface mounted at the top and bottom was placed in a box 1.2 m in length, 0.6 m width and 0.91 m in height. This box shielded the model from ambient air flow within the laboratory. Three sides of the box were made of Plexiglas to allow optical access. The flow field generated by the twin SDBD plasma actuators was measured non-intrusively by using a TSI particle image velocimetry (PIV) system. The air within the box was seeded with olive oil droplets of nominally 1 micrometer diameter. The droplets were generated by a TSI atomizer. A model Y120-15 New Wave Research Nd:Yag laser produced double pulses with a 50 μsec time interval. The pulse repetition rate was 15 Hz.

Figure 2.4 presents a vector plot of the flow field induced by the steady operation of a single (top) actuator only. This vector velocity field represents an ensemble average over 100 sample flow field realizations. This figure shows that the body force associated with the top SDBD actuator effectively produces local tangential blowing which adheres to the surface of the cylinder for a considerable distance via an apparent Coanda-like effect. That the plasma actuator propels comparatively high momentum fluid along the cylinder surface should be beneficial in maintaining flow attachment and is one key feature of the plasma fairing concept. In Figure 2.4, the highest mean velocities indicated are on the order of 2 m/s. However, this is limited by the resolution of the flow field images (which was set to show the global character of the flow). In fact, Pitot probe velocity measurements made by Forte et al [14] indicate that the peak plasma induced velocity at comparable conditions is approximately 6 m/s.
2.2 Experimental results

This section summarizes a series of flow control experiments utilizing four SDBD plasma actuators flush mounted on a circular cylinder in cross-flow as described previously in sections 2.1.1 —2.1.3. This work extends initial experiments utilizing twin actuators that were reported by previously by Thomas et al [16]. Unless otherwise noted, the Reynolds number for the current series of experiments (based on free stream velocity and cylinder diameter) is $Re_D = 30,000$ (the magnitude of freestream velocity $U_\infty = 4\pm0.3$ m/s). Measurements to be presented include smoke injection flow visualization, wake mean velocity and rms velocity profiles, velocity autospectra, phase-locked particle image velocimetry (PIV) of the near wake and microphone sound pressure
level measurements in order to characterize the near-field pressure fluctuations. All of these were performed both with and without plasma actuation.

2.2.1 Flow visualization results

The influence of the plasma actuators on the global structure of the cylinder flow is presented first. The flow with the actuators off is shown in Figure 2.5. Here the flow visualization was accomplished by introducing continuous smoke streaklines upstream of the wind tunnel inlet contraction. The smoke generator is described in detail by Mueller [56] and used propylene glycol as the smoke producing fluid. The smoke streaklines were contained in the spanwise centerplane of the wind tunnel test section where they were illuminated by a high intensity photo floodlight. Figure 2.6 shows a corresponding PIV image of the cylinder near-wake obtained by seeding the flow with 1 micron diameter olive oil droplets. These are illuminated by a pulsed Nd-Yag laser. With the actuators off, the flow obviously undergoes subcritical separation leading to a large-scale separated flow region that is accompanied by unsteady, Karman vortex shedding at a Strouhal number of 0.21 (approximately 8 Hz in the present experiment). Along with Karman vortex shedding, Figure 2.6 clearly shows the presence of smaller scale Bloor-Gerard vortices (as investigated by Bloor [53] and Gerrard [54]) that result from the convective instability of the separated shear layer. These occur at a frequency of approximately 150 Hz, which is consistent with data summarized in Williamson [55].
Figure 2.5: Smoke flow visualization image with the plasma actuators off.

Figure 2.6: Near-wake PIV flow visualization image with the plasma actuators off.

Figure 2.7 and Figure 2.8 present corresponding flow visualization images with the four plasma actuators operating in steady mode. These figures show that the plasma actuation has a profound influence on the global structure of the flow. The plasma actuators are shown to substantially reduce the extent of the separated flow region and the associated Karman vortex
shedding appears to be eliminated. With the actuators on, the flow streaklines possess strong top-bottom, as well as fore-aft symmetry indicating that the flow separation from the cylinder has been greatly reduced. That the flow remains attached over a much larger extent of the cylinder surface is likely associated with the Coanda effect shown previously in Figure 2.4 which would serve to channel comparatively high momentum fluid to the near-wall region with a consequent favorable effect on maintaining flow attachment.

Figure 2.7: Smoke flow visualization image with the plasma actuators on (steady actuation).
Figure 2.8: Near-wake PIV flow visualization image with the plasma actuators on (steady actuation).

Flow visualization was also used in order to initially characterize the effect of unsteady plasma actuation. The duty cycle was fixed at 25% and the excitation frequency was varied over a wide range. In each case the plasma actuators were fired either symmetrically or asymmetrically. Symmetric plasma excitation at frequencies near the natural shedding frequency of $St_D = 0.21$ were found to give rise to large amplitude unsteady Karman vortex shedding at the subharmonic of the excitation frequency. Since a primary goal of the investigation was the suppression of shedding, the use of higher frequency excitation was explored. It was found that optimum suppression and minimum wake defect occurred for unsteady forcing at a frequency of approximately 50 Hz which is over five times the cylinder shedding frequency. Figure 2.9 and Figure 2.10 show sample flow visualization images obtained with unsteady symmetric and asymmetric, 50 Hz excitation at 25% duty cycle. In both of these images the near wake has been considerably reduced in width from that
shown in Figure 2.5 and Figure 2.6, Karman vortex shedding is again eliminated and the cylinder appears to have been effectively streamlined by the plasma actuators.

Figure 2.9: Unsteady symmetric plasma actuation at excitation $St_D = 1$, and 25% duty cycle.
Figure 2.10: Unsteady asymmetric plasma actuation at excitation $St_D = 1$, and 25% duty cycle ($Re_D = 30,000$).

