Investigation of Three Dimensional Forcing of Cylinder Wake with Segmented Plasma Actuators and the Determination of the Optimum Wavelength of Forcing

DISSERTATION

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By

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Abstract

The wake of a circular cylinder was forced in a three dimensional manner with the help of spanwise non-uniformly located dielectric barrier discharge plasma actuators. The segmented actuators created a square wave forcing profile due to alternate existence of plasma and no plasma region on the cylinder at ±80° from the forward stagnation point. The wavelength (λ) of the actuators was varied from 1d to 6d (d = diameter of the cylinder) and the induced velocities from all the actuators were matched. Below a threshold power level, vortex shedding was not significantly attenuated for any wavelengths, although distinct patterns of streamwise vortices formed for λ > 2d. Due to this, the near wake developed a spanwise wavy structure: in the no-plasma region the spanwise vortex came closer to the centerline, while it was shifted away from the centerline in the plasma region. In this low-power forcing regime, the drag in the wake was not significantly affected as compared to the case when the forcing power level was above the threshold. Forcing with the λ = 4d actuator at this high power level resulted in substantial drag reduction and an increase in three-dimensionality of the near wake accompanied by a drastic attenuation of vortex shedding. The energy of the shedding was distributed over a wide range of frequencies, with the most prominent frequency in the velocity spectra being lower than the natural shedding frequency indicating reduced formation length. For λ > 4d, the wake behind the no-plasma region was much wider.
compared to that of the plasma region along with a clear difference in formation length, which resulted in higher drag than the $\lambda = 4d$ case. This finding lead to the recognition of $\lambda = 4d$ as the optimum wavelength of forcing. In the high power-forcing regime, counter-rotating vortices were formed in the horizontal plane at the edge of each buried electrode, which created an alternate zone of backflow in the no-plasma region and downstream flow in the plasma region. Appearance of a saddle point marked the boundary of the backflow region indicating increased level of strain in the no-plasma region in the high power forcing case. The transition from a lower power level below the threshold to that above it was marked by a change in the sense of rotation of the streamwise vortices for $\lambda > 3d$. This change was the result of the dominance of vortices created by high power forcing over a secondary vorticity whose sign matched that of the low power case. It is concluded that this change in the sense of rotation of streamwise vortices with power level of actuation is an inherent feature of the segmented forcing for any wavelength; however, it is the optimum wavelength for which this transition is achieved with minimum induced velocity. The streamwise vortices in the low power case could not disrupt the shedding process, whereas in the high power regime, existence of strong counter-rotating vortices created backflow in front of no plasma region, which diverted flow from the spanwise vortex and thus stymied its growth.
Dedication

This document is dedicated to my parents.
Acknowledgments

After reaching this point, when I reflect back on the starting days of PhD, I realize how unfit I was for this journey to begin with. Fortunately, my advisor, Dr. Jim Gregory has been very patient and given me ample time to learn and improve on my shortcomings. I have a long way to go to match his penchant for quality and detailing in every aspect of research, but at least now, I know what level of perfection is required for a good quality work. This has been a valuable learning experience and I must thank him for teaching me that and for being kind and helpful. I would also like to thank him for providing an unfettered access to a high quality wind tunnel and instruments for long period.

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experiments. Kevin Disotell reviewed this dissertation and my papers many times. Mehmet Tomac, Matt Metka and Chris Clifford helped me a lot with PIV set up. I would like to thank Mr. Chad Bivens for helping me with the fabrication part. Lastly, I am grateful to my parents for giving me the moral support during the course of this journey.
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Nomenclature

\( A_{cylinder} = \) surface area of cylinder perpendicular to free stream

\( A_{plasma} = \) surface area of plasma formation

\( b = \) width of buried electrode

\( C = \) capacitance

\( C_d = \) drag coefficient

\( C_{\mu} = \) blowing coefficient

\( d = \) diameter of cylinder

\( d_{vortex} = \) diameter of streamwise vortex

\( f_{st} = \) frequency of shedding

\( h = \) plasma formation length

\( I = \) current

\( l = \) length of cylinder

\( n = \) number of buried electrode

\( P = \) power

\( Q = \) charge of the capacitor

\( Re = \) Reynolds number

\( St = \) Strouhal number

\( T_s = \) vortex shedding period

\( U_{\infty} = \) free stream velocity
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U$</td>
<td>velocity along $x$ direction</td>
</tr>
<tr>
<td>$&lt;U&gt;$</td>
<td>mean velocity along $x$ direction</td>
</tr>
<tr>
<td>$u'$</td>
<td>fluctuation in streamwise velocity</td>
</tr>
<tr>
<td>$\tilde{u}$</td>
<td>phase averaged streamwise velocity</td>
</tr>
<tr>
<td>$u''$</td>
<td>incoherent fluctuation in streamwise velocity</td>
</tr>
<tr>
<td>$V$</td>
<td>velocity along $y$ direction</td>
</tr>
<tr>
<td>$V_b$</td>
<td>band passed version of $V$</td>
</tr>
<tr>
<td>$V_h$</td>
<td>voltage from high voltage probe</td>
</tr>
<tr>
<td>$V_c$</td>
<td>capacitor voltage</td>
</tr>
<tr>
<td>$v'$</td>
<td>fluctuation in transverse velocity</td>
</tr>
<tr>
<td>$W$</td>
<td>velocity along $z$ direction</td>
</tr>
<tr>
<td>$w'$</td>
<td>fluctuation in spanwise velocity</td>
</tr>
<tr>
<td>$X_{saddle}$</td>
<td>distance of saddle point from cylinder in $xz$ plane</td>
</tr>
<tr>
<td>$x$</td>
<td>streamwise direction</td>
</tr>
<tr>
<td>$y$</td>
<td>transverse direction</td>
</tr>
<tr>
<td>$z$</td>
<td>spanwise direction</td>
</tr>
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**Greek**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>wavelength of actuator</td>
</tr>
<tr>
<td>$\phi_{phase}$</td>
<td>phase angle</td>
</tr>
<tr>
<td>$\rho_j$</td>
<td>density of induced jet</td>
</tr>
<tr>
<td>$\rho_{\infty}$</td>
<td>density of free stream air</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>circulation</td>
</tr>
</tbody>
</table>
\( \omega_x = \) streamwise vorticity

\( \omega_z = \) spanwise vorticity

**Acronyms**

AC = alternating current

AR = aspect ratio

CCD = charge coupled device

DBD = dielectric barrier discharge

EMI = electromagnetic interference

FFT = fast fourier transform

PDF = probability density function

PIV = particle image velocimetry

POD = proper orthogonal decomposition

STFT = short time fourier transform
Chapter 1: Introduction

1.1 Aim of the proposed research

Flow past a bluff body creates vortex shedding which causes a periodic force. This periodic force may threaten the structural integrity of the body if the frequency of shedding matches the natural frequency of the body. Apart from this type of vortex-induced vibration, a considerable drag force acts on a bluff body due to the presence of a wide wake. This drag force is Reynolds number ($Re$) dependent. Few researchers have shown that three-dimensional control was more effective in reducing drag and cancelling shedding compared to two-dimensional forcing. In the present research, this line of thought was pursued. This work focuses on investigating the effect of three-dimensional forcing on the turbulent structures in the wake and on the resulting drag characteristics. Three-dimensional forcing was implemented using dielectric barrier discharge plasma actuators (DBD) and the optimum forcing wavelength was identified. Afterwards, the existence and the physical mechanism of the optimum condition for this specific forcing strategy was explained.

1.2 Flow past cylinder

The flow past a bluff body has been the topic of numerous investigations. Circular cylinders are used as a canonical case for bluff body flow. In this section, the important characteristics of flow past a cylinder will be discussed. Much of this discussion is inspired by the works of Williamson and Zdravkovich. The flow is governed by a non-
dimensional ratio known as Reynolds number \((Re)\). Up to a \(Re = 50\), the flow over a cylinder approximates a potential flow with two distinct recirculation regions in the wake of the cylinder. As \(Re\) is increased, the wake flow starts to oscillate. After \(Re = 60-70\), the separated flow from both sides of the cylinder rolls up to form vortices, which eventually shed into the wake alternately. This phenomenon is known as vortex shedding. Strouhal number \((St)\) characterizes the frequency of this periodic event. After the laminar vortex shedding regime (up to \(Re = 140\) or 194), the wake becomes three-dimensional due to inception of streamwise vortices. Initially in the wake, the streamwise vortices form as vortex loops with a spanwise wavelength of 3-4 cylinder diameters. They have been termed as “mode A” structures by Williamson\(^4\). After a certain \(Re\), the mode A structures are replaced by finer streamwise vortices (“mode B”) with a spanwise wavelength of around one cylinder diameter. At a higher \(Re = 1000\), the separated shear layers from the cylinder surface are subjected to the Kelvin-Helmholtz instability. This flow regime is termed as ‘transition in the shear layer region’\(^6\). The boundary layer on the surface of the cylinder is still laminar in this flow regime. However, the vortices formed in the wake are turbulent due to transition in the separated shear layer. As \(Re\) is increased, the transition point starts to move upstream. With further increase in \(Re\), the boundary layer, leading up to separation becomes turbulent.

**1.3 Background on flow control method**

Flow control methods can be broadly divided into two categories: passive and active approaches\(^7\). This classification is based on the use of an external power source or not. In passive control methods, various devices such as a splitter plate\(^8\), tabs\(^9\), or wavy
surfaces\textsuperscript{10-14} have been used for flow control on bluff bodies without using external power sources. These passive control schemes act by altering the body geometry or by changing the surface roughness characteristics. Active control methods use different kinds of actuators with an external power supply. For example, suction and blowing have been used by many researchers to control boundary layer flow.\textsuperscript{15} Active forcing schemes can also be categorized into global or local forcing based on the location of the actuators. Global forcing affects the whole flow system, while local forcing schemes target a specific aspect of the flow, which can be controlled locally, for example controlling the location of the separation point or introducing a local perturbation to trip a boundary layer flow. One example of global flow control is given in the work of Browand,\textsuperscript{16} who forced the flow with a speaker placed downstream of the test section in order to produce distinct periodicity in the flow.

The work described in references \textsuperscript{9-14} (using passive forcing schemes) had one common feature in the resultant wake dynamics. Each of the passive control techniques created a boundary condition, which varied in the spanwise direction. Therefore, in principle they represented three-dimensional forcing. A major finding from these works was the resulting increase in the three dimensionality of the wake. Park \textit{et al.} concluded that variation of the wake width in the spanwise direction forced the Kármán vortex street to lose its two dimensional nature and thus led to vortex dislocation and reduced drag.\textsuperscript{9} The wavy trailing edge used by Tombazis and Bearman caused vortex splitting in the wake due to the phase mismatch between two neighboring cells of different frequencies.\textsuperscript{11} In work with a wavy cylinder (Ahmed and Bays-Muchmore\textsuperscript{10}; Lam \textit{et al.}
al\textsuperscript{13}.) the three-dimensionality was caused by the difference in flow characteristics between the nodal and saddle plane. Lam et al. observed that the wake in the formation region of the saddle plane was wider than that of nodal plane.\textsuperscript{13} They concluded that three-dimensional vortex structures would break down more rapidly when they interacted with each other. This was indeed one of the clear benefits of three-dimensional forcing. Kim and Choi obtained a considerable insight into the effect of segmented forcing of cylinder wake from their numerical work.\textsuperscript{17} Sinusoidal blowing and suction through a straight slot on the surface of the cylinder was implemented as a boundary condition in the simulation. They argued that the increased effectiveness of the three dimensional forcing could be explained in terms of a spanwise phase mismatch in the Kármán vortex street. This phase mismatch caused vortex dislocations, which disrupted the formation of the Kármán vortex street downstream of the bluff body. Due to the increased three-dimensionality, the momentum transfer increased in the wake region leading to increased base pressure and reduced drag on the body.

\textbf{1.4 Control by exploiting secondary instability}

The action of three-dimensional forcing in the wake of a cylinder is entwined with the existence of secondary instabilities. After a certain Reynolds number ($Re$), the wake of the cylinder becomes three-dimensional due to the emergence of streamwise vortices that coexist with the spanwise oriented Kármán vortices. Around $Re = 140$, the streamwise vortices have a wavelength of 4-5 $d$, which Williamson\textsuperscript{4} referred to as mode A structures. Mode B, with a spanwise wavelength of 1$d$, appears in the wake at $Re = 230$-260. Mode A also differs from mode B in terms of sense of rotation between each shedding cycle.
The sign of vorticity of the mode B structures does not change between two consecutive shedding cycles. However, in the case of mode A it changes after every half-shedding cycle. Due to this, vortices of opposite sense are arranged in a staggered manner from one-half cycle to the next. A number of researchers have shown that these secondary instabilities play an important role in three-dimensional forcing. In an optimization study, Poncet et al.\textsuperscript{18} observed that three-dimensional control led to a much higher drag reduction compared to a two-dimensional approach. The maximum drag reduction was obtained when the three-dimensional variation corresponded to modes A and B. Similar observations have been made by Dobre et al.\textsuperscript{19} in a study with square cylinders having wavy upstream faces. The wavelength of the sinusoidal front face was the same as the mode A wavelength. They reported suppression of shedding and accelerated decay of the turbulent fluctuations in the wake. Researchers working with wavy cylinders have also demonstrated the effectiveness of three-dimensional perturbation techniques. Lam et al.\textsuperscript{13} reported a drag reduction of 20\% for $\lambda/d=2.27$ where $d$ was the mean cylinder diameter. In a later paper, Lam et al.\textsuperscript{14} explained the three-dimensional nature of the wake induced by the wavy cylinder. The vortex street in this case had a natural waviness due to the difference in the location of separation point between a nodal plane (the maximum diameter location) and a saddle plane (the minimum diameter location). Flow visualization revealed that the wake region behind the saddle plane was wider than that of the nodal plane due to early separation. The average vortex-formation length of the wavy cylinder was more than a regular cylinder, which contributed to reduced drag. Researchers working with square cylinders or bluff bodies with blunt trailing edge have
implemented similar ideas. Darekar and Sherwin\textsuperscript{12} performed a numerical investigation with square cylinders having sinusoidal waviness at a $Re = 100$. The maximum drag reduction was obtained when the wavelength of forcing was comparable to the wavelength of mode A instability, a case they termed regime III type A. They argued that suppression of vortex shedding and consequent reduction of drag was because of the redistribution of spanwise vorticity to the streamwise and vertical directions. Compared to studies with passive forcing, there is a dearth of active forcing experiments in the literature with different wavelength of forcing. This is probably due to the ease of setting up a passive forcing experiment without the need of any external actuator, electronics etc. Lahouti \textit{et al.} have reported one such experiment with active forcing where they explored the possibility of controlling the wake of a blunt trailing edge body by injecting secondary instability in the flow through a series of injection slots.\textsuperscript{20} The wavelength of the perturbation was equal to that of the mode B instability and they obtained a 19\% reduction in drag at $Re = 815$.

1.5 Active forcing with plasma actuators

The use of plasma actuators as active flow control devices has been the focus of many studies over the last two decades. The main benefits of such actuators are low power consumption, quick response time, mechanical simplicity, robustness, and easy operation. Among the different kind of plasma actuators, attention has been mostly concentrated on DBD plasma actuators. In a review paper, Corke \textit{et al.} have summarized both the physics and the application of DBD plasma actuators.\textsuperscript{21}
When a high-voltage AC signal is applied across a pair of electrodes, separated by a dielectric medium, plasma is created due to the collision of free electrons with air molecules, which locally ionizes the gas. The charged particles are accelerated through the strong electric field. They subsequently collide with neutral particles, creating a body force on the fluid in the form of a wall jet. This jet can be utilized for flow control purposes. McLaughlin et al.\textsuperscript{22} and Munska and McLaughlin\textsuperscript{23} used plasma actuators to control the flow around a circular cylinder by achieving lock-on of vortex shedding with the forcing frequency. They also found that forcing created a spanwise coherence in the shedding. Sosa et al. used a three-electrode DBD actuator on a cylinder surface and achieved drag reduction of 25\% with respect to the base flow configuration.\textsuperscript{24} The electrodes could be configured such that the net force due to ion drift was in the streamwise direction leading to suppression of flow separation. Thomas et al.\textsuperscript{25} and Kozlov and Thomas\textsuperscript{26} implemented DBD plasma actuation for flow control on a circular cylinder at $Re$ as high as 85,000. They used both spanwise- and streamwise-oriented actuators to suppress vortex shedding, in a manner based primarily on separation control. The pulsed mode of actuation of plasma actuator was found to be very effective at low power levels by Jukes and Choi.\textsuperscript{27} They achieved a maximum drag reduction of 32\% with pulsed actuation. For a high value of actuation frequency, it was possible for them to terminate vortex shedding. They argued that high frequency actuation created smaller scale shear layer vortices, which prevented the roll up process and thus attenuated vortex shedding.
1.6 Motivation of the present research

The present research focuses on augmentation of three-dimensional structures in the wake with the help of segmented forcing. The motivation of the work stems from the results obtained by spanwise non-uniform passive forcing\textsuperscript{9-15} and the numerical work by Kim and Choi.\textsuperscript{17} The primary interest of the present research was to force streamwise vortices such that the three dimensionality in the wake increases with an attendant reduction in shedding strength. Very few works have been reported in the literature where segmented forcing has been implemented with active flow control techniques. Active forcing is superior to passive forcing in the sense that the forcing parameters can be variably adjusted and the use of fixed geometric modifications to the body can be avoided.

Recent developments in DBD plasma actuators\textsuperscript{27-30} have enabled three-dimensional flow control strategies to be implemented on bluff bodies. These new actuators are not limited to producing the traditional tangential wall jet, but can also produce wall-normal jets that provide directed momentum. Three-dimensional plasma actuators hold much more promise for control authority since they effectively penetrate the boundary layer and more readily direct high-momentum fluid for control purposes.\textsuperscript{27-30} This property of the three-dimensional DBD plasma actuators can be implemented for effective generation of streamwise vorticity. Gregory\textit{ et al.} used force-shaped plasma actuators for three-dimensional control of a circular cylinder wake at a $Re = 6500$.\textsuperscript{31} A sinusoidal induced velocity pattern with alternating regions of wall-normal and wall-tangential blowing was produced by plasma actuators fixed at azimuthal locations of $90^\circ$ and $270^\circ$ on the cylinder
surface. Both X-wire wake surveys and flow visualization studies revealed a substantial modification of the spanwise wake structure.

In the present work, symmetrically placed plasma actuators were used to force the wake of a circular cylinder in a three-dimensional manner. The geometry of the actuator was varied in the spanwise direction with a segmented buried electrode such that a square-wave pattern of plasma formation was created; this configuration resulted in square-wave spatially modulated tangential blowing. The primary aim of this work was to study the wake response to this actuation at various power levels and spanwise wavelengths. Two-component hot wire measurements were taken at different downstream locations in the wake in order to obtain the velocity profile and spectra. The effect of forcing on the streamwise vorticity was investigated with the help of PIV. Flow visualization with smoke wire technique was carried out to photograph the state of the wake under the action of forcing.
Chapter 2: Experimental methods

2.1 Wind tunnel and cylinder models

The experiments were conducted in a closed-return low-speed wind tunnel in the Department of Mechanical and Aerospace Engineering at The Ohio State University. The wind tunnel has a test section with 0.6-m x 1.22-m cross sectional area. The flow uniformity of the tunnel in the vertical direction (at the point where the cylinder was mounted) was measured by a pitot tube; the free stream velocity variation was found to be less than 1%. The cylinder model was mounted directly between the test section sidewalls at a vertical height of 0.6 m and distance of 0.6 m from the end of the contraction section. The free-stream velocity was monitored by a pitot tube connected to an electronic manometer (Datametrics, Dresser). The cylinder model was made of Plexiglas tubing with an outer diameter of 25.4 mm. End plates were mounted at both ends of the cylinder to minimize the effect of sidewall boundary layers on the flow. The end plates were designed following the guidelines recommended by Stansby.³² The aspect ratio (l/d) of the cylinder model was 20. All of the experiments were carried out at a \( Re = 4700 \), based on cylinder diameter and a free stream velocity of 3.0 m/s.
2.2 Plasma actuator construction and operation

The DBD plasma actuators were constructed by using two copper tapes (thickness of 0.074 mm) as electrodes and two layers of Kapton tape as the dielectric material between them (total thickness of 0.18 mm). The width of the exposed electrode was 6.4 mm and it covered the entire span of the cylinder. The buried electrode was made from copper tape of 13-mm width and was mounted on the surface at regular (segmented) intervals. The length of the buried electrode was changed based on the wavelength of actuation under consideration. A strip of copper tape was mounted on the downstream face of the cylinder and used as a common power bus to the buried electrodes. The sharp corners of the electrodes were rounded off to avoid high electric field concentrations at the corners and possible burn out. The actuators were positioned on the cylinder surface at ±80° from the forward stagnation point (Figure 1), which is an optimum angle for maximum flow effectiveness. Step-changes in thickness of the actuator were minimized as much as
possible, in order to avoid disturbing the flow. The validity of this was evaluated by measuring wake profiles of a bare cylinder and of one with plasma actuators installed; differences in the wake structure and flow statistics were negligible. A representative data set has been plotted in Appendix C.

The DBD plasma actuator was driven by an AC signal from a function generator (Agilent 33220A). The signal consisted of a sine wave at a frequency of 5 kHz. The peak-to-peak amplitude of the sine wave was varied to change the power level of actuation. The output of the function generator was fed to an audio amplifier (Crown, XTi 2000). The amplified signal was then taken through a step-up transformer (Corona Magnetics, CMI 5530) with a turn ratio of 1:137. The output of the transformer was connected to the exposed electrode lead. The buried electrode was connected to the ground. To measure the current to the buried electrode a 47-nF capacitor was connected between ground and the buried electrode. A high voltage probe (Tektronix P6015A) was used to measure the voltage applied across the electrodes. The three waveforms (input to the amplifier, high voltage probe output and voltage across the capacitor) were saved in a digital oscilloscope (Tektronix TDS 2014B). Power was calculated in the following way. Let,

\[ Q = CV_C \]
\[ I = \frac{dQ}{dt} \]
\[ I = C \frac{dV_C}{dt} \]

\[ P = \int_{\tau}^{\tau+2\pi} V_n I dt = \int_{\tau}^{\tau+2\pi} V_n C \frac{dV_C}{dt} dt \]  

(1)
The integration was carried out over one period of the AC cycle. The final power was calculated by computing the average over all cycles.

2.2.1 Induced velocity measurement with pitot tube

The ions created by the action of the plasma actuators, collide with neutral air molecules to create a jet of air close to the surface. Measurement of this induced velocity was carried out with a glass pitot tube. The glass pitot tube was mounted on the traverse and the traverse was controlled in the single pulse mode. This micro-movement enabled successful capturing of the maximum velocity point. It is to be noted that the maximum velocity point stays very close to the actuator surface and fine resolution of the traversing is essential for correct evaluation of the induced velocity. In the present case, it was observed that the tip of the pitot tube had to be touched on the surface of the actuator to capture the maximum velocity point in every case. The glass pitot tube was connected to an electronic manometer (Datametrics, Dresser).

2.3 Hot wire measurement

A multichannel hot wire anemometer system (Dantec Dynamics multichannel MiniCTA) was used along with two $X$-wire sensors for acquiring velocity samples from the wake of the cylinder. One of the $X$-wire probes (labeled as probe 1 in Figure 1) was positioned directly downstream of the middle of the region where plasma formation was prevented due to absence of the buried electrode (region 1). The other $X$-wire (probe 2) was held directly downstream of the middle of the region where plasma formed between the exposed and buried electrodes (region 2). The $X$-wire sensors (Auspex) consisted of 5-micron diameter tungsten wire spot-welded between the prongs. The output of the
anemometer was sampled simultaneously by an A/D board (NI-6035E) at 50 kHz. Post processing of the acquired data was performed in MATLAB. A fourth-order Butterworth digital filter was used to band-pass filter the data with lower cutoff frequency of 5 Hz and upper cutoff frequency of 1000 Hz.

### 2.3.1 Calibration of X-wires

The X-wires were calibrated in-situ in the tunnel. The advantage of in-situ calibration procedure was that it took care of the effect of wind tunnel confinement, blockage due to traverse etc. The look-up table approach was followed for this purpose. In this method; the X-wires were pitched from +45° to −45° in the free stream at different tunnel velocities. A look-up table was generated which gave a surface plot of U and V velocity with two voltage output of the X-wire. Figure 2 and Figure 3 show representative plots of the look-up table calibration.

![Figure 2](image1.png)  
**Figure 2.** Typical pitch angle calibration data for X-wire  

![Figure 3](image2.png)  
**Figure 3.** Surface plot of streamwise velocity with X-wire voltages
2.4 Particle image velocimetry

Particle image velocimetry (PIV) is a non-intrusive measurement technique, which can yield important information about the flow over a significant area. During a typical 2D-PIV experiment, the flow field is filled with seeder particles, which scatter light when illuminated. Generally, a laser source is used to create a light sheet for illumination purposes. Pairs of images are acquired at rapid succession with the help of a CCD camera. The time delay between two images of a pair can be of the order of milliseconds. Most of the time, a double pulsed laser source is used and the triggering of the laser and camera are synchronized. The velocity vectors are computed by correlating the shift of the illuminated particles between the two frames.

Understanding the nature of the streamwise vortices called for a detailed investigation in the $yz$ plane where the cross sections of these vortices could be visualized. For this interrogation plane, the camera was mounted inside the tunnel viewing towards the cylinder from a downstream location of approximately $x/d$ of 80 (see Figure 4). Raw images from this view showed regions of “glow” resulting from light emission from the plasma. To avoid false correlations of this fixed pattern, a background image (with the plasma actuator operating and the flow off) was subtracted from subsequent data images.

For PIV in the $xz$ plane, the camera was placed on top of the wind tunnel, viewing the flow field at an angle through a cutout in the tunnel wall (see Figure 5). The effect of the inclined viewing angle was accounted for by a calibration method in the PIV system software (LaVision DaVis 7), which applied a perspective correction on the calibration image.
2.4.1 Data processing

An X-wire sensor was used to acquire a reference signal along with the PIV images for computing phase-averaged images. A total of 2000 images were acquired in each case at a frame rate of 10 Hz. With the natural vortex shedding near 23 Hz the flow could not be time resolved since the maximum frame rate of the camera in double exposure mode was less than shedding frequency. However, meaningful convergence in the time-averaged quantities was reached with 2000 images. Convergence was ensured by checking data points in the centerline of the wake where the fluctuation in velocity was a maximum. The pulse separation timing was fixed at 700 microseconds. This particular value was selected after several trials with other pulse separation timings, which did not yield satisfactory results. A check on PIV data quality was based on three parameters, namely the percentage of rejected vectors, $Q$ value and agreement with time-averaged $V$ velocity with the literature. The $Q$ value is a measure of the ratio of the first and second highest correlation peak. This ratio is an indication of the “goodness” of the computed vector field. A high value of $Q$ ($Q>2$) implies that a computed vector is likely a valid vector. Before computing vector fields from 2000 raw image pairs, a test evaluation was carried out on a single image pair. If the percentage of rejected vectors was below 10%, the corresponding settings of batch processing was continued, otherwise the different parameters were changed to reduce the percentage of rejected vectors. A proof of validation of the PIV data in the unforced case has been provided in Appendix C.