It is important to point out that the optimum actuation frequency of 50 Hz corresponds to a Strouhal number (based on freestream velocity and cylinder diameter) of $St_D = f_D U_\infty = 1$. This is perhaps not surprising since the excitation Strouhal number may be thought of as a ratio between the time scale for actuation, $1/f$, and the characteristic time scale for the separated flow region, $O(D/U_\infty)$. Hence, the fact that $St_D = 1$ is optimum, in terms of effectiveness of bluff body separation control, indicates that the time scale for actuation must approximately match that characterizing the separated flow region. It is interesting to note that Huang et al [59,60] found unsteady actuation at $St = 1$ optimum for separation control on a low pressure turbine blade. As was the case here, the characteristic length scale on which the excitation Strouhal number is based is the length of the separated flow region. In addition to excitation frequency, the effect of duty cycle was examined. It was found that the effect of duty cycle is small unless it is reduced to a value near 10% in which case a reduction in flow control efficiency resulted. Obviously it was desired to operate the
actuators at as small a duty cycle as possible without compromising the ability to control the flow. In this sense 25% duty cycle was deemed near optimum.

Looking at the unsteady flow visualizations Figure 2.9 and Figure 2.10 it is still possible to distinguish the relatively large scale vortices created by the plasma actuators form the smaller Bloor–Gerrard shear layer vortices. The large scale vortices initially move in a regular symmetric or asymmetric way, then they form larger and more irregular structures as the turbulent wake develops downstream. In the symmetrical case the vortices tend to rearrange asymmetrically with a distance.

2.2.2 Aerodynamic drag force measurements

For this experiment, another model of a smaller size was used. Two plasma actuators were installed on the top and the bottom (±90°) of a 38 mm in diameter quartz cylinder with the wall thickness of 3 mm. The actuators had a common encapsulated electrode which occupied the back part of the cylinder. The smaller size of the cylinder reduces the blockage effect and allows one to investigate the wake at relatively farther distance from the model. The applied voltage and frequency was the same as for the larger model.

Cross-flow traverses of a Pitot-static probe over a representative range of streamwise locations downstream of the cylinder were used to obtain wake mean velocity profiles with and without actuation. As an example, Figure 2.11 compares wake mean velocity profiles with and without actuation as obtained 10 diameters downstream of the cylinder at a Reynolds number of ReD = 18,000. This figure shows the significant effect the two surface-mounted plasma actuators have in modifying the wake mean velocity profile. Particularly notable is the reduction in the velocity defect.
Figure 2.12 presents the measured drag coefficient of the cylinder, both with and without plasma actuation, as a function of $Re_D$. These drag measurements were obtained by integration of cross-stream mean velocity profiles like those shown previously in Figure 2.11 along with application of appropriate tunnel blockage corrections. As expected for subcritical separation, with the plasma off the cylinder drag coefficient is just above 1.0 and is largely independent of Reynolds number. With the plasma on, drag reduction of approximately 90% is noted at the lowest Reynolds numbers tested. The reduction in drag obviously decreases in a continuous manner with Reynolds number.
number which suggests that the degree of effective streamlining depends on the magnitude of actuator-induced perturbation in relation to the freestream velocity, $U_\infty$. Recall that the plasma actuation amplitude has been kept fixed as the approach velocity was varied.

Figure 2.12: Variation in measured drag coefficient with $Re_D$ for plasma On and Off.

Figure 2.13 compares the streamwise variation in wake maximum velocity defect (normalized by the external freestream velocity) with the plasma on and off. These data were acquired at a Reynolds number of $Re_D = 24,000$. Consistent with Figure 2.11 and Figure 2.12, the maximum velocity defect is reduced considerably with the plasma actuators on. Note however, that
the influence of the actuators is global. That is, it is not localized to the near wake region but extends to larger values of x/D, which is consistent with the idea that the actuators have effectively streamlined the cylinder. Also apparent from Figure 2.13 is that the velocity defect decay rate is reduced with the plasma on.

![Graph showing streamwise variation of the wake normalized maximum velocity defect.](image)

Figure 2.13: Streamwise variation of the wake normalized maximum velocity defect.

### 2.2.3 Hot-wire measurements

Here we return to the four actuator model since it has demonstrated the maximum performance at higher Reynolds numbers. In order to investigate the effect of the plasma actuators on the unsteady vortex shedding characteristics, constant temperature hot-wire anemometry was used to acquire fluctuating streamwise velocity component time-series data. These data were acquired at a sample frequency of 5 kHz, with an anti-alias filter cutoff of 1 kHz. Standard Fast
Fourier Transform (FFT) techniques were used to compute the corresponding autospectral density functions. A blocksize of 8192 points was used for the FFT and the spectra were ensemble averaged over 128 blocks (a number sufficient to provide smooth, fully converged spectral estimates). The autospectral measurements were made at several representative positions in the near-wake. An example of the results obtained is shown in Figure 2.14 which presents a comparison of velocity autospectra obtained at x/D = 4, y/D = 1 for plasma off, steady plasma and both symmetric and asymmetric unsteady plasma actuation at f = 50 Hz, 25% duty cycle conditions. As shown in Figure 2.14, velocity autospectra obtained with the plasma off are generally broadband in nature except for a dominant spectral peak centered at a Strouhal number St_D = 0.21 which is associated with Karman vortex shedding from the separated flow region. When the four SDBD actuators are operated in a steady mode, the vortex shedding is totally suppressed and the resulting velocity autospectra are broadband as shown in Figure 2.14. Not only is the discrete peak at St_D = 0.21 eliminated by the steady plasma actuation, but the broadband spectral levels are suppressed as well. This elimination of Karman shedding and wake turbulence level seems consistent with the flow visualization images shown in Figure 2.7 and Figure 2.8. With the unsteady, symmetric and asymmetric plasma actuation at f = 50 Hz, the shedding is also completely suppressed as evidenced by the broadband autospectra shown for those cases in Figure 2.14. There is a small discrete peak at f = 50 Hz and its harmonics associated with the unsteady plasma actuation frequency. Note that unsteady plasma actuation also gives rise to a significant reduction in broadband spectral content which indicates that turbulence levels in the wake have been reduced.
Mean velocity and streamwise-component turbulence intensity cross-stream profiles were obtained at selected $x/D$ locations in order to characterize the cylinder wake under natural and plasma actuated conditions. Figure 2.15 and Figure 2.16 present sample mean velocity and turbulence intensity profiles, respectively, obtained over a representative range of $x/D$. In each case profiles are shown for plasma off, steady plasma and symmetric unsteady plasma actuation at $f = 50$ Hz ($St_D = 1$), 25% duty cycle. Results for asymmetric unsteady actuation were similar to those for the symmetric case. From Figure 2.15 it is apparent that the wake defect is greatly reduced for the steady plasma case. Unsteady plasma actuation at 25% duty cycle gives rise to a wake defect reduction intermediate between the steady and plasma off cases. At a given streamwise location, unsteady actuation clearly results in a thinner wake than without the plasma. Note that the effect of
the plasma actuation on the wake mean velocity profiles persist with $x/D$. In effect, the plasma has provided a virtual streamlining of the cylinder.