Before computing the vectors, the images were pre-processed by applying a sliding background filter and a particle-intensity-normalization filter. The sliding background
filter worked as a high pass filter to smooth out high intensity fluctuation. Particle intensity normalization helps to correct any high fluctuation of intensity (due to inhomogeneous particle diameters) present inside the window. This normalization increases the intensity of small particles such that they also contribute to the correlation. The vector field was computed by using a standard FFT technique in DaVis software. A multi-pass iteration scheme with decreasing window size (two passes consisting of 64x64 and 32x32-pixel interrogation windows) was used with 50% overlap between the windows. During post-processing, a median filter was applied to improve the vector field computation.

### 2.4.2 Perspective error

To explore the extent of three-dimensionality, PIV was first carried out in the \( yz \) plane. For this purpose, the camera was held inside the tunnel at a downstream location. Figure 4 shows the schematic of the experimental set up in the wind tunnel. Since the flow (\( U \)) in this case was predominantly out-of-plane towards the camera, the images contained perspective errors in \( V \) and \( W \). Due to this error, the velocity vectors appeared to diverge out of the image plane (see Appendix C ). These effects were substantially visible in the outer boundaries of the images. To account for this error, PIV images were acquired in an empty tunnel at the same free-stream flow speed. The average \( V \) and \( W \) across the plane computed from this run were treated as the bias errors in \( V \) and \( W \). These errors were subtracted from vector fields obtained in later experiments in \( yz \) plane. The profile of transverse velocity \( V \) was checked against literature and it yielded a good match.
in the unforced case. A discussion on the various sources of uncertainty is given in Appendix B.

2.5 Flow visualization

Smoke wire flow visualization was carried out to obtain a visual representation of the state of the wake under the action of different types of forcing. The main region of interest was the near wake. A 0.004” diameter Nichrome wire (with knots periodically spaced along the length) was stretched vertically (perpendicular to the cylinder) at an upstream location of 1 inch from the cylinder. SAE 20W motor oil, brushed onto the wire, produced smoke when an electric current was passed through the wire, which formed streaklines in the flow. The wire was heated by applying a voltage from a variable transformer. Images of the smoke flow were taken using a high-speed camera (Vision Research Phantom v311) at a rate of 400 frames per second.
Figure 4. Schematic of PIV setup in the wind tunnel, the laser sheet was formed in \( yz \) plane at \( x/d = 5 \)

Figure 5. Schematic of PIV setup in the wind tunnel, the laser sheet was formed in \( xz \) plane at \( y/d = 0.5 \)
Chapter 3: Results and discussion

3.1 Baseline flow

The flow past a circular cylinder at various $Re$ is well documented in the literature. The baseline flow for the present research corresponds to the flow over cylinder in an unforced condition with the actuators mounted on the cylinder. Characterization of the cylinder wake in the unforced case was carried out using $X$-wires, PIV and flow visualization using smoke wire. The velocity profiles obtained in the unforced case were compared with the literature.\(^{34}\) Figure 6a to Figure 6c represent the mean and fluctuating velocity profiles acquired in the near wake. The present case is referred to as probe 2 since the $X$-wire designated as probe 2 was traversed in the center $xy$ plane of the wake. The natural shedding frequency of the unforced case was near 23 Hz, which corresponded to a $St$ of 0.19. The velocity spectra presented in Figure 7 shows a distinct peak at 23 Hz indicating strong presence of periodic shedding. Occurrence of vortex shedding was clearly observed in the smoke wire flow visualization image in Figure 8. In the unforced case, regular pattern of streamwise vorticity was absent in the near wake. This was confirmed by Figure 9 which represents the contour of the mean normalized streamwise vorticity obtained at $x/d = 5$. The mean was computed from 2000 images acquired with the help of PIV. This finding signifies that in the case of flow past a regular cylinder the streamwise vortices do not occur at fixed locations rather their existence is spatially random in nature.
Figure 6. Validation of baseline cylinder results with Ong and Wallace$^{34}$
Figure 7. Velocity spectra in the unforced case. The hot wire was placed at $x/d = 5$, $y/d = 0.5$

Figure 8. Smoke wire flow visualization image of the baseline flow

Figure 9. Contour plot of mean $\omega_x d / U_z$, unforced baseline case
3.2 Selection of power levels

The breakdown voltage of the Kapton film serving as a dielectric material limited the maximum power supplied to the actuators. In order to select the power level to operate the plasma actuators, a power sensitivity study was carried out at $Re = 4700$. In this experiment the actuators (with $\lambda = 4d$) were held at $+90^\circ$ from the forward stagnation points. An X-wire was held at $x/d = 5$ and $y/d = 0.5$. The actuators were then operated at different power levels. At each power level, the spectra were computed from the acquired $U$ velocity signal. It was observed that with increasing power the value of the shedding frequency (represented by the frequency corresponding to the peak amplitude in the spectra) gradually decreased along with its amplitude. After a certain threshold power, the shedding was drastically reduced leading to its near elimination (Figure 10). From this result, two different power levels of 5.6 watts and 13.6 watts were selected for further experiments. The main idea behind this selection was to conduct experiments in two distinct regions of forcing: one in which the forcing is mild in the sense that it does not completely cancel shedding but may have some subtle influence in the wake, and another, stronger forcing level where the Kármán shedding is completely cancelled.

3.3 Induced velocity matching

The effective actuator surface area is different for each wavelength tested (due to the difference in the number of wavelengths able to be accommodated given the fixed aspect ratio of the cylinder). Therefore, the same supply signal would create different levels of induced velocity due to differing impedances between the actuators (impedance differs
because of different surface area, wiring length etc.). In order to compare the different actuators, the induced velocity in each case was maintained constant. This was done in the following way. First, the induced velocity was measured for the reference $\lambda = 4d$ actuator in both low and high power settings with the help of a glass pitot tube. Next for any other actuator, the supply signal from the function generator was manipulated to yield the same induced velocity as measured for the reference geometry. Therefore, the numerical values of dissipated power vary slightly between actuators for the same induced velocity. The induced velocities for all the actuator designs are presented in Figure 11. Velocity samples were acquired over two segments of buried electrode in each case and checked for consistency. It is to be noted that the quantity $\delta z$ varies for all the cases depending on the wavelength such that data could be acquired at the same fractions of spatial wavelength. The mean induced jet velocity for low power was 0.55 m/s and the mean velocity for high power was 1.77 m/s.

Based on the measured velocity profiles, a blowing coefficient may be determined as,

\[
C_\mu = \frac{\rho_j U_j^2 A_{\text{plasma}}}{\rho_{\infty} U_{\infty}^2 A_{\text{cylinder}}} = \frac{\rho_j}{\rho_{\infty}} \left( \frac{U_j}{U_{\infty}} \right)^2 \frac{2nbh}{ld} \approx \left( \frac{U_j}{U_{\infty}} \right)^2 \frac{h}{d} \tag{2}
\]

where $h$ is the plasma formation length along the circumference of the circle, $d$ is the cylinder diameter, $l$ is the spanwise length of the cylinder, $b$ is the width of the buried electrodes, $n$ is the number of buried electrodes on one side of the cylinder, and the subscript $j$ indicates induced jet properties. A blowing coefficient ($C_\mu$) of 2.7x10^{-3} was obtained for the low-power plasma actuation (based on a plasma formation length $h = 2$ mm and the cylinder diameter $d = 25.4$ mm), and for the high-power case it was 2.7x10^{-2}.  

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3.4 Forcing location

The free shear layers show increased response to disturbances if the disturbances can be introduced at the most receptive location for the shear layer. To locate the most
effective angular location of the plasma actuators, the following experiment was carried out. One X-wire sensor was located at $x/d = 2$ and $y/d = 0.5$ in front of region 2 (plasma region). The actuator on the opposite side of the cylinder was disconnected from the actuation circuit for this experiment. The cylinder was rotated such that the junction line between the exposed electrode and the buried electrode of the top actuator (hereafter referred to as the junction line) was located at various angles from the forward stagnation point with plasma being operated at a modulation frequency matched to the shedding frequency, $f_{st}$. From the literature it is known that the tentative separation angle of the flow over a circular cylinder at $Re = 4700$ is around $86^\circ$ from the forward stagnation point. Thus, the junction line was rotated from $75^\circ$ to $90^\circ$ from the forward stagnation point. The raw output voltage of one of the wires from the X-wire was connected to a spectrum analyzer (HP 35665A). The power spectrum option was selected with long time averages (300 samples of 500 ms). Each sample was windowed with a Hanning window and with 50% overlap between windows. From the display monitor of the spectrum analyzer the time-averaged amplitude and the frequency of the shedding peak were recorded manually. The criteria for determining the most effective angular location for the actuation was based on the locked-on amplitude of the natural shedding peak in the spectrum. The result of this study is given in Figure 12. Based on this result the most effective angle for forcing was selected as $80^\circ$ from the forward stagnation point. It is to be noted that in reality the forcing actually takes place over an arc on the cylinder, which spans several degrees. By fixing the junction line between the exposed and the buried electrode at $80^\circ$, it was ensured that the induced momentum was added to the flow before
the point of separation. Based on this result, the actuators were mounted at ±80° from the forward stagnation point, to ensure a symmetric forcing condition.

![Graph](image)

Figure 12. Amplitude of the shedding peak vs. angle of actuator junction line from the forward stagnation point.

3.5 **Drag measurement and determination of optimum wavelength**

The study for the selection of power levels of forcing (Section 3.1) revealed strong attenuation of vortex shedding in the wake in the high power range. Initial measurements showed that segmented forcing with low power setting was not effective in reducing drag. For this reason, extensive drag measurement was carried out only in the high power forcing case of all the actuators. To assess the performance of different actuators, drag was measured in the intermediate wake at a streamwise distance of $x/d = 40$. Two $X$-wires were used for this purpose. One $X$-wire was held straight behind the no-plasma region (probe 1) and another was held behind the plasma region (probe 2). Two separate drag coefficients were computed by numerically integrating the velocity profiles obtained from the two $X$-wires. The mean of these two values is presented as the overall
coefficient of drag. This approach provides a better estimation of the overall drag in the case of segmented forcing than using a single velocity profile. To verify this approach, velocity profiles were acquired in other spanwise locations in the wake of a \( \lambda = 6d \) actuator under high power forcing. It was found that considering two velocity profiles obtained in the middle of plasma and no plasma region, was sufficient to obtain the coefficient of drag (see Appendix C for representative data). Equation 3 was used for numerical integration of the velocity profiles.\(^\text{36}\)

\[
C_d = 2 \int_{y/d = 6}^{y/d = 6} \frac{U}{U_\infty} \left( 1 - \frac{U}{U_\infty} \right) d \left( \frac{y}{d} \right) + 2 \int_{y/d = 6}^{y/d = 6} \left( \frac{v^2 - u^2}{U_\infty^2} \right) d \left( \frac{y}{d} \right)
\]

Equation 3

This equation also accounted for the Reynolds stresses in the wake. Figure 13 shows the computed \( C_d \) values for all the cases. This figure clearly shows that the coefficient of drag has a minimum at \( \lambda = 4d \). The increase in the drag in case of \( \lambda = 1d \) case could not be explained as this case was not investigated in detail. However, the trend line connecting the \( C_d \) values shows gradual decrease of drag after \( \lambda = 1d \) up to \( \lambda = 4d \) indicating the success of segmented forcing.

Figure 14(a) to (f) show the velocity profiles at \( x/d = 40 \) obtained for each actuator in the high power case. It is evident that the \( \lambda = 1d \) and \( 2d \) actuators do not show large deviations from the unforced case. Consequently, the average \( C_d \) values in these cases were close to the unforced case. However, a significant effect can be observed for actuators having wavelength greater than \( \lambda = 2d \). The velocity profiles begin to show signatures of reduced defect for \( \lambda = 3d \) actuator and higher. As a result, the drag was concomitantly reduced. The average \( C_d \) for the \( \lambda = 3d \) actuator was 0.74 which was very
close to that obtained for $\lambda = 4d$ actuator (0.73). An important feature can be observed in the velocity profiles for $\lambda = 4d$ and higher. The velocity profiles obtained by probe 1 (no-plasma region) show a much wider wake (flatter profile) compared to probe 2 (plasma region). Due to the existence of a wider wake in front of the no-plasma region the $C_d$ computed from these profiles have higher values from those of the probe 2 profiles. The average $C_d$ values in these cases were always greater than those for $\lambda = 3d$ and $4d$. The noticeable difference in probe 1 (no plasma) and probe 2 (plasma) velocity profiles for $\lambda = 5d$ and $6d$ is a direct consequence of segmented actuation. Based on these drag measurements, a spatial wavelength of $\lambda = 4d$ represents the best actuator configuration in terms of aerodynamics performance. The supremacy of the segmented forcing over two dimensional forcing was established by measuring the drag under high power forcing in the wake of a cylinder mounted with two dimensional spanwise uniform actuator. The induced velocity of the two dimensional actuator was matched with the reference $\lambda = 4d$ actuator. In this case, the measured $C_d$ was 0.96.
Figure 13. Drag coefficient values for all wavelengths, measured at $x/d = 40$, high power forcing case.
Figure 14. Streamwise velocity profiles at $x/d=40$ for high power forcing (a) $\lambda = 1d$, (b) $2d$, (c) $3d$, (d) $4d$, (e) $5d$, (f) $6d$. 
3.6 Low power case

Figure 15(a) to Figure 15(f) display contours of time-averaged non-dimensional streamwise vorticity ($\langle \omega_x \rangle * d/U_\infty$) computed from PIV data, which were obtained in the low power forcing cases, in the transverse plane ($yz$) at $x/d = 5$. In each contour plot, the black dashed lines denote the boundaries of the cylinder in the field of view and the spanwise location of the plasma formation is denoted by the purple rectangles. With the cylinder coordinate system being a left-handed one, the blue-colored contours (negative) denote rotation in the anticlockwise direction, and red colored contours denote clockwise rotation. In the unforced case, organized patterns of $\omega_x$ were not observed (see Figure 9). As a general characteristic of cylinder wakes, the streamwise vortices do not occur at fixed spanwise locations; rather, their appearance is spatially random in nature. For this reason, any naturally-occurring streamwise vortices did not survive the long time averaging in the unforced case. The same inference can be drawn for the $\lambda = 1d$ and $\lambda = 2d$ actuator low power forcing cases. No organized pattern of time averaged streamwise vorticity can be found in either Figure 15(a) or (b). This finding clearly shows the ineffectiveness of these actuators in introducing considerable three-dimensionality in the wake. A qualitatively different picture of the wake is obtained in Figure 15(c) to Figure 15(f). The contour plots show clear emergence of spatially organized streamwise vorticity in the wake at $x/d = 5$. Figure 16 depicts the variation in the size of the streamwise vortices with wavelength of actuation in the case of low power forcing. In order to calculate the size of the vortex, the following procedure was applied. The contours corresponding to positive vorticity (clockwise rotation) were considered for this
calculation. The maximum positive vorticity was determined from the computed vorticity field with 10% of the maximum level taken as a cutoff value. The contour corresponding to the cutoff vorticity level was plotted and the enclosed area was calculated. The size of the vortex was represented by the diameter of a circle having an area equal to the area enclosed by the contour with the cutoff level. Figure 16 shows that the size of the streamwise vortex increases monotonically in the low power forcing case. This feature is also visible in the contour plots (Figure 15(c) to (f)). The circulation of the streamwise vortices was calculated from the same closed contours used for estimation of the vortex size. Figure 17 represents the variation of the normalized circulation levels with wavelength of actuation in the low power forcing case. The normalized circulation also follows an increasing trend with wavelength of actuation. This is directly related to an increase in the size of the streamwise vortex.
Figure 15. Contour plot of mean $\omega_d/U_x$, low power forcing case, (a) $\lambda = 1d$, (b) 2d, (c) 3d, (d) 4d, (e) 5d, (f) 6d
Figure 16. Diameter of streamwise vortex at $x/d = 5$, low power forcing case

Figure 17. Normalized circulation of streamwise vortices, low power forcing case
3.6.1 On the generation of streamwise vortices in low power case

To further shed light on the emergence of streamwise vorticity revealed by the PIV investigations in the near wake, phase-averaged spanwise vorticity reconstructions are presented in Figure 18 through Figure 20. The phase averaged spanwise vorticity was computed from velocity signals obtained by traversing two X-wires in the vertical direction at \( x/d = 5 \) in the wake of \( \lambda = 4d \) actuator. The idea of phase averaging the velocity signal is applicable here since the strong periodic occurrence of vortex shedding can be detected from the sharp peak in the spectrum of the velocity time series. The streamwise velocity \( U \) (or the transverse velocity \( V \)) at any such point in the wake where shedding can be detected, can be written as a sum of a mean velocity and its fluctuating component, e.g., \( U = \langle U \rangle + u' \). The fluctuating component, in turn, can be thought of as a sum of a periodic component due to the passage of large-scale structures and a component due to random fluctuation, \( u' = \tilde{u} + u'' \). The periodic component, \( \tilde{u} \), can be obtained by phase averaging the \( U \) and \( V \) signals obtained from the X-wires, following the analysis of Kiya and Matsumura.\(^{37}\) The method is briefly described here for reference. The \( V \) velocity signals obtained from the X-wires at each \( y/d \) location were band-pass filtered (\( \pm 1 \) Hz). The central frequency of the band was set at the peak frequency \( f \) of the spectra of \( v' \) obtained at that individual \( y/d \) location. Thus, \( f \) denotes the shedding frequency obtained at each \( y/d \) location. The band-pass filtered version of the \( V \) (denoted by \( V_b \)) signal itself was used as a reference signal to carry out the phase averaging. An arbitrary origin of time was chosen from the reference signal such that \( V_b = 0 \) and \( dV_b/dt > 0 \). This denoted the starting point of the shedding cycle. The end point of a half-cycle
was chosen such that \( V_b = 0 \) and \( dV_b / dt < 0 \). The interval of this portion of \( U \) and \( V \) was then stretched or compressed such that each half-cycle occupied the same length of time. The phase average was obtained after averaging the original \( U \) and \( V \) signals over all the cycles of the band-pass filtered \( V \). This procedure was repeated for all of the \( U \) and \( V \) signals obtained at different \( y/d \) locations. It is to be noted that the averaging was done over two cycles. The spanwise vorticity \( (\omega_z) \) was computed from the phase-averaged \( U \) and \( V \) signals by employing a central difference technique, and invoking Taylor’s hypothesis.

Figure 18 shows the computed phase averaged vorticity contours for the unforced case at \( x/d = 5 \), while Figure 19 and Figure 20 show phase averaged vorticity for the no-plasma and plasma regions, respectively, when flow control is active (low power). It is apparent that the vortices are closer to the centerline downstream of the no-plasma region (probe 1, Figure 19), compared with the unforced case (Figure 18). Conversely, the transverse spacing of the vortices is greater in the region downstream of plasma (probe 2, Figure 20), compared to the unforced case. Furthermore, the level of peak vorticity downstream of the no-plasma region (probe 1, Figure 19) is lower compared to the peak vorticity of the plasma region (probe 2, Figure 20). There is little difference in the peak vorticity between the unforced wake and the plasma region of the forced wake. The difference in the location of the center of the spanwise vortices between the plasma and the no plasma region is evidence of a wavy vortex street in the low power forcing case.

To further emphasize the variation of near wake structure, images obtained from smoke wire flow visualization are presented next. Figure 21 displays streaklines in the
no-plasma region of the wake (where probe 1 was held) under low power forcing, while streaklines in the plasma region are shown in Figure 22 (flow is from left to right in both images). The portions of the spanwise vortices in the no-plasma region (Figure 21) are located closer to the centerline than those in the plasma region (Figure 22). Furthermore, the spanwise vortices in the plasma region appear to be stronger and have a wider range of influence across the transverse direction. These inferences from flow visualization are in agreement with the findings from the phase-averaged spanwise vorticity.

Figure 18. Unforced phase averaged spanwise vorticity ($\langle \omega_z \rangle d/U_\infty$) at $x/d=5$. Contour levels are 0.2 to 1.2 (solid) and -0.2 to -1.2 (dashed), with intervals of 0.2.
3.7 High power case

In the high power case, the plasma actuators were operated with a higher supply voltage from the function generator, with the induced velocity matched for all actuators
(see Figure 11). The emergence of a distinct pattern of streamwise vorticity became more prominent with high power forcing. The contour plots of streamwise vorticity, Figure 23(a) to (f), clearly demonstrate this. It is to be noted that the direction of rotation of the streamwise vortices have changed in the case of the $\lambda = 4d, 5d$ and $6d$ actuators, from that of the low power forcing case [Figure 15(d), (g) and(f) vs. Figure 23(d), (e) and (f)]. The sense of the vortices formed at the corner of the electrodes in $\lambda = 2d$ and $3d$ high power forcing cases differs from other actuators tested ($\lambda = 4d, 5d$ and $6d$). In order to emphasize this particular feature, attention is drawn towards the middle electrode (centered at $z/d = 0$) in the top half ($y/d > 0$) of Figure 23(b) and (c). The vortex formed at the left corner of each of the middle electrodes in these two contour plots has negative vorticity (anti clockwise rotation in a left-handed coordinate system). The direction of rotation changed for $\lambda = 4d$ and $5d$ actuator high power forcing cases, Figure 23(d) and Figure 23(e). The sense of vorticity is the same at both low and high power forcing for $\lambda = 3d$ [see Figure 15(c) and Figure 23(c)]. Therefore, it can be assumed that, for $\lambda = 4d$ and higher, the dominant mechanism for streamwise vortex formation (in high power forcing case) is characteristically different from lower wavelength actuators. When $\lambda = 2d$ and $3d$ actuators were operated in high power mode, the streamwise vortices became more organized and stronger than those in low power forcing case but they retained the same sense of rotation. When the $\lambda = 2d$ and $3d$ actuators were driven with increased power, it strengthened the mechanism responsible for generation of streamwise vorticity in the low power forcing case. On the other hand, in case of $4d$ and higher wavelength actuators, the circulation zones at the corner of each electrode was strong enough to
create a spanwise variation which completely changed the direction of rotation of the streamwise vortices from the low power case.

Figure 24 represents the variation of the size of streamwise vortices with different wavelengths of actuation, in the high power forcing case. The method of calculation has been described before. In this case, the vortex size is maximum for $\lambda = 5d$. The average diameter is smaller in the case of $\lambda = 6d$. The reason becomes clear from inspection of Figure 23(f). This figure represents a complicated pattern of streamwise vorticity, which was not observed in other cases. The vorticity field is comprised of vortices created by segmented forcing which surround a cell of secondary vorticities. Figure 25 shows the variation in circulation for the high power forcing case. The circulation level follows the same trend with wavelength as the vortex size. The smaller size of the streamwise vortices in the $\lambda = 6d$ actuator case also contributes to its reduced circulation levels.
Figure 23. Contour plot of mean $\omega_x d/U_\infty$, high power forcing case, (a) $\lambda = 1d$, (b) $2d$, (c) $3d$, (d) $4d$, (e) $5d$, (f) $6d$
Figure 24. Diameter of streamwise vortices, $x/d = 5$, high power forcing case

Figure 25. Normalized circulation of streamwise vortices, high power forcing case
3.7.1 On the generation of streamwise vortices in high power case

High power forcing altered the wake dynamics significantly. This kind of significant attenuation was not observed in the low power forcing with any of the actuators. Changes in the wake characteristics under high power forcing will be portrayed through the vorticity field in the \(xz\) (horizontal) plane and phase averaged spanwise vorticity computed from \(X\)-wire signals. All of these different findings will help to reconstruct the structure of the wake under high power forcing.

The strong attenuation of shedding in the near wake hinted at the possibility of significant base flow modification by forcing. The extent of this modification was not completely understood either from hot wire data or cross plane PIV data. In order to obtain better insight into the flow field close to the actuator, PIV was carried out in the \(xz\) plane at a distance of \(y/d=0.5\) from the centerline of the wake. Figure 26 and Figure 27 show the streamline traces obtained in the \(xz\) plane in the high power forcing case with \(\lambda = 5d\) and \(6d\) actuators. In both of these figures, distinct circulating regions have formed at the edges of the electrodes (denoted by purple rectangles). Counter-rotating vortices formed at the corner of each electrode, entraining fluid from the no-plasma region. As a result, a significant amount of backflow occurs in front of the no-plasma region and the flow in front of the plasma region is accelerated. A saddle point marks the boundary of the backflow region. The periodic occurrence of accelerating flow and backflow appears to be the primary manifestation of segmented forcing in the high power case. A similar experiment was carried out with the low power case, although no such circulating regions were found [see Figure 76(d)]. The counter-rotating structures in the \(xz\) plane are
definitely the cross section of longitudinal vortices developed very close to the cylinder in the high power forcing case. Attenuation of vortex shedding can also be explained by the existence of the backflow regions. The counter-rotating streamwise vortices divert a significant amount of flow from the near wake towards the cylinder. Because of this, the supply of fluid to the Kármán vortex is reduced and subsequently formation of the spanwise vortex is hampered due to discontinuity in the fluid supply. The counter rotating vortices also induce a considerable strain field in the wake. The existence of a distinct saddle point in front of the no-plasma region clearly indicates the presence of a strong strain field in the near wake under high power forcing.

Insight into the corresponding spanwise vortex structure can be obtained from the phase-averaged hot-wire data. The phase-averaged spanwise vorticity was computed in the same way as described before in the discussion of the low power case. Figure 28 represents the normalized spanwise vorticity in front of the no-plasma region (probe 1). Under high power forcing for the $\lambda = 5d$ actuator case, the shedding frequency in the no-plasma region was near 19 Hz. This frequency was used as the reference signal during phase averaging. The same procedure was adopted for probe 2 (Figure 29). The phase-averaged vorticity contours in Figure 28 provide an insightful connection with Figure 27. Saddle points in the wake are characteristics of highly strained regions. In the wake of the circular cylinder, saddle points exist in the braid region between two consecutive rollers having opposite sense of rotation. In Figure 27, the near wake of the no-plasma region is strained due to severe backflow towards the cylinder. Probe 1 was located in front of the no-plasma region during the X-wire survey. The effect of the strain field is clearly visible.
in the phase-averaged vorticity contours in Figure 28. The axes of the vortices are inclined at a specific angle, which was close to 45 degrees. This finding indicated that the spanwise vortices in front of the no-plasma region were oriented along the direction of the principal plane in the strain field induced by high power forcing. The contour levels have a reduced value compared to the low power forcing case as vortex shedding was severely attenuated in the high power case for actuator with wavelength greater than $\lambda = 2d$.

A meaningful comparison of Figure 28 and Figure 29 also helps to understand the reason behind the change of orientation of the vortices at a specific location between low power and high power forcing. Unlike in Figure 19 the vortices in Figure 28 have been pulled away from the centerline due to the strain field in the no plasma region of the near wake. This is not the case in Figure 29 where the centers of the vortices are staggered close to the centerline. Therefore, the differences in the locations of the vortex centers between the no-plasma and plasma regions are exactly opposite in the high power forcing case compared to the low power forcing. This relative displacement of the spanwise vortex (with reduced strength due to high power forcing) is caused by the change in orientation of the streamwise vortices. The phase averaging technique also yielded important insight into the relative performance of different actuation wavelengths. Forcing with the $\lambda = 2d$ actuator did not prove as effective as the $\lambda = 4d$ or $5d$ actuator in terms of drag reduction. The inability of the $\lambda = 2d$ actuation to impart any drag benefit will be explained later using velocity spectra. A similar argument can also be made by comparing the phase-averaged vorticity contours for the $\lambda = 2d$ actuator with other
wavelengths. The phase-averaged vorticity in the no plasma region of the $\lambda = 2d$ actuator with high power forcing is shown in Figure 30. A qualitative comparison of Figure 30 with Figure 28 shows that for the $\lambda = 2d$ actuator, the vortices in the no plasma region are not oriented in the direction of the principal axes, which signifies an absence of elevated strain levels compared to the higher wavelength actuators. However, the vortices in Figure 30 show the formation of a distinct lobed region due to elongation of the outermost contour. This elongation is likely due to the action of less strain induced by segmented forcing. Apart from this, high power forcing with the $\lambda = 2d$ actuator shows an important departure from the higher wavelength case. There are less appreciable differences in the vortex centers for the plasma (Figure 31) and no-plasma regions (Figure 30) compared to the higher wavelengths.