Figure 2.15: Comparison of streamwise-component mean velocity profiles in the near-wake.
The plasma-off turbulence intensity profiles exhibit a characteristic saddle shape and peak intensity occurs in the two wake shear layers. The steady plasma actuation case exhibits the most
significant reduction in turbulence levels and peak intensity occurs on the wake centerline. For example, at \( x/D = 8 \) the peak turbulence intensity under steady plasma actuation is only about 20% of the peak value observed in the natural wake. Unsteady symmetric actuation also gives rise to a significant reduction in wake turbulence levels that is intermediate between the steady plasma and natural wake cases. The turbulence intensity profiles shown in Figure 2.16 also serve to demonstrate that the wake is much thinner under steady and unsteady plasma actuation than in the plasma off case.

2.2.4 Near-wake PIV measurements

The flow visualization and hot-wire measurements presented previously indicate that both steady and unsteady SDBD plasma actuation has a profound effect on the structure of the cylinder wake flow field. At a given \( x/D \) location not only is the Karman vortex shedding suppressed, but so too is the wake turbulence level. Consequently, the mean velocity defect and wake width are both reduced.

In order to investigate the physics of this observed modification in wake flow structure, the cylinder near-wake was investigated non-intrusively by using PIV measurements. The air upstream of the wind tunnel inlet was seeded with olive oil droplets of nominally 1 micrometer diameter that are produced by a TSI atomizer. A model Y120-15 New Wave Research Nd:Yag laser produced double pulses with a 50 \( \mu \)sec time interval. The maximum pulse repetition rate for this laser was 15 Hz. PIV images were captured by a PIV CAM 10-30 digital camera. TSI Insight 5 software was used to obtain a vector velocity field from each image pair. Three types of plasma actuation were investigated: steady, unsteady symmetric and unsteady asymmetric. For unsteady plasma actuation, the excitation frequency was 50 Hz (\( St_D =1 \)) with 25% duty cycle. The charge on the droplets resulting from their (shear dominated) formation process is, at most, only a few hundred electrons.
Dimensional reasoning shows that even for the maximum electric field encountered in the experiment, the aerodynamic force on the droplets is several orders of magnitude larger than the electrostatic force. This result is consistent with the PIV measurements to be presented which show no evidence of seed particles following electric field lines.

For the unsteady actuation cases, the PIV images were acquired phase-locked to the plasma excitation. In order to do this, the PIV laser was synchronized with the unsteady plasma actuation circuit. Since the maximum laser pulse repetition rate was smaller than the unsteady actuation frequency, the laser fired every fourth cycle (i.e. PIV images were taken at frequency of 12.5 Hz). The two-component PIV velocity fields were acquired at 8 different phase angles (i.e. every 45°) with respect to plasma initiation. Conditional sampling was used to acquire 150 image pairs at the same phase of unsteady actuation in order to form a conditionally averaged flow field from which movies of the dynamic behavior of the near-wake during an actuation cycle were created. In order to provide sufficient spatial resolution, the camera was positioned to acquire phase-locked flow field images of several locations in the near-wake and a composite mosaic for a given phase angle was subsequently created.

The conditionally averaged flow field images (for a given phase angle) were used to compute the spanwise component vorticity field. Figure 2.17 presents a sequence of images of the spanwise vorticity for unsteady, symmetric plasma actuation at $St_D = 1$, 25% duty cycle. The phase angles of 0°, 90°, 180° and 270° relative to plasma initiation are indicated. When the actuators are on, the region of plasma formation on the cylinder surface is indicated in the figure. Figure 2.17 shows that compact, discrete vortices of opposite sign form symmetrically on either side of the wake centerline and emerge from the cylinder surface near the actuators located on the back side of the cylinder. The discrete vortices are shed at the unsteady plasma excitation frequency of $St_D = 1$. It is
important to point out that these are not Bloor-Gerrard type vortices which are associated with the convective instability of the separated shear layer and would occur at a much higher frequency. The vortices shown in Figure 2.17 propagate along the edge of the separated flow region and converge toward the centerline of the near wake. There, the vortices of opposite sign meet and there appears to be significant cancellation of phase coherent vorticity of opposite sign. As a result, the spanwise vorticity emanating from the near wake is quite small and phase incoherent in comparison to the natural wake flow. Note also that there appears to be little cross-stream mixing of vorticity of opposite sign.
Figure 2.17: Near-wake spanwise vorticity field phase locked to symmetric plasma actuation ($St_D=1$, 25% Duty Cycle). The phase angle is indicated in each case.

Figure 2.18 presents the phase-locked, two-component near-wake velocity field at the same phase angles corresponding to the spanwise vorticity field shown previously in Figure 2.17. This figure clearly shows that the region of maximum velocity defect takes on a symmetric, tapered appearance due to the unsteady plasma actuation. Note that the spanwise vortices shown previously in Figure 2.17 propagate along the shear layers that form the boundary of the separated flow region. In Figure 2.18 these vortices are manifest as wave-like undulations traveling along the outer boundary of the maximum velocity defect region.
Figure 2.18: Near-wake, two-component velocity field phase locked to symmetric plasma actuation (StD=1, 25% Duty Cycle). The phase angle is indicated in each case.

The mean velocity magnitude and corresponding mean spanwise vorticity field for steady, symmetric operation of all four actuators is presented in Figure 2.19. Since there is no phase reference for steady plasma actuation, these figures present ensemble averaged fields. The velocity field shows that with steady plasma induced blowing, the flow remains attached to the cylinder surface and the separated flow region is very small. This is consistent with earlier results of Thomas et al [16] who demonstrated greater than 90% drag reduction using steady blowing with two actuators on a cylinder in cross-flow for Re_D = 12,000. The vorticity field of Figure 2.18 shows that
two shear layers containing vorticity of opposite sign bound the separated region and meet on the wake centerline. The downstream cylinder wake contains little coherent spanwise vorticity.

Figure 2.19: Near-wake, ensemble-averaged velocity magnitude and spanwise vorticity fields for steady, symmetric plasma actuation.