Figure 26. Streamline traces in $xz$ plane at $y/d=0.5$, 5$d$ actuator high power forcing case.

Figure 27. Streamline traces in $xz$ plane at $y/d=0.5$, 6$d$ actuator high power forcing case.
Figure 28. Phase averaged spanwise vorticity ($\langle \omega_z \rangle d/U_\infty$, calculated from probe 1) at $x/d = 5$ for $5d$ actuator, high power forcing. Contour levels are 0.2 to 0.6 (solid) and -0.6 to -0.2 (dashed), with intervals of 0.1.

Figure 29. Phase averaged spanwise vorticity ($\langle \omega_z \rangle d/U_\infty$, calculated from probe 2) at $x/d = 5$ for $5d$ actuator, high power forcing. Contour levels are 0.1 to 0.3 (solid) and -0.2 to -0.1 (dashed), with intervals of 0.1.

Figure 30. Phase averaged spanwise vorticity ($\langle \omega_z \rangle d/U_\infty$, calculated from probe 1) at $x/d = 5$ for $2d$ actuator, high power forcing. Contour levels are 0.2 to 1 (solid) and -1 to -0.2 (dashed), with intervals of 0.1.

Figure 31. Phase averaged spanwise vorticity ($\langle \omega_z \rangle d/U_\infty$, calculated from probe 2) at $x/d = 5$ for $2d$ actuator high power forcing. Contour levels are 0.2 to 1 (solid) and -0.9 to -0.2 (dashed), with intervals of 0.1.
### 3.7.2 Velocity spectra obtained in the near wake

The passage of Kármán vortices about the centerline of the wake is a prime contributor to the momentum deficit. Knowing the effect of high power segmented actuation on the primary instability would provide a better understanding of the drag reduction mechanism. This question was addressed by acquiring hot wire spectra at $x/d = 5$. The arrangement of $X$-wire probes was the same as for the drag measurement. The two $X$-wire probes (probe 1 held behind the no-plasma region and probe 2 held behind the plasma region) were traversed in the $y/d$ direction. At each $y/d$ location velocity samples were acquired and the transverse velocity fluctuation ($v'$) was computed. The spectra were computed from this fluctuating signal by using Welch’s power spectral density estimate. This was carried out in MATLAB with the help of the command ‘pwelch’. The fluctuating velocity signal was divided in certain number of segments with 50% overlap, before computing the spectra. Each segment was windowed with a Hamming window. Figure 32(a) to (n) represent the spectra obtained for different actuation wavelengths under high power forcing. The unforced case is shown first in Figure 32(a) and (b). Both probes 1 and 2 detected a strong presence of vortex shedding. The natural shedding frequency can be recognized from the predominant sharp peak, which was near 23 Hz. With the amplitude of $v'$ being stronger at the centerline, the highest peaks are observed in this region. The height of the shedding peak decreases due to the weakening of the $v'$ signal as the probes traverse away from the centerline. Figure 32(c) and (d) show that high power forcing with the $\lambda = 1d$ actuator, did not have much of an effect on the vortex shedding. The peak heights in this case are comparable to the unforced case. For the $\lambda =
2d actuator, it is observed that in front of the plasma region [Figure 32(f)], the strength of shedding is not only less than the unforced case but it is also less than the shedding peak for the no-plasma region [Figure 32(e)]. In other words, the influence of segmented forcing began to reveal itself at this actuator wavelength. A significant decrease in the height of the shedding peak was observed in the case of high power forcing with the \( \lambda = 3d \) actuator [Figure 32(g) and (h)]. This decrease in height is due to severe weakening of \( v' \) around the centerline, which is a result of attenuation of vortex shedding strength. However, the frequency of the attenuated peaks is not shifted; rather, the shedding frequency remains fixed at the natural shedding frequency. A shift in shedding frequency is observed in Figure 32(i) and (j). These figures represent the high power forcing with the \( \lambda = 4d \) actuator. The strength of vortex shedding has been severely attenuated in both spectral plots. In Figure 32(i), which represents spectra obtained in front of the no-plasma region, the prominent frequency peaks are situated near 18 Hz. This denotes a clear downshift in the shedding frequency. The reason for this shift will become clear once the definition of formation length is taken into account. Formation length signifies the distance of the point (from the center of cylinder) where a complete vortex forms for the first time. Due to the action of high power forcing with the \( \lambda = 4d \) actuator, the vortex shedding was highly attenuated and the formation length increased. This means the time between two successive vortex formations will be longer. Thus, a decrease in shedding frequency is observed. Apart from the shift, another important feature in Figure 32(j) is the diffusion of the main peak to other frequencies. This distribution of energy signifies the appearance of structures of similar strength at nearby frequencies. Inspection
confirms that in the case of the $\lambda = 4d$ actuator the peak heights are lower than for the $\lambda = 3d$ actuator. Moving on to the spectra for the $\lambda = 5d$ actuator in Figure 32(k) and (l), several interesting features are observed. The prominent frequencies in the probe 1 spectra (no-plasma region) are still near 18 Hz but are of higher magnitude compared to the $\lambda = 4d$ case. Nevertheless, it is the probe 2 spectra, which are surprising, where two peaks appear in the spectra. The first peak is at a lower frequency (18 Hz) and the other is at a higher frequency (32 Hz) compared to the natural shedding frequency (23 Hz). The appearance of the double peak in the probe 2 spectra for the $\lambda = 5d$ actuator case signifies that in front of the plasma region the wake alters between two states denoted by these two frequencies. To gain deeper insight into this behavior, the Short Time Fourier Transform (STFT) was plotted for the probe 2 and probe 1 signal (see Figure 34 and Figure 35). The purpose of checking the STFT was to capture any trend in the occurrence of the two peaks. However, no clear trend was found in the spectra. For some time interval (denoted by the column number of STFT matrix), both peaks were of similar strength. At other times, one state grew at the cost of other. As expected velocity spectra obtained from probe 1 always showed a single shedding peak (Figure 35). In conclusion, a cogent explanation of the double peak behavior remains elusive for the probe 2 spectra of $\lambda = 5d$ actuator under high power forcing. The exact reason for double peak spectra could not be determined from hot wire, PIV results, or high speed flow visualization. At this stage, it can only be described as a bi-modal state of the wake, which unfurls due to existence of simultaneous peaks. Figure 32(m) and (n) have similar characteristics to the $\lambda = 5d$ actuator. In this case ($\lambda = 6d$, high power forcing), the strength of the shifted peaks has
increased. The remnants of the double peak behavior are visible in the probe 2 spectra, Figure 32(n), but the higher frequency peak is much stronger. From the previous discussion of the spectral results, it appears that the \( \lambda = 3d \) and \( 4d \) actuators are more efficient in attenuating the strength of vortex shedding compared to other wavelengths. The \( 5d \) actuator also reduced the strength of shedding in front of the plasma region, but the peak heights in front of the no-plasma region are comparatively higher.

Figure 32. Spectra obtained at \( x/d = 5 \) from probe 1 (no plasma) and probe 2 (plasma), probe 1 spectra (a) unforced case, high power forcing with (c) 1d, (e) 2d, (g) 3d, (i) 4d, (k) 5d, (m) 6d. probe 2 spectra (b) unforced case, high power forcing with (d) 1d, (f) 2d, (h) 3d, (j) 4d, (l) 5d, (n) 6d (Continued)
Figure 32: (Continued)
To compare the relative heights of the spectral peaks for all the wavelengths, the centerline spectra ($y/d=0$) were singled out and plotted in Figure 33. All the features discussed earlier, are more prominent in these two spectral plots.
Figure 33. Centerline spectra at $x/d = 5$ in the high power forcing case, (a) no plasma region, (b) plasma region
Figure 34. STFT of $v'$ signal obtained from probe 2 in the wake of $\lambda = 5d$ actuator under high power forcing. The probe was located at $x/d = 5$ and $y/d = 0.5$.

Figure 35. STFT of $v'$ signal obtained from probe 1 in the wake of $\lambda = 5d$ actuator under high power forcing. The probe was located at $x/d = 5$ and $y/d = 0.5$. 
3.7.3 Discussion of vorticity growth in the wake

In the previous section, the change in sense of vorticity from low power forcing to high power forcing was observed for \( \lambda = 4d, 5d \) and \( 6d \) actuator. This change in the sign of the vorticity seems to be related to a competition between two different types of streamwise vortex generation in the wake. In order to demonstrate the interplay between these two types of streamwise vortices in the wake, results obtained in a cross flow plane at \( x/d = 2 \) will be presented. Figure 36(a) shows the contour plot of mean streamwise vorticity at \( x/d = 2 \) in case of high power forcing with \( \lambda = 2d \) actuator. Due to the forcing, four “rows” of streamwise vorticity have been generated in the near wake. The topmost and bottommost rows of vortices are formed due to the action of forcing. Attention is again drawn to the middle actuator (centered at \( z/d=0 \)) in the top half \( (y/d>0) \) of the contour plot. The positive (red-colored) vorticity level at the left corner of this middle electrode signifies that the high power forcing does have a similar influence in the case of \( \lambda = 2d \) actuator as the higher wavelengths, shown in Figure 36(b) and (c). However, the interesting feature in Figure 36(a) is the formation of the inner rows of vorticity. The two inner rows of vortices may have been the result of induced field from the outermost rows of vortices. The sense of rotation of the inner rows matches exactly that of the low power case, shown previously in Figure 15(c) to (f). The same kind of secondary vortex formation can also be found in Figure 36(b) for the \( \lambda = 4d \) actuator high power forcing and Figure 36(c) for the \( \lambda = 6d \) actuator high power forcing. Both these vorticity fields were obtained at the same \( x/d \) location, although, there is a distinct difference in the character of the secondary vortices between the \( \lambda = 2d \) actuator and \( \lambda = 4d \) actuator. In the
case of $\lambda = 4d$, shown in Figure 36(b), the size of the secondary cells are much smaller compared to the outermost vortices. It is obvious that these smaller structures will diffuse quickly in the wake and will not be able to grow, whereas the vortices in the outermost rows will survive diffusion due to mixing and will convect in the downstream direction. The opposite phenomenon happens in the case of high power forcing with $\lambda = 2d$ actuator. In this case, the secondary structures are of comparable size to the outer row of vortices. It seems that they surpass the growth of vortices in the outermost rows and become dominant in the downstream wake. For this reason, at $x/d = 5$ [Figure 23(b)] the vorticity field resembles the orientation of the inner row of vortices at $x/d = 2$ in Figure 36(a). The same explanation can be given for the $\lambda = 3d$ actuator under high power forcing. Therefore, it can be hypothesized that the effectiveness of the segmented forcing actually depends on the competition between these two types of streamwise vortices. Up to the point of optimum wavelength, the secondary structures outgrow the vortices generated by forcing from the electrodes. When the optimum wavelength is used for actuation, the opposite phenomenon happens. The outer row structures in $\lambda = 4d$ and higher, become dominant in the wake, extract energy from the primary Kármán vortex, and thus weaken it further.
Figure 36. Contour plot of mean $\omega_x d/U_\infty$ at $x/d = 2$, high power forcing case, (a) $\lambda = 2d$, (b) $4d$, (c) $6d$

3.8 Additional evidence of wake modification with power level

It was demonstrated in the previous sections that the structure of the wake changed from low power to high power forcing. The main revelation came from the change in the direction of rotation of the streamwise vortices. Supporting evidence of this behavior was obtained by monitoring the evolution of velocity at the centerline of the wake ($y/d = 0$) at a streamwise location of $x/d = 5$. As before, two X-wires (probe 1 in front of the no-plasma region and probe 2 in front of the plasma region) were held in the wake of the $\lambda = \ldots$
4\textit{d} actuator. The power level was gradually increased by changing the supply voltage. The mean streamwise velocity ($U$) was computed from the $X$-wire signal at each power level. Figure 37 illustrates the changing pattern of centerline velocity with increasing power level. In the low power range (less than 7 watts), the centerline streamwise velocity computed from probe 2 (held in front of the plasma region) was consistently lower than that obtained from probe 1 (held in front of the no-plasma region). The exact opposite trend was observed in the high power range. Figure 37 clearly shows the fundamental change in wake structure with increasing power level. This behavior can be explained in light of the discussion in Section 3.6.1. The phase-averaged spanwise vorticity presented in Figure 19 showed that in front of the no-plasma region the vortices crossed the centerline. Due to this crossing, high momentum fluid from the outside was brought into the wake, which decreased the velocity defect in front of the no-plasma region in the low power forcing case. At the probe 2 location (plasma region), the spanwise vortices shifted away from the centerline. The direction of induced velocity (from these shifted vortices) was opposite to the direction of $U$ along the centerline. For this reason, the centerline velocity defect was greater in front of the plasma region. However, with increasing power, the opposite phenomenon occurred and the existence of the recirculating regions at the corner of each electrode supported this development (Section 3.7.1).
The gradual change of the wake structure was also evident through the changing streamwise vorticity level in the $yz$ plane, obtained from a series of PIV experiments carried out with different power levels in the wake with the $\lambda = 5d$ actuator. The objective was to quantify the change in streamwise vorticity with power level. The contour plots of mean streamwise vorticity have been presented in Figure 38(a) to (e). It is to be noted that Figure 38 (a) corresponds to the lowest power level in this experiment. This case is similar to the low power case. The sense of rotation of the vortices matches with the vorticity field obtained in the low power forcing. A qualitative assessment of the contour plots clearly delineates the gradual change in the wake structure through a change in the streamwise vorticity field. Attention is drawn to Figure 38 (b) and (c). It is evident in Figure 38 (b) that the vorticity level is reduced compared to (a), although the plasma actuators were operated at a higher power level. The sense of rotation of the vortices changes in Figure 38 (c) indicating the beginning of the high power regimes. Therefore, these two power levels can be assumed to be located very close to the transition regime.
when the wake structure changes. To obtain more insight into the changing vorticity levels, the maximum of the positive vorticity was plotted against power level in Figure 39. It shows that the maximum positive vorticity passes through a minimum value between the two forcing regimes. The minimum value definitely corresponds to the transition point in the wake structure.

Figure 38. Contour plot of mean $\omega_{d/U_\infty}$, $\lambda = 5d$ actuator, $x/d = 5$, for various power levels, (a) 3.5 watts, (b) 4.47 watts, (c) 5.45 watts, (d) 6.74 watts, (e) 8.38 watts,
3.9 Optimum wavelength consideration from POD

The selection of optimum wavelength in the high power forcing case was based on the drag reduction performance of the actuators. It was shown in the previous section that the $\lambda = 4d$ actuator produced the most drag reduction. In this section, additional evidence will be presented in support of this claim. This evidence was obtained from the results of proper orthogonal decomposition (POD) analysis. Limited POD analysis was performed
on the data sets obtained from PIV in the $yz$ plane of the wake. POD is a mathematical technique, which helps to reduce the dimensionality of a process. This is achieved with the help of mutually orthogonal basis functions. The higher dimensional process is decomposed into a combination of mutually orthogonal basis functions. Each of these basis functions can be imagined to be individual contributors to the complete process. The degree of contribution depends on the energy of the individual components. Mathematically speaking, the basis functions are related to eigenvectors of the system and the energy is related to the eigenvalues. When POD is carried out on two dimensional vector fields obtained from PIV, it decomposes a large number of sequential velocity data set into a set of POD coefficients and corresponding eigenfunctions or modes. These modes are associated with different flow structures (each with different length scales). In the present case, the snapshot POD method was applied on the 2,000 vector fields obtained in each forcing case.\textsuperscript{51} In the snapshot POD method, the number of modes is equal to the number of the snapshots (2,000 in this case). However, in terms of energy distribution, it is only the first few modes, that contain 80% of the total energy of the flow field, which are most important to representing the measured process. In the wake of a circular cylinder, a periodic flow field exists due to the occurrence of regular vortex shedding. The first few modes in such a flow field always correspond to the structures resulting from vortex shedding (largest length scale in the flow) and contain a significant percentage of the total energy of the flow field. By studying the energy distribution among these modes, it is possible to extract important information about the flow field under consideration.
POD analysis was applied to the vector fields obtained in the yz plane at \( x/d = 5 \) under high power forcing. Figure 40 below shows the distribution of energy among the first 10 modes in each case of forcing.

![Figure 40. Distribution of energy among POD modes for each actuator wavelength](image)

Attention is drawn to the first two modes of the flow field. It is evident that the energy of the first mode was reduced the most for the \( \lambda = 4d \) actuator with high power forcing. The \( \lambda = 5d \) and \( 6d \) actuators contain a higher percentage of the total energy than the \( \lambda = 4d \) case. This observation is also true for the second mode. The higher modes correspond to structures with smaller length scales or secondary structures. A careful look into the distribution of energy among the higher modes reveals that in most of the cases forcing with the \( \lambda = 4d \) actuator resulted in slightly higher energy content compared to \( \lambda = 5d \) or \( 6d \). These findings signify that forcing with \( \lambda = 4d \) actuator resulted in maximum attenuation of energy in the Kármán vortex and this energy was distributed to smaller secondary structures. This also led to a reduction of drag in the wake. These
observations provide further evidence, to regard the $\lambda = 4d$ actuator as the optimum wavelength of forcing in the high power case.

### 3.10 Evidence of optimality from phase averaged spanwise vorticity

Valuable insight into the existence of an optimal wavelength of forcing was obtained from the phase averaged spanwise vorticity data. The phase averaging was carried out on the $X$-wire data (probe 1 and probe 2) acquired at $x/d = 5$ in the high power forcing cases. The principle of phase averaging has been detailed in Section 3.6.1. The magnitude of maximum positive vorticity (phase averaged) was used as a metric to evaluate the effect of high power forcing with actuators of different wavelength. The value of maximum vorticity is an indicator of the strength of the Kármán vortex in the wake. In Section 3.7 it was shown that high power forcing caused a distinct pattern of streamwise vorticity in the wake and Figure 25 showed how the circulation of these vortices varied with wavelength of actuation. This circulation was generated by diverting the flow from the spanwise vortex (Figure 26) which resulted in the attenuation of its strength. In addition to this, the shedding frequencies varied between the plasma and no plasma region for the $\lambda = 5d$ and $6d$ actuators. The maximum of the phase averaged spanwise vorticity for different wavelengths of actuation is presented in Figure 41. This plot provides a new look in to the spanwise varying response of the Kármán vortex under high power segmented forcing. It can be observed that for all other actuators except $4d$ the maximum positive vorticity was different between the plasma and no plasma region. As the spectra plots demonstrated, for the $\lambda = 5d$ and $6d$ cases, the peak heights for the no-plasma region were higher than the $\lambda = 4d$ case. Therefore, shedding was more dominant compared to the $\lambda =$
Moreover, the difference in frequency suggests a state where shedding with two different Strouhal numbers exists. It is only in the $\lambda = 4d$ case where the maximum vorticity matched between the plasma and no-plasma regions. The reason for this matching was the equal attenuation of spanwise vortices between the two regions, which indirectly points to the optimum performance of the $\lambda = 4d$ actuator in the high power forcing case. In higher wavelength actuators ($\lambda = 5d$ and $6d$) shedding was attenuated in front of the plasma region but the attenuation was not equally strong in front of the plasma region. Rather, shedding took place with a different frequency than the natural shedding frequency (23 Hz).

![Figure 41. Maximum phase averaged spanwise vorticity vs. wavelength of actuation](image_url)
3.11 Why 4d is the optimum wavelength?

3.11.1 Formation of mode A

Poncet et al.\textsuperscript{18} have shown that the existence of optimum wavelength of forcing of a cylinder wake is contingent on the excitation of Mode A and B. The present work partly conforms to this hypothesis. To elaborate on this topic, phase-averaged streamwise vorticity plots obtained at $x/d = 2$ will be presented in this section. The voltage signal from an X-wire sensor (placed in the wake) was acquired simultaneously with the pulse output signal from the timing box (used to trigger the laser and the camera). The X-wire signal was later band-pass filtered at the most prominent frequency of the wake to get the sinusoid representing vortex shedding. Afterwards each cycle of the sinusoid was divided in 30 bins and the images were allocated among them depending on the occurrence of each pulse during one period. The contour plots of phase averaged vorticity, obtained in the low power case clearly matched the structure of mode A. Figure 42 represents the contour plot of phase-averaged streamwise vorticity obtained at $x/d = 2$ in the $\lambda = 4d$ case under low power forcing. Figure 43 represents the same but the phase bin corresponding to this vorticity field occurred after half cycle of the previous figure. It is evident that between these two plots, the location and the arrangement of the vortices have been altered. This is exactly one of the main features of the mode A structure. It was mentioned in section 1.4 that mode A has a wavelength of approximately 4$d$ and the vortices are arranged in a staggered manner. Another important trait of mode A was the change of direction of vorticity after half shedding cycle. The streamwise vorticity field in the case of low power forcing with $\lambda = 4d$ actuator matches these two criteria. Since
the wavelength is $4d$, it can be concluded that low power forcing with the $\lambda = 4d$ actuator instigated the formation of the Mode A structure, which otherwise does not form at this $Re$. Despite this excitation of Mode A at low power, drag reduction was not significant under low power forcing. In the event of high power forcing with the $4d$ actuator, the phase-averaged vorticity plots showed a different wake structure. Figure 44 and Figure 45 represent the phase-averaged vorticity fields in the high power forcing case. It is clear that in this case, the vortices did not change their location after half cycle. Moreover, the two rows of vorticity were locked spatially throughout the shedding cycle. Therefore, though the spanwise wavelength of these structures is $4d$, they are probably a modified version of mode A structures. The spatial locking of the streamwise vortices occurred due to the fixed location of the circulation regions, which formed at the corner of the each buried electrode (e.g. Figure 26). Overall, it can be surmised that excitation of mode A structures with low power forcing is an event that facilitates the breaking of spanwise vortex in the high power forcing case. The strengthening of this structure causes the development of vorticity patterns observed in the high power case, which itself was a modified version of mode A.

3.11.2 Distance of saddle point and size of longitudinal vortices

Deeper insight into the existence of the optimal wavelength was obtained by comparing the near wake velocity fields in the $xz$ plane of all the actuators. The important findings from this data set have been discussed in Section 3.7.1. It was shown that counter rotating vortices, formed at each corners of buried electrodes under high power forcing, resulted in a saddle point in front of the no plasma region. A significant region of
backflow was created behind the saddle point. The distance of the saddle point from the cylinder can be considered as a proxy for the formation length. It is to be noted that formation length is generally measured on the wake centerline. Since PIV was carried out in the $xz$ plane at $y/d = 0.5$, this distance of saddle point cannot be the taken as the true formation length. However, this distance still provides an estimate for backflow. Figure 46 illustrates the variation of this distance ($X_{saddle}$) with actuator wavelengths in the high power forcing case. For the $\lambda = 4d$ case, the saddle points were furthest from the cylinder. This finding also indicates the likely occurrence of maximum backflow in front of the no-plasma region, leading to disruption of the spanwise vortex.

The location of the saddle points was directly related to the size of the vortical regions formed at the corners of the buried electrodes. To estimate the size of these vortices a method similar to that described in Section 3.6 was adopted. However, in the present case, the cutoff value was taken as 50% of the maximum vorticity. Applying a 10% cutoff (as in Section 3.6) resulted in ambiguous vortex diameters as the vorticity was spread over a considerable region in the image plane. Figure 47 displays the variation in the average diameter of the vortices with actuator wavelength. The mean diameter is maximum for the $\lambda = 4d$ actuator which is the main reason for the furthest location of the saddle points. It can be argued that because mode A is a natural instability in the wake with a spanwise wavelength near $4d$, vortices with same spanwise wavelength form spontaneously in $\lambda = 4d$ case under high power forcing. Triggering this natural instability with forcing caused maximum disruption of the spanwise vortex leading to significant drag reduction.
Figure 42. Contour of phase averaged $\omega_x d/U_\infty$, showing the bin location during one shedding cycle, obtained in the low power forcing case at $x/d = 2$ of $\lambda = 4d$ actuator.

Figure 43. Contour of phase averaged $\omega_x d/U_\infty$, after half cycle of the instant in Figure 42, obtained in the low power forcing case at $x/d = 2$ of $\lambda = 4d$ actuator.

Figure 44. Contour of phase averaged $\omega_x d/U_\infty$, showing the bin location during one shedding cycle, obtained in the high power forcing case at $x/d = 2$ of $\lambda = 4d$ actuator.

Figure 45. Contour of phase averaged $\omega_x d/U_\infty$, after half cycle of the instant in Figure 44, obtained in the high power forcing case at $x/d = 2$ of $\lambda = 4d$ actuator.
Figure 46. Variation of the distance of saddle points ($X_{saddle}$) from the cylinder in $xz$ plane with actuator wavelength

Figure 47. Variation of the mean diameter of vortex with actuator wavelength
Chapter 4: Detailed study of optimum wavelength

In the previous section, the $\lambda = 4d$ actuator was identified as the optimum wavelength based on the results obtained from drag measurement in the intermediate wake. In order to gain more knowledge about the state of wake under the optimum forcing condition, detailed hot wire investigations were pursued. The present discussion provides deeper insights into the effect of optimum forcing at the two power levels. Velocity profiles were acquired in the near wake at a streamwise distance of $x/d=5$ and 10 with the help of two X-wires. As mentioned previously one of the X-wires was held in front of the no plasma region (probe1) and the other was held in front of plasma region (probe 2). The two X-wires were also traversed along the centerline of the wake to obtain centerline velocity profiles at a fixed $y/d$ location. In the following section, detailed discussions of the velocity profiles under both forcing condition are presented.

4.1 Wake profiles, low power

When the actuators were forced with a total power of 5.6 watts, a considerable difference was found between region 1 and region 2 in the wake (downstream of the regions of no plasma and plasma formation, respectively). Figure 48 through Figure 51 show this difference very clearly. In Figure 48 the non-dimensional mean streamwise velocity, $\langle U \rangle$, obtained at $x/d = 5$ is presented. Due to low power forcing the mean velocity in the centerline of region 1 (no plasma) has increased from the unforced case, whereas it has decreased in front of region 2 (plasma). This differential nature of the
wake is also evident in the plot of transverse fluctuating velocity, \( v' \). A careful inspection of Figure 49 reveals that the transverse fluctuation has reduced in front of region 2. The decrease of transverse fluctuation near the centerline denotes a lesser degree of entrainment in front of region 2. The same trend of mean velocity profile and transverse fluctuation was obtained at \( x/d = 10 \) (Figure 50 and Figure 51). The difference in the mean velocity and fluctuation level between region 1 and region 2 is more prominent in the plots obtained at \( x/d = 10 \). At both measurement locations (\( x/d = 5 \) and \( x/d = 10 \)), the wake width downstream of the plasma region is slightly larger.