In order to provide a more direct comparison of the effects of steady and unsteady symmetric plasma actuation, Figure 2.20 presents the ensemble-averaged spanwise vorticity field for unsteady actuation at \( \text{St}_D = 1, \) 25\% duty cycle. Comparison with the ensemble-averaged spanwise vorticity shown in Figure 2.19 for steady blowing highlights both the smaller separated region (associated with delayed separation) for the steady actuation case as well as a more rapid demise of spanwise vorticity.
In a first attempt to investigate the effect of plasma actuator phasing, the actuators were operated in an asymmetric mode. As in the unsteady, symmetric case, the excitation Strouhal number remained set to $St_D = 1$ and the duty cycle was 25%. In this case, however, the top and bottom pairs of actuators were fired in anti-phase as shown in Figure 2.3. Figure 2.21 presents the conditionally averaged spanwise vorticity phase locked to the firing of the top pair of actuators. The results are remarkably similar to those shown previously in Figure 2.17, with the exception that the shed vortices are now arranged asymmetrically with respect to the wake centerline. As before, the vortex shedding occurs at the plasma excitation frequency. As in the symmetric forcing case, the
separated flow region is quite small and the apparent elimination of large-scale spanwise vorticity downstream of the cylinder still occurs. In this manner, both symmetric and asymmetric unsteady actuation are observed to eliminate Karman shedding and reduce wake turbulence levels as shown in the autospectra of Figure 2.14.

Figure 2.21: Near-wake spanwise vorticity field phase locked to asymmetric plasma actuation ($St_D=1, 25\%$ Duty cycle). The phase angle is indicated in each case.
2.2.5 Near field microphone measurements

In this section, preliminary acoustic measurements obtained in the same test section are presented which document the effect of the plasma actuation on the near-field pressure fluctuations measured with a microphone that is flush mounted in the wind tunnel wall.

The acoustic transducer used in this experiment was a 1/2inch ACO model 7046 free-field condenser microphone with 51.3mV/Pa output sensitivity. The microphone was preamplified with an ACO ½ in XLR model 412 pre-amp powered by a two-channel 200/28Vdc PS2900 power supply. The microphone signal was acquired by a personal computer utilizing a Microstar iDSC1816 A/D board. This board has onboard software-controlled anti-aliasing filters. The microphone was flush-mounted to the bottom wall of the wind tunnel test section and was located 150 mm (Δx/D = 1.5) downstream of the cylinder. The data were acquired at a sample frequency of 1024 Hz, with an anti-alias filter cutoff of 400 Hz. The power spectral density (PSD) of the signal was calculated with a frequency resolution of 0.5 Hz. Smooth, fully converged spectral estimates were obtained by ensemble averaging 256 blocks of 2048 sample points each.

The fluctuating pressure measured at the microphone will contain contributions from the cylinder wake, the tunnel wall boundary layer, and downstream fan noise. For this reason, the objective of the microphone measurements reported in this paper is to document changes in the acoustic spectrum that result from operation of the actuators in steady and unsteady mode. Sample power spectral density plots of the fluctuating pressure are presented in Figure 2.22. These were obtained at Re_D = 30,000. Three cases are shown: (1) no actuation, (2) steady actuation, and (3) unsteady, symmetric actuation at 50Hz with a 25% duty cycle. Near-field pressure fluctuations at Karman vortex shedding frequency is apparent in the no-actuation spectrum (i.e. “plasma off” case). Note that this spectral peak is is completely suppressed in both the steady and
unsteady plasma actuated cases. The power spectral density was numerically integrated from 6 to 10 Hz to obtain a sound pressure level associated with the Karman wake vortices. Calculations show that the near-field sound pressure level was reduced by plasma actuation by $13.3 \pm 0.1$ dB. This corresponds to a reduction in mean-square fluctuating pressure by a factor of about 21.4. The difference between steady and unsteady actuated spectra is small except for the presence of a 50Hz unsteady actuation frequency tone and its harmonics. The contribution from the discrete peaks associated with unsteady plasma actuation was evaluated similarly and found to be small in comparison to the level associated with the Karman wake vortices. After accounting for the discrete spectral peaks, there remained a net reduction in SPL of $4 \pm 0.1$ dB.

![Figure 2.22: The effect of plasma actuation on near-field SPL spectra.](image-url)
In a second, related experiment, two cylinders were mounted in a tandem arrangement. A smaller second cylinder of diameter 21 mm and not instrumented with any plasma actuators was placed downstream of the larger cylinder at the centerline of its wake. The distance between the axes of the two cylinders was 150mm ($\Delta x/D = 1.5$). This geometry is similar to that of a landing gear bracket mounted downstream of a larger strut. Figure 2.23 compares power spectral density plots of the fluctuating pressure measured at the microphone for the tandem cylinder arrangement. The case without plasma actuation indicates that the Karman shedding frequency is modified by the presence of the downstream cylinder. In this case plasma flow control reduces the natural shedding noise by 6.7dB which is equivalent to a reduction in mean-square pressure fluctuations by a factor of 4.7.

Figure 2.23: The Effect of Plasma Actuation on Near-Field SPL Spectra for Tandem Cylinders.
3.1 Problem formulation

In spite of growing interest in flow control using dielectric barrier discharge plasma actuators, studies regarding optimization of plasma actuators are relatively scarce. Notable exceptions include [14,63,64,65,66]. In addition, it is obvious that the application of plasma flow control at higher freestream velocities and Reynolds number range requires significant improvement in actuator authority. The goal of the current study is to increase the body force produced by plasma discharge which is a function of various parameters such as dielectric material, electrode geometry, voltage magnitude, frequency and waveform.

3.2 Experimental setup

3.2.1 Actuator and plasma generation circuit

A schematic of the plasma actuator and the photograph of the plasma optimization setup are shown in Figure 1.1 and Figure 3.1, respectively. Teflon (PTFE) and quartz square plates of dimension 12x12 inches and with thickness of 1/2, 1/4, 1/8 inch or quartz disks 6 inches in diameter, 1/16 inch thickness are used as the dielectric for the plasma actuator. Most of the experiments are conducted using quartz as a dielectric material due to its excellent electrical and thermal strength (extremely low heat expansion coefficient, very high melting temperature). Unlike plastics it does not degrade and shows excellent durability in plasma discharge. Copper tape of thickness 1.6 mil is used for the electrodes. The length of the electrodes is 8 inches for the square plate dielectric and 4 inches for quartz disk dielectric. The exposed electrode is 1 inch wide; the insulated electrode was 2
inches wide. Three layers of high voltage Scotch® rubber splicing tape (0.761 mm thickness, 69 kV max) are used as additional insulation for the encapsulated electrode to prevent the discharge at the edge of that electrode. In the current optimization study all plasma actuators are made with overlap equal to one half of the dielectric thickness.

Figure 3.1: Plasma actuator optimization experimental setup.

The high-frequency, high-amplitude a.c. voltage is created using the circuit shown in Figure 3.2. A low amplitude signal from an arbitrary waveform function generator (e.g. Agilent Technologies model 33220A) is first supplied to two, two-channel power amplifiers (Crown XTi4000). The amplified voltage from each of four channels is then fed through a resistor module containing four 2 Ohm, 300 Watt ballast resistors which are connected together at the primary coils of two 1:360 transformers with the maximum output voltage 25kV AC (Corona Magnetics). The primary coils of the transformers are connected in parallel but in the opposite polarity. The low potential leading-out wires of the secondary coils are connected to the ground. High voltage required
by the plasma actuator is taken from the two high potential leads of the transformers giving the same signal in the opposite polarity so that the effective winding ratio of this system is 1:720.

![Plasma generation circuit](image)

Figure 3.2: Plasma generation circuit for optimization study.

Dielectric barrier discharge is accompanied by high intensity radio frequency electromagnetic noise. An anti-noise filter is used to suppress this noise. The custom made filter is installed on the plastic foam base near the actuator. In essence, it is a low-pass filter consisting of an two inductors (8 turns, ferrite core, 31.1 mm OD, 19.1 mm ID, 15.9 mm Height) and a battery of four high-voltage capacitors (25pF, 15kV DC max). The filter does not affect the 1…10 kHz actuating frequency but prevents high frequency noise from entering the high-voltage wires which
the feed plasma actuators. For typical laboratory experiments, these wires have a relatively large length and radiate electromagnetic waves like an antenna if the filter is not installed.

The photograph of the whole experimental setup is shown in Figure 3.3. Plasma actuator voltage is measured by a LeCroy PPE20kV DC frequency compensated high voltage probe. The current through the actuator is measured by two Pearson Electronics Model 2100 current meters (sensitivity 1.00 Volt per Amp). The current meters are installed on both high voltage wires near the plasma actuator to exclude the additional current due to the corona discharge around relatively long high-voltage wires. The signals from all these devices are processed in real time by LeCroy LT262 oscilloscope, calculating AC power dissipation at the plasma actuator. The signals from two current meters are slightly different (within 10%) due to some charge leaking to ambient space. An average of those current meter signals is used for power calculation.
Two types of voltage waveform are used in the present optimization study: sinusoidal and positive sawtooth (ramp) suggested in [10]. These waveforms acquired by the oscilloscope are presented in Figure 3.4. In the case of sinusoidal voltage one can notice that the phase shift between voltage and current through the plasma actuator is close to 90 degrees which demonstrates the capacitive character the loading.
3.2.2 Plasma jet thrust measurement setup

One of the most important parameters that characterize the performance of plasma actuator is the thrust produced by an actuator installed on a plate in initially still air. The reaction force is measured by a precision weighting balance. Due to the momentum conservation theorem the thrust is proportional to the total body force. The advantage of this technique is a quality and rapidity of measurements.

The schematic of the thrust measurement setup and its photograph are shown in Figure 3.5 and Figure 3.6. The plasma actuator and the anti-noise filter are mounted on a plastic foam platform, which is placed on a high precision electronic weighing balance (AND model GF-6100 with resolution of 0.01 gram). The plasma actuator is oriented in such a way that when a.c. voltage is applied, the ionic wind is directed upward and the reactive force acts downward and is measured on
the weighing scale. The entire actuator assembly and the weighing scale are enclosed in a chamber with no external flow. Time averaged thrust data is read from the display of the scale.

Figure 3.5: Schematic of thrust measurement.

Figure 3.6: Thrust measurement setup.
3.3 Results of the parametric study

3.3.1 Influence of dielectric material

In the most of the previous cited studies the plasma actuator dielectric is made of several layers of 1…5-mil-thick polyimide tape [9,10]. This type of actuators undergoes fast surface degradation and, finally, irreversible electric breakdown in a barrier discharge. The typical lifetime of Kapton actuator was from 1 to 30 minutes depending on the discharge power. To increase the lifetime and the discharge power of plasma actuators melted quartz and PTFE Teflon are tested as the dielectric material and the thickness of the dielectric is increased. The increased dielectric thickness reduces the local electric field in the dielectric and allows one to apply the higher voltage, having lower heat dissipation in the discharge. Figure 3.7 shows the comparison of the thrust created by the original Kapton tape actuator and the new improved actuators. The plots show the dependence of the thrust measured by the weighting balance on the RMS voltage applied. One order of magnitude improvement in the maximum body force limited by the plasma actuator electric strength is observed. While quartz and Teflon actuators of the same dielectric thickness demonstrates the thrust of the same order of the magnitude it is reasonable to mention that Teflon actuator degrades for several minutes at a maximum power.
3.3.2 Influence of frequency and voltage waveform

Figure 3.8 shows the dependences of the power dissipation in the plasma actuator on the peak to peak voltage magnitude for the same plasma actuator at different frequencies and voltage waveforms. The dielectric is quartz with 1/8 inch thickness. The power dissipation at given voltage is roughly proportional to the frequency which is consistent with the results presented in [10]. One can notice that ramp waveform gives the same power dissipation as sinusoidal at the same frequency.
Figure 3.8: Effect of frequency and voltage waveform on power dissipation. (0.125in. quartz glass).

The dependence of thrust on the voltage magnitude for 1/8-inch-thick quartz actuator is shown in Figure 3.9. Higher frequencies produce higher body force, similar to the power dissipation behavior in Figure 3.8. It is interesting that thrust at sawtooth waveform is almost two times greater than at sinusoidal waveform at the same voltage and frequency, unlike power dissipation which is the same. This clearly demonstrates the advantage of the sawtooth waveform. This fact is in agreement with the velocity measurements of Forte et al [14] where it was found that the negative discharge at sinusoidal voltage induced more velocity than the positive one. In case of the positive sawtooth waveform, the positive discharge has the shortest duration time and the negative discharge
(the most efficient) occupies the rest of the AC cycle having maximum duration (Figure 3.4). In case of sinusoidal voltage there are significant parts of the cycle without any kind of discharge.