### 4.2 Centerline velocity profiles, low power

After obtaining transverse wake profiles at \( x/d = 5 \) and 10, the \( X \)-wires were traversed from \( x/d = 3 \) to 20 along the centerline \( y/d = 0 \). This was done in order to obtain a clear picture of the development of the wake behind the two regions. The results presented in Figure 52 and Figure 53 corroborates the finding from the transverse wake profiles. Here it is observed that the development of the wake behind region 1 and region 2 is indeed very different in nature. Figure 52 shows that, in front of region 2, the mean velocity remains lower than the unforced case up to around \( x/d = 17 \), whereas the increase in the mean velocity in front of region 1 is evident in the region surrounding \( x/d = 5 \). The transverse velocity fluctuation plot (Figure 53) again supports the finding of Figure 49 and Figure 51, in that the \( v' \) level is reduced downstream of the plasma formation region, along the centerline of the wake.
Figure 48. Mean streamwise velocity at $x/d=5$.

Figure 49. Transverse velocity fluctuation at $x/d=5$.

Figure 50. Mean streamwise velocity at $x/d=10$.

Figure 51. Transverse velocity fluctuation at $x/d=10$.

Figure 52. Mean streamwise velocity profile along the centerline ($y/d=0$).

Figure 53. Transverse fluctuating velocity profile along the centerline ($y/d=0$).
4.3 Spectral development, low power

The results presented in Figure 48 to Figure 53 have shown that the development of wake is quite different in front of the regions of plasma or no-plasma formation. As was mentioned during the discussion of power level selection, the low power forcing did not cancel the Kármán shedding. However it is now clear that forcing has a more subtle influence on the wake. To obtain a deeper understanding of the underlying reasons for this behavior, waterfall spectra obtained at $x/d = 5$ are presented in Figure 54 through Figure 56. Each of these spectra was obtained by averaging 30 spectra of the $v'$ signals obtained from probe 1 or probe 2. For comparison purposes, the spectrum of the unforced wake is also provided in Figure 54. After comparing the three spectra the qualitative difference in their appearance is quite visible. The spectra obtained from probe 1 (downstream of no-plasma region, Figure 55) bears similarity to Figure 54 (spectra of unforced wake) in terms of distribution of energy among the $y/d$ locations. However, the effect of forcing can be seen in the width of the peaks. Although probe 1 was not in front of the plasma-forming region, the peaks in Figure 55 are comparatively wider than those in Figure 54. Compared to Figure 55, the spectra obtained from probe 2 in Figure 56 have a very different distribution of energy among the $y/d$ locations. In this spectral plot the peak power levels are more uniformly distributed from $y/d = 1$ to $-1$. Apart from this feature, another noticeable difference is the maximum value of the power among the peaks. It can be clearly observed that the values of the power corresponding to the shedding peak are lower than that of Figure 54 or Figure 55.
Figure 54. Spectra of $v'$ in the unforced wake at $x/d=5$.

Figure 55. Spectra of $v'$ obtained from probe 1 at $x/d=5$.

Figure 56. Spectra of $v'$ obtained from probe 2 at $x/d=5$.

4.4 Spanwise coherence, low power

The degree of spanwise coherence between probes 1 and 2 (downstream of the no-plasma and plasma formation regions, respectively) is an indicator of, or proxy for, the
level of three-dimensionality induced into the wake. A high degree of coherence between the two regions indicates in-phase shedding and two-dimensional shed vortex structures. Conversely, a low level of coherence indicates a breakup of the spanwise uniformity of the wake structure. Figure 57 and Figure 58 show the spanwise coherence for \( U \) and \( V \) hot wire data acquired at \( x/d = 5 \) and \( y/d = 0.28 \), near the shear layer region. For the unforced case, both the \( U \)- and \( V \)-components of velocity show a strong coherence between the two probes at the shedding frequency, as expected for nominally two-dimensional shedding. The forced case for \( U \) shows a marked decrease in the coherence and a shift to the second harmonic (indicating a possible phase difference). The \( V \) component shows little change in the spanwise coherence at the fundamental frequency, but reduced coherence at the third harmonic.

![Figure 57. Spanwise coherence of \( U \) at \( x/d=5, y/d=0.28 \).](image1)

![Figure 58. Spanwise coherence of \( V \) at \( x/d=5, y/d=0.28 \).](image2)
4.5 Vortex dislocations

An important measure of the tendency of the spanwise coherence to break up is the frequency of vortex dislocations in a given region of the wake. For example, Williamson\textsuperscript{49} demonstrated that a vortex dislocation (a breakup of the spanwise coherence of a vortex roller) can be identified in a velocity time history as a glitch or irregularity in the signal – in other words, a momentary cessation of fluctuations. In the present work, a rake of eight single-wire hot wire probes was positioned at $x/d = 2$ and $y/d = 0.5$ with an inter-probe spacing of $0.5d$ (spanning from $z/d = -1$ to $1.75$). Figure 59 shows the voltage time histories from the array of eight probes (calibrated velocity is not necessary to infer dislocations), with the signal band-pass filtered at the shedding frequency ($\pm 1$ Hz). Each voltage waveform is shifted by a consistent amount along the y-axis, yielding the arbitrary scale. The top four hot wire signals were recorded from probes located downstream of the no-plasma region, while the bottom four hot wire signals were acquired across the plasma region. As in Williamson’s work,\textsuperscript{49} the momentary cessation of fluctuations is an indication of vortex dislocation. It is clear that vortex dislocations are consistently measured by several adjacent probes, and that the frequency and magnitude of dislocations are higher in the no-plasma region (the top four waveforms).
Figure 59. Band-pass filtered hot wire signals from an array of eight single-wire probes. The top four signals are downstream of the no-plasma region, while the bottom four signals are from the plasma region.

4.6 Spanwise phase difference

Determination of the phase difference between the velocity signals from the two X-wire probes can provide insight into the relative timing of the periodic disturbances at each sensor, and inference for the overall structure of the wake. However, it is to be noted that at $Re=4700$ the cylinder wake is turbulent in nature, leading to strong temporal fluctuation of the phase difference between the two probes. This fluctuating phase relationship is in accordance with the findings of Szepessy,\footnote{Szepessy, 38} whose investigation concentrated on computation of spanwise correlation and phase difference among signals obtained from three pressure taps located on the cylinder surface. Szepessy showed that three-dimensionality in the cylinder wake caused the correlation between two points in the wake to oscillate with a period of 10 to 20 times the Strouhal period. The approach used by Szepessy to compute the phase difference between two velocity signals was adopted here, and is described as follows. The $U$ signal from probe 1 was band-pass
filtered (± 1 Hz) with the center of the pass band set at the shedding frequency. From this band-pass filtered version of the $U$ signal (which resembled a sinusoid) eight cycles were chosen. The phase difference was then computed by calculating the cross-correlation between the band-pass filtered $U$ signal of probe 1 and the corresponding part of the $U$ signal time series from probe 2 (with the same start and end time). This window of eight cycles was then moved by one cycle and then again, the previous step was repeated. This was done for the total length of the time series. A PDF was computed from the values of phase differences thus obtained. The peak value of the PDF was taken as a representative value of phase angle between the signals from the two probes. Figure 60 shows the variation of the mean of the phase angle along the $x/d$ direction in the low power forcing case. It can be observed that across the transverse direction of the wake, the measured velocity signal in the plasma region led the velocity from the no-plasma region (negative lag). The phase relationship for the unforced case exhibited random phase correlation, while the forced data showed the plasma region consistently leading the no-plasma.
Figure 60. Variation of mean of the phase angle between no plasma and plasma region along the centerline, low power forcing.

4.7 Discussion

A summary of the results presented thus far is as follows. At a distance five diameters downstream from the cylinder, wake profiles indicate an increased velocity deficit downstream of the plasma formation region (Figure 48). For all distances downstream of the plasma formation region, the velocity fluctuations were lower than those in the no-plasma region (Figure 53). The plasma region exhibits a wider wake, with lower amplitude peaks in the v-component spectra (Figure 55 vs. Figure 56). The spanwise Kármán vortices are located closer to the centerline, downstream of the no-plasma region, and have reduced vorticity (Figure 19 vs. Figure 20). This results in a reduction in the spanwise coherence of the wake (Figure 57) and an increase in the number of vortex dislocations (Figure 59).
The primary wake control mechanism at work is postulated to be breakup of the spanwise coherence of the Kármán vortices. It is important to note that this method of flow control is not due to simple delay of separation, as has been done on many other occasions.\textsuperscript{46-47} Rather, this flow control scheme employs direct wake control, as described by Choi \textit{et al.}\textsuperscript{7} Destruction of the spanwise coherence is evidenced by the reduced coherence between the hot wire probes positioned downstream of the plasma and no-plasma regions (Figure 57), the increased number of vortex dislocations seen in the no-plasma region (Figure 59), and the phase difference between the velocity waveforms measured in the plasma and no-plasma regions.

The primary mechanism that forces this spanwise non-uniformity is the development of streamwise vorticity at the junction between the plasma and no plasma regions. The formation of this streamwise vorticity results from delayed separation in the plasma region (this is a well-established impact of local plasma forcing on a circular cylinder), which locally accelerates the flow and reduces the local pressure. In contrast, the flow over the cylinder in the no-plasma region separates earlier. This discontinuity and resulting pressure gradient leads to the development of spanwise flows near the surface of the cylinder from the no-plasma regions to the plasma regions. The streamwise vorticity serves to widen the wake downstream of the plasma region and narrow the wake downstream of the no-plasma region (Figure 48 and Figure 55). This causes the spanwise vortex rollers to move closer to the wake centerline in the no-plasma region (Figure 19), and the portion of the rollers in the plasma region to move farther away from the centerline (Figure 20). This relative movement (deformation) of the Kármán rollers
results in lower fluctuations in the plasma region relative to the plasma region (Figure 53, Figure 55, and Figure 56). A notional diagram of the impact of streamwise vorticity on the spanwise vortex is shown in Figure 61.

![Notional diagram of Kármán vortex in the low power forcing case.](image)

These findings are consistent with observations of the wake downstream of a wavy circular cylinder in cross-flow. The geometric nodes of the wavy cylinder (maximum local diameter) correspond to the plasma regions, and the geometric saddles (minimum diameter) correspond to the no-plasma regions. Ahmed et al.\textsuperscript{10,42} demonstrated the existence of streamwise vorticity forming at the midpoint between the saddles and nodes. Lam et al.\textsuperscript{14} found that a spanwise pressure gradient established spanwise flow from the saddles to the nodes, resulting in streamwise vorticity. Lam et al.\textsuperscript{14} also showed that the flow separated earlier in the saddle region relative to the node. The resulting flow had
higher fluctuations (\(v'\)), reduced velocity deficit, and a narrower wake at \(x/d=5\) behind the saddle region (discussion 3.3 in Lam et al.\(^{20}\)) – all of which are consistent with the no-plasma region in the current work. These three-dimensional aspects of the wake were further elucidated by Zhang et al.\(^{43}\) where the periodic variation in the near wake was distinct in the cross plane PIV images.

### 4.8 Wake profiles high power

The high power case represents forcing with a power of approximately 13.6 watts. This high power forcing created a strong induced velocity as was measured by the glass pitot probe (Figure 11). Velocity profiles were obtained in the same manner by the two X-wires as before at the streamwise distance of \(x/d=5\) and 10. Figure 62 to Figure 65 show the profiles of mean velocity and the transverse velocity fluctuation obtained at \(x/d=5\) and 10 when high power forcing was applied to the plasma actuators for wake control. It is evident that due to the high power forcing there was considerable change in the wake properties, in a manner not necessarily consistent with the low power forcing data. In the \(x/d=5\) streamwise location the mean velocity deficit for both spanwise locations has increased and the fluctuations were suppressed to a great extent compared to the unforced case. The suppression of the fluctuations is very clear at \(x/d=10\). Compared to the low power case the development of the wake is uniform in the sense that in both places in front of region 1 and 2 the velocity defect decreased (at \(x/d=10\)) and the fluctuation level was reduced. Thus, the strength of the large scale Kármán vortex street is reduced due to the action of forcing. Figure 62 and Figure 64 also show that the wake downstream of the
no-plasma region (probe 1) is wider than the wake downstream of the plasma region (probe 2).

4.9 Centerline velocity profiles

The streamwise mean velocity profile, $<U>$, and the transverse velocity fluctuation profiles, $v'$, along the centerline of the wake ($y/d=0$) are presented in Figure 66 and Figure 67. Both of these figures show the relatively consistent spanwise structure of the wake in front of region 1 (no-plasma) and region 2 (plasma). Figure 66 indicates that up to a streamwise distance of $x/d=7$ the centerline mean velocity was less than the unforced case, but at locations further downstream the wake defect is less than that of the unforced case for both spanwise locations. The $v'$ levels were consistently lower than the unforced case in both spanwise locations, for all distances downstream. Furthermore, the vortex formation length, identified by the streamwise location of peak $v'$ in Figure 67, has shifted further downstream for the forced case.
Figure 62. Mean streamwise velocity for the high power forced case at $x/d=5$.

Figure 63. Transverse velocity fluctuation for the high power forced case at $x/d=5$.

Figure 64. Mean streamwise velocity for the high power forced case at $x/d=10$.

Figure 65. Transverse velocity fluctuation for the high power forced case at $x/d=10$.

Figure 66. Mean streamwise velocity profile for the high power forced case along the centerline ($y/d=0$).

Figure 67. Transverse fluctuating velocity profile for the high power forced case along the centerline ($y/d=0$).
Chapter 5: Conclusion

Three-dimensional forcing is superior to spanwise-uniform actuation in attenuating vortex shedding in the wake of a bluff body. This work was based on the premise that segmented forcing yields better control authority and the key research question involved the change in wake structure under three-dimensional forcing. The motive was to investigate the existence of an optimum wavelength and to understand the changes in wake dynamics by the optimum condition. The forcing was implemented by placing DBD plasma actuators on the cylinder in a spatially-modulated square-wave pattern consisting of a straight exposed electrode covering the whole span and a segmented buried electrode placed intermittently in the spanwise direction. The most receptive azimuthal location of forcing was found to be located at $\pm 80^\circ$ from the forward stagnation point; accordingly, two sets of actuators were mounted on the top and bottom surfaces of the cylinder to generate a symmetric forcing pattern. Six different wavelengths of actuation were tested, ranging from $\lambda = 1d$ to $6d$. In order to compare the performance of the actuators the induced velocity from all the wavelengths were matched with one another.