The advantage of the negative discharge may be explained in the following way. It is well known from gas discharge physics that the ignition of the negative corona discharge (i.e. when small or sharp electrode has negative potential) requires higher voltage than the positive one [12]. Thus the negative discharge should have higher electric field strength in the vicinity of the sharp or in case of plasma actuator the exposed electrode, with more volume charge accumulated and, consequently, greater body force generated. In addition, relatively higher uniformity or finer time-spatial streamer structure of the negative discharge should help more efficient momentum transfer to the non-ionized air. It is widely noted (for example, [10, 11]) that the positive discharge is accompanied by much more intensive and irregular current spikes and light emission.
Initially, the thrust grows very fast (Figure 3.9), with voltage magnitude increasing, but at a certain point it stops growing, although the power dissipation (Figure 3.8) keeps going up. This body force saturation is accompanied by a visible change in the discharge structure. In addition to the blue uniform glow, bright filaments appear, as shown in Figure 3.10. At high frequency (8 kHz), the saturated discharge contains many small filaments, while at the low frequency (1 kHz) the discharge has a small amount of very large filaments. Further increases in voltage, beyond the saturation point, result in an increase of the filament intensity, very high heat dissipation, dielectric degradation, and, finally, plasma actuator’s breakdown. The dotted line in Figure 3.9 connects all
the saturation points for the sinusoidal voltage. The dependence of the thrust on the saturation voltage at the varying frequency is close to linear.

Figure 3.10: Filamentary structure of plasma discharge at various frequencies for 0.125in. quartz glass: (a) 1 kHz, (b) 2 kHz, (c) 4 kHz, (d) 8 kHz, (e) normal discharge at 1 kHz.

3.3.3 Influence of dielectric thickness and electrode geometry

The thrust measurements, similar to those represented at Figure 3.8 and Figure 3.9, were taken for different dielectric thicknesses, 1/16, 1/8, and 1/4 inch. The saturation plasma body force data are summarized in Figure 3.11 and Figure 3.12. The saturation body force varies linearly with applied voltage magnitude. It may be considered to be proportional to the voltage, while its
dependence on the dielectric thickness is weak. Frequency reduction improves the saturation body force (Figure 3.12), but this approach implies the increase of the voltage and, consequently, the size of the plasma actuator.

Figure 3.11: Saturation thrust vs. voltage for different dielectric thicknesses.
To compare the energetic efficiency of the plasma actuator, the dependence of thrust on the power dissipation at different frequencies and voltage waveforms is shown in Figure 3.13. The quartz dielectric thickness is 1/8 inch thick. Lower frequency gives higher efficiency, and the positive sawtooth waveform has a significant advantage at the same frequency which is in agreement with Enloe at al. [66].
Figure 3.13: Thrust vs. power dissipation for different frequencies and waveforms.

Figure 3.14 shows a similar dependence for plasma actuators with different dielectric thickness working at the same frequency of 2 kHz. The thicker dielectric is used in the plasma actuator, the more efficiently the electrical power is utilized. Both frequency reduction and dielectric thickness increase require the increase of the voltage magnitude to keep the body force constant.
Figure 3.14: Thrust vs. power dissipation for different dielectric thickness at 2 kHz sinusoidal voltage.

The size of the plasma actuator in the direction of the induced flow is determined by the maximum voltage magnitude. The electrode width should be enough for plasma layer width, and the dielectric should be wide enough to prevent an arcing discharge between the electrodes across the edge of the dielectric. Since the voltage required for this surface arcing breakdown is proportional to the length of the discharge and the electric field in the plasma discharge does not vary significantly, the plasma actuator size should be roughly proportional to the maximum applied voltage. Therefore, summarizing the data from Figure 3.13 and Figure 3.14, it is possible to draw a conclusion that larger plasma actuators working at higher voltage have higher energetic efficiency.
3.3.4 Plasma actuator array

Further enhancements in thrust can be achieved by adding more actuators in series. In order to demonstrate the idea, experiments were performed with arrays of different number of actuators. The general arrangement of the multiple actuator arrangement is shown in Figure 3.15. The widths of the exposed and insulated electrode are 1/2 inches and 2 inches respectively. The spacing between the downstream edge of insulated electrode and upstream edge of next exposed electrode is kept constant at 1/2 inches. Figure 3.16 shows the thrust obtained by single, two, and three actuators configuration plotted against applied peak-to peak voltage. At any given voltage, adding an actuator certainly increases the thrust value compared to single actuator. However, the thrust is little lower than the sum of the thrusts of all the actuators in the array. This may be explained by additional friction losses and jet interactions.

Figure 3.15: Schematic of multiple actuators arrangement
Figure 3.16: Thrust vs. voltage for plasma actuator array.
3.4 Triode plasma actuator development

In order to increase the thrust we are developing the so-called “triode actuator” which utilizes both AC and DC voltages. The schematic and the photograph of the discharge are shown in Figure 3.17 and Figure 3.18. Preliminary tests show that the thrust of the triode plasma actuator exceeds the thrust of the regular two-electrode actuator.

![Diagram of triode plasma actuator]

Figure 3.17: Schematic of triode plasma actuator

![Photographs of discharge]

(a) (b)

Figure 3.18: SDBD discharge, DC power supply is off (a) and hybrid corona–barrier discharge (b).
CHAPTER 4: PLAN FOR PhD DISSERTATION

This chapter presents conclusions related to the plasma actuator optimization study, cylinder flow control, acoustic noise reduction and experiments. It also suggests recommendations for the future work toward further optimization of plasma actuator and flow control at higher Reynolds numbers.

4.1 Summary and discussion of current results

The optimization study has shown a one order of magnitude improvement in body force induced by a plasma actuator (measured as thrust) with the use of quartz and Teflon dielectric as compared to 6 mil Kapton actuator which has been widely used in previous flow control studies. The effect of plasma body force saturation was studied. It was found that initially both power dissipation and body force grow with increasing voltage (approximately as a 7/2 power law [10]) but at a certain voltage magnitude of the body force stops growing while the heat dissipation grows rapidly. The magnitude of the saturation voltage depends on the applied frequency. The higher the frequency, the lower the saturation voltage. This saturation phenomenon is accompanied by visible changes in plasma discharge (non-uniform, filamentary structure and additional sound generation). Since this saturation point limits maximum body force, the optimal plasma actuator operation is near the saturation point.

A strategy to increase the plasma actuator thrust was proposed. It was found that if a signal applied at optimal frequency (which means that the actuator always stays near the saturation point) while changing voltage magnitude, the body force for a single plasma actuator depends primarily on the voltage magnitude and this dependence is close to a linear one. That is, thicker dielectric
material and lower frequency help increase maximum voltage and, hence, the maximum thrust. The positive saw-tooth waveform was confirmed to produce maximum thrust and energetic efficiency. The results of the optimization study are partially used in the flow control experiments, since these two studies were conducted in parallel. Among them are a new dielectric material (quartz glass) for the cylinder model, an increase in the dielectric thickness, use of the optimal frequency, voltage waveform and magnitude.

The results of the flow control experiments presented in this paper clearly demonstrate the feasibility of the plasma fairing concept for effectively streamlining bluff body flows. In particular, it is demonstrated that a (sparse) array of surface mounted SDBD plasma actuators can effectively streamline a circular cylinder in cross-flow. Steady operation of the actuators is shown to drastically reduce the degree of flow separation, the associated Karman vortex shedding being eliminated. As a consequence, both the wake mean velocity defect and width are reduced, as shown in the mean velocity profiles in Figure 2.15. An associated benefit of the steady plasma actuation is that peak turbulence levels in the downstream wake are reduced by approximately 80% from those in the natural wake.

It is shown that the use of unsteady plasma actuation at 25% duty cycle and a frequency corresponding to $St_D = 1$ also eliminates Karman shedding, and downstream wake turbulence levels are reduced. Both symmetric and asymmetric unsteady actuations are shown to produce similar effects. For unsteady actuation, compact vortices are shed at the unsteady plasma actuation frequency and propagate to the wake centerline where considerable cancellation of coherent vorticity of opposite sign occurs. In this case, the peak turbulence level in the wake is reduced by 66%, relative to the peak values in the natural wake. Furthermore, this is accomplished with only
25% of the power input to the actuators required for steady actuation. Lower duty cycles approaching 10%, however, were found to lead to reduced flow control effectiveness.

Microphone measurements confirm the reduction of near-field pressure fluctuations associated with suppression of vortex shedding. For both steady and unsteady actuation, near-field sound pressure levels are reduced by 13.3 dB in a frequency band centered on the shedding frequency. Similarly, for tandem cylinders, near-field sound pressure level is reduced by 7.7 dB. Since unsteady plasma actuation is associated with an unsteady body force, it produces tones at the actuation frequency and its harmonics. In the experiments reported here, there is still a net SPL reduction of 4dB despite the tones. However, for those flow control applications which are focused at aerodynamic noise reduction, there is an advantage in using the plasma in a steady mode of operation. We estimate these achievements to be encouraging, with regard to the utilization of these devices in aeroacoustic control applications.

It is evident, that with the fixed actuator authority, the effectiveness of the flow control will lose substantially, as the Reynolds number goes up [16]. For a commercial transport on landing approach, the Reynolds number for the flow over the landing gear oleo will be \( O(10^6) \). Hence, for application in flight, the actuation authority must undergo a commensurate increase. Increased body force can be achieved by (1) increasing the applied voltage and optimizing the waveform, (2) utilizing improved dielectric materials for construction of the actuators, and (3) increase the number of actuators in series. The behavior of multiple actuators in series has been examined by Post [13] and Forte et al [14]. It has been demonstrated that the thrust due to actuators in series is approximately additive. According to our measurements, increasing the number of actuators in series increases the thrust but the total thrust is lower than the sum of the thrusts of all the actuators in the array. The utility of adding additional actuators is clear by comparing the results of this study
which utilizes four actuators on the cylinder surface with those of Thomas et al [16] which utilized only two. The Reynolds number range for effective flow control more than doubled with the addition of two actuators.

In addition to overcoming problems associated with achieving sufficient actuator authority, the extreme geometric complexity of landing gear must be addressed. It has been shown that the removal of small parts like hoses, tubes, etc. reduces high frequency gear noise [1,67]. Hence, it is envisioned that landing gear noise control might be best achieved by shielding small elements behind larger elements which are effectively streamlined through a combination of passive shaping and plasma actuation. In such a case the plasma actuation could be used for wake vectoring away from downstream gear elements and/or suppression of shedding and fine scale turbulence.

Since the possibility to efficiently control the flow around a circular cylinder has been demonstrated, the main goal of the future study is to extend the Reynolds number and freestream velocity range as close as possible to the range of technical interest. In this view, in order to deal with the higher Reynolds numbers in our studies, a new cylinder model was designed and tested. This model is of the same size and uses thicker quartz glass and more powerful plasma generation circuit which has been used in the optimization study. This circuit is capable of generating the sawtooth voltage waveform. The width of the electrodes was increased, to improve the body force, and the amount of actuators was limited by two, instead of four, to satisfy packing constraints. Preliminary smoke flow visualization, hot-wire and PIV results of this new model demonstrate the ability to efficiently control the flow at freestream velocity up to 13m/s (Re=84000).

4.2 Proposed future work and plan for dissertation

The following is proposed as a research plan for PhD dissertation:
(1) Develop DBD plasma actuators with sufficient actuator authority to operate at airspeeds typical of commercial transport landing approach. This will involve utilization of new dielectric materials like quartz and Macor, integrating multiple actuators in series, and operating at increased applied voltages and lower frequency (since velocity perturbation varies as voltage to the 7/2 power). Quantify plasma-induced velocity and thrust as function of applied voltage and power. Incorporate the effect of the plasma actuators into numerical simulations that can be used as a design tool in order to establish optimum actuation strategies for elimination of the major sources of airframe noise.

We are convinced that it is possible to implement further modernization of the electronic plasma generation circuit, in order to increase output voltage magnitude and, therefore, the body force.

It should be observed that certain aspects of the actuators’ optimization are not yet elucidated which makes us go on in our plasma optimization studies. In particular, it was found that the efficiency of the plasma actuator grew with the reduction of the frequency of applied voltage. That’s why investigation of a very low frequency range as well as direct current discharge may be especially interesting.

(2) Continue developing a “triode” plasma actuator. Investigate the influence of the applied AC voltage magnitude, frequency and waveform DC voltage magnitude on thrust and power dissipation. Optimize this actuator in terms of body force, electrical power consumption and packing constraints for the plasma actuator array. Compare performance of the “triode” plasma actuators to the regular “diode” plasma actuator.

(3) Improve flow field diagnostic capabilities. Rapid degradation of constant temperature hot-wire probes during use in the actuated flow was revealed. This may be caused by ozone
production and small intensity corona discharge around the probe. Being extremely chemically active, ozone causes oxidation of the tungsten wire in the anemometer probe. According to another conjecture, the plasma actuator also creates high intensity electric field and ion flow in the test section. The electric potential of the hot-wire is close to the ground, so the small intensity corona discharge ignites around the exposed high-curvature parts of the probe. To resolve this issue, quartz coated hot-films with coating thickness of 2 µm were tried, instead of tungsten hot-wires. The degradation of the coated hot-films was slower than tungsten hot-wires but it was still high enough to affect the measurements. As the next step to reduce the probe degradation, we propose to use a Faraday cage around the hot-film probe. This Faraday cage should be designed in such a way that it does not disturb the velocity field near the probe. After that, a comprehensive hot-wire anemometry study of the wake will be done. If it is impossible to overcome the hot-wire degradation, PIV or LDV will be used instead.

PIV results presented in the current study show a good resolution far from the cylinder. However, the quality of the velocity field near the cylinder surface was not sufficient, due to reflected laser light and plasma glare. For future PIV experiments, we propose to apply a special non-reflective coating and an optical filter, in order to resolve the velocity field as close to the surface as possible.

(4) Demonstrate the application of the plasma fairing concept for landing gear noise reduction to more realistic gear model and to Reynolds numbers typical of landing approach. It is suggested to continue to investigate flow control with tandem cylinders and to use a model similar to shown in Figure 1.4. The plasma actuators will be installed on the main cylinder. We envision a scenario in which small gear components are positioned aft of larger elements (hence reducing high frequency noise) and the large elements are effectively streamlined by the plasma fairing.
For the sake of further extension of the Reynolds number range, certain optimizations of plasma actuator angular location and applied voltage will be done. For the subcritical Reynolds numbers range, plasma actuators can be installed closer to the front of the cylinder at the location of the separation point of the non-actuated flow. The new location of plasma actuators is supposed to increase the efficiency of the flow control. Due to additional free space on the cylinder surface an extra of pair plasma actuators will be installed to the back of the cylinder. It is also suggested to compare the effect of plasma flow control with the effect of passive vortex generators installed on the cylinder surface. The study of the simultaneous work of plasma actuators and vortex generators are of particular interest. In this case we can investigate plasma flow control of a turbulent boundary layer. Preliminary tests at Reynolds numbers close to the transition regime ($Re=200,000…250,000$) of the supercritical boundary layer separation are in progress. For the supercritical Reynolds numbers range, it is planned to install the plasma actuators closer to the back of the cylinder at the location of the supercritical separation point of the non-actuated flow.

A cylinder model of a smaller diameter (about 60mm) with two plasma actuators is also planned to be constructed. This will reduce blockage effect and allow one to conduct the wake measurements at greater relative distances from the cylinder. In case of successful “triode” actuator optimization, a pair of actuators of this type will be installed on this cylinder instead of regular.

The difference between steady and unsteady flow control mechanisms is not well understood from the cylinder flow control experiments. Currently we are in the process of investigating the physics of steady and unsteady jets induced by a plasma actuator on the flat plate without external flow. This includes hot-wire and PIV measurements of the jet velocity at different unsteady actuation frequencies and duty cycles.
Since the capabilities of the low speed subsonic windtunnel are not exhausted, the experiments with the cylinder models described above will be performed in this windtunnel up to freestream velocities of 30…40 m/s (Reynolds numbers up to 250,000). A new windtunnel for the Mach number 0.6 with 3x3 feet test section is under construction. It is planned to develop new models from a single 100mm in diameter cylinder to more complicated configurations mentioned earlier for this windtunnel. The flow control experiments will be conducted at higher Reynolds numbers (250,000…1,000,000), depending on the progress with low Re experiments in the low speed windtunnel.

(5) Obtain more accurate acoustic data for cylinder model and investigate plasma-based noise control for more complicated landing gear models mentioned earlier. It is suggested to conduct new microphone measurements in an anechoic openjet wind tunnel, since regular subsonic wind tunnel used in the present study produced considerable fan noise. There is a possibility to use the second hard wall test section in which the top and bottom walls contain acoustically absorbent cavities. A detailed description of the acoustic liner is presented in Olson [57]. The design of the acoustically absorbent cavities was based on the acoustically absorbent test section liner applied to the NASA ARC Fluid Mechanics Laboratory 35.5cm by 35.5cm wind tunnel (Allen and Soderman [58]). But for frequency range of our interest (5…100Hz) this wall treatment is not efficient so we prefer to conduct our future acoustic measurements in the openjet anechoic wind tunnel. Circular cylinders and more complicated landing gear models are planned to be tested with a single microphone or microphone array to investigate the angular dependence of the radiates acoustic noise intensity. The same 1/2inch or 1/4inch ACO free-field condenser microphones will be used in these measurements. The Reynolds number range for this study will be from 30,000 to 200,000 since the
anechoic windtunnel has approximately the same maximum velocity as the regular subsonic low speed windtunnel.

(6) Develop performance and efficiency metrics for DBD plasma flow control. Using existing data compare performance and efficiency of DBD plasma flow control with passive vortex generators installed on the cylinder surface. Quantify advantages and limitations, if any, on the application of DBD flow control and airframe noise reduction for flight speeds of commercial transport aircraft in landing approach or take-off configurations.

(7) Perform experimental validations of the LES-based computational tool for the design of plasma-based airframe noise control strategies. LES modeling of plasma flow control experiments of single and tandem cylinders will be performed by other collaborators. Quantify uncertainties in experiments and predictions and differences between experimental results and predictions. The low Reynolds number data (Re=30000 and 86000) already exist but additional measurements may be needed for different Re depending on the numerical study progress. This validation involves taking near wake velocity data using PIV and far wake measurements using hot-film or laser technique.
BIBLIOGRAPHY