A threshold power level was found, below which segmented forcing did not attenuate vortex shedding but induced a wavy structure in the wake. This was found to be the result of augmentation of streamwise vorticity in the wake which was very prominent for $\lambda > 2d$. In this low-power regime the drag of the cylinder was not considerably reduced for
any spatial wavelength. The size and circulation of the streamwise vortices were found to increase monotonically with increasing wavelengths. The wavy structure in the low power forcing case caused the spanwise vortex to come closer to the centerline in the no-plasma region and to shift away from the centerline in the plasma region.

Forcing at a power level above the threshold severely attenuated vortex shedding and led to considerable reduction in the pressure drag acting on the cylinder. This reduction was the most significant in the case of the $\lambda = 4d$ actuator. Near-wake spectra revealed maximum level of three-dimensionality for this particular case. These findings led to the recognition of the $\lambda = 4d$ case as the optimum wavelength of forcing. For $\lambda > 4d$, high-power forcing created distinct differences in wake properties in the spanwise direction. In the no-plasma region the wake width was larger compared to the plasma region along with a noticeable difference in the formation length denoted by the peak in the velocity spectra. High-power forcing created well-defined counter-rotating vortices at the edge of each buried electrode. The existence of these vortices established significant backflow right next to the no-plasma region. The boundary of the backflow was marked by the existence of a saddle point indicating a high level of strain. The creation of backflow likely hampered the formation of a large-scale spanwise vortex by drawing fluid from it.

The evolution of the mean streamwise vorticity generated by segmented forcing with increasing power level showed that the transition from a low power regime to a high power regime was accompanied by a switch in the sense of rotation of the streamwise vortices. The transition point was marked by a minimum in the maximum positive vorticity level in the wake. Although this flip in the sign of the vortices was observed...
only for $\lambda > 3d$, it is believed that this process is an inherent feature of segmented forcing. The optimum condition occurs where this transition is achieved with minimum induced velocity. In the high power forcing case, the streamwise vortices created by forcing surrounded an inner cell of secondary vorticity whose sense of rotation matched that of the low power case. The success of the optimum wavelength was attributed to the dominance of vortices created by segmented forcing, which outgrow the secondary vortices.

To summarize, an extensive investigation was carried out on the aspect of three-dimensional forcing of a cylinder wake with segmented DBD plasma actuator. This research has shown the existence of an optimum wavelength for which the strength of vortex shedding was greatly attenuated, leading to a reduction in drag. As anticipated, segmented forcing induced a strong level of streamwise vorticity in the wake compared to the unforced case. A competition between vortices created by segmented forcing and a secondary vorticity seem to be the key mechanism guiding the transition of the wake structure from the low to high power regime.
Chapter 6: Recommendation and future work

The present research focused mainly on the fluid dynamics of the wake under the action of segmented forcing. The cylinder wake is inherently three dimensional due to the existence of streamwise vorticity and the segmented forcing added to the complexities of this three-dimensional system. With all of the instrumentation used in this work being planar in nature, a complete three-dimensional view of the wake was not readily available from the experimental data. Inferences were drawn by stitching together all the planar two dimensional data obtained from different instruments. A volumetric measurement technique such as tomographic PIV would be much more effective in conveying the three-dimensional structure of the wake. This shortcoming of the two dimensional techniques left a few questions unanswered which can probably be tackled with a three dimensional volumetric method. Moreover, monitoring the temporal evolution of a three-dimensional system in space requires a combination of finer time resolution generally associated with point measurement techniques such as hot wire anemometry with the large measurement region of techniques like PIV. A combination of these two features can be achieved with the use of a time-resolved PIV system.

A number of questions emerged from the present research, which still lack satisfactory explanation. The relationship of the streamwise vortices with the spanwise Kármán vortex is a complicated subject, which demands more investigation. In the low power forcing case, even though streamwise vorticity of equal strength with high power
forcing was present, the vorticity could not extract energy from the spanwise vortex as effectively as high power forcing could. The existence of two senses of streamwise vorticity (primary and secondary) in the near wake of the segmented actuators in the high power case was another interesting finding. For the $\lambda = 2d$ case they were of comparable size. The competition between these two kinds of vorticity needs more in-depth investigation. A volumetric measurement in the near wake is probably the best way to understand the complicated picture of the vortex system and its evolution in time.

The velocity spectra obtained in the plasma region of the $\lambda = 5d$ actuator under high power forcing revealed the existence of dual peaks, which indicated a bimodal nature of the wake. However, distinctive features of this bimodal structure were lacking in the streamwise vorticity data. The reason for the appearance of the bimodal state was not clear from the current results. PIV in the $xy$ plane may be carried out to obtain a phase-averaged picture of the spanwise vortex and glean better insight. Another aspect of segmented forcing which requires a better explanation is the growth of the streamwise vortices with different wavelength of forcing. The monotonic increase in the size of the streamwise vortices with increasing wavelength in the low power forcing case was replaced by the existence of an optimum wavelength in the high power forcing case. It is yet to be understood what caused the appearance of the secondary vorticity cells in the $\lambda = 2d$ and $6d$ cases under high power forcing.

The parameter space for the present research was quite extensive in terms of the number of variables involved. Naturally, it was not possible to investigate the effect of variation in each of them on the dynamics of the wake. These untested parameters
constitute the future work that can be pursued as a logical extension of the present research. The first parameter is Reynolds number. It would be worthwhile to test the effect of segmented forcing in the higher $Re$ regime and find out whether the optimum wavelength shifts to some other values. A higher $Re$ scenario will likely require more induced velocity from the actuators so a higher power level of forcing would be required. It can be also interesting to study the effect of different duty cycles of the supply waveform or to modulate it with multiples or submultiples of the shedding frequency. Preliminary research with modulated forcing has shown that modulation of the supply sine wave with a square wave having frequency twice that of shedding frequency resulted in increased unsteadiness in the wake. A study can be conducted to investigate the effect of other supply waveforms to the actuators on the wake apart from a sine wave. Another possibility for future research may involve a difference in the segmented actuator design and in their operation. In the present configuration the actuators on the top and bottom surface have no spatial phase difference. The bottom actuator set can be shifted spatially in order to generate more strain from actuation. Instead of an in phase operation the actuators can be operated out of phase. This may lead to greater three-dimensionality with a better reduction in drag.
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Appendix A: Discussion on end effects

Boundary conditions play an important role in the flow over cylinder. This is known as end effect. To minimize end effects, end plates were used. End plates insulate the cylinder from the tunnel boundary layer developed on the sidewalls. Williamson $^4$ has shown that it is possible to manipulate the nature of vortex shedding by carefully setting up the end plates at specific angles. In the present work, the aspect ratio of the cylinder was fixed at 20. Along with aspect ratio, the distance of the extreme buried electrode from the end plate is also an important parameter. In the present work all the actuators were constructed following a simple principle. For any wavelength, a buried electrode was placed in the middle of the cylinder such that the mid-point of the copper tape (representing the buried electrode) was at equal distance from the two end plates (10 inches in the present work). After that, other buried electrodes were placed accordingly to create the desired waveform. It is to be noted, that under this design procedure, the total number of electrodes were decided only by the space available within the fixed aspect ratio. This in turn decided the distance of the extreme electrode from the end plate. To obtain a rudimentary picture of the end condition the following experiment was performed. The $\lambda = 5d$ actuator was used in two other aspect ratio ($AR$) configurations, namely $AR=16$ and 18 in addition to $AR=20$. This was achieved by sliding the endplates inwards. The CCD camera was positioned such that the junction of the cylinder with one
of the end plates was in view. Afterwards, images were taken at $x/d = 5$ in the $yz$ plane with the help of PIV in the high power forcing condition.

The schematic of the generic vorticity field (under high power forcing) is given in Figure 68. The vortices have been numbered for identification purposes. The left most part of the schematic denotes the location of the end plate. The vortex pair numbered $1+ \text{ and } 1-$ is the result of the interaction of end plate with the cylinder. They are representative of the necklace vortex formed at the juncture of the cylinder with the bluff body. Figure 69(a) to (c) represents the time averaged streamwise vorticity (normalized) with different aspect ratios. In all these figures, the purple rectangles denote the locations of the buried electrode and the white dashed line indicates the location of the end plate. When the aspect ratio was 20 [Figure 69(a)], the formation of the necklace vortices was very distinct in the end plate region. It is evident that the necklace vortices have attracted the neighboring vortices (generated by forcing) strongly due to mutual induction. As the aspect ratio was reduced to 18 [Figure 69(b)], the size of the necklace vortices reduced. The reduction in size became more prominent in Figure 69(c) [$AR=16$]. This finding proved that with decreasing aspect ratio the necklace vortices did not grow in size compared to those generated by segmented forcing. As the strength of the necklace vortices reduced, the mutual induction between the former and the neighboring vortices also decreased. This fact became clear when the circulations of the vortices with positive vorticity were plotted with aspect ratio. The numbering of the vortices follows the nomenclature displayed in Figure 68. The decreasing mutual induction is evident in the gradual decrease in circulation level of the vortex marked $2+$. The effect of the necklace
vortices is less perceptible on the vortices marked 3+ and 4+, which were located in the middle region of the image plane. This finding proved that end effect has a severe effect on the circulation of the vortex, which is closest to the end plate. However, as has been mentioned before, the distance of the extreme electrode from the end plate is also an important factor. The same study was repeated with a $\lambda = 4d$ actuator in which case, the aforementioned distance was less. It was observed that the vortices, which were formed due to forcing and located closer to the endplate, shrouded the formation of the necklace vortex. In other words, the necklace vortices were barely visible in that case.

The main outcome from this end effect study was the understanding that results (drag reduction, spectra etc.) obtained around the middle region of the wake would not change significantly with aspect ratio. Therefore, the major conclusion about the optimum wavelength will also remain valid at other aspect ratios.

Figure 68. Depiction of numbering convention for the streamwise vortices.
Figure 69. Contour plot of time averaged streamwise vorticity ($\omega_x d/U_\infty$) at $x/d=5$, $\lambda = 5d$ actuator high power forcing, (a) $AR = 20$ (b) $AR = 18$ (c) $AR = 16$.

Figure 70. Aspect ratio versus circulation level of the streamwise vortices. For numbering convention of the vortices, see Figure 68
Appendix B: Discussion on uncertainty level

B1. Sources of uncertainty

Several sources of uncertainty were identified during this research work. In this section, these sources will be discussed and efforts taken to minimize uncertainty from those sources will be outlined.

B1.1. Uncertainty in induced velocity measurement

During the measurement of induced velocity from the plasma actuator, a glass pitot tube was used. It was found that measurement of induced velocity was highly sensitive on the proper positioning of the pitot tube on the buried electrode surface. A slight movement of the tip of the probe, by a millimeter or less, was enough to miss the maximum velocity point. To avoid this, the traverse was moved in the single pulse mode, which resulted in a fine movement for each pulse sent to the controller. The pitot tube was moved back and forth around the maximum velocity point to ensure the correct location of the peak velocity point. To ensure maximum accuracy in the induced velocity measurement, data was acquired over multiple segments of the buried electrode. It is to be noted that DBD discharge is not spatially uniform in character rather it has streamer like appearance. For this reason, maximum induced velocity on a single segment of electrode was not always uniform. During experiment, the induced velocities were measured frequently to ensure actuator degradation have not caused its reduction.
B1.2. **Uncertainty in velocity measurement with hot wire sensors**

The uncertainty in the $X$-wire measurement was due to several reasons like proper probe positioning, accuracy of calibration, temperature variation in the tunnel, unsteadiness in the tunnel speed etc. To ensure maximum accuracy, the calibration was carried out in-situ in the tunnel before each run using a special calibration mount. The calibration used a pitching angle method whereby the $X$-wires were pitched in the vertical plane during calibration. The data was acquired shortly after the calibration. After finishing the calibration, velocity signals were acquired in the free stream and the deviation from free stream speed reported by the pitot tube was calculated. It was found that a maximum of 2-3% difference existed between the free stream reading of the pitot tube and that computed from the $X$-wire signal. The major reason for this difference was the difference in the location of the free stream pitot tube (upstream of the cylinder) and the $X$-wire (downstream of the cylinder). To ensure that temperature drift in the $X$-wire did not cause inaccurate measurement, the free stream velocity was measured after each run. If the difference with the pitot tube reading was more than 3%, a new calibration was carried out. Therefore, a maximum of 2-3% uncertainty level can be assumed in the $X$-wire data. Velocity signals were acquired for 10 seconds (in many cases for 20 seconds) at 50 kHz sampling frequency, which ensured reliable convergence of the computed velocity data.

B1.3. **Uncertainty in the PIV data**

During the PIV experiments in the $yz$ plane, the main source of uncertainty was the perspective error due to existence of velocity vectors out of the image plane. The method
adopted to correct this error has been detailed in Section 3. To ensure convergence of the data statistics, 2000 images were acquired for each case.

A common source of error in PIV is poor calibration. This in turn is related to proper camera placement in the tunnel, creation of laser sheet at the desired plane, focusing of camera etc. To avoid inaccuracy in the calibration, utmost care was taken to form a vertical laser sheet which grazed the surface of a ruler placed in the desired plane ($x/d = 5$ or 2). Before each run background subtraction was carried out in the plasma on condition to avoid false correlations due to actuator brightness.
Appendix C: Validation of data and other results

C1. Validation of PIV data with literature

In order to validate the PIV data, the mean transverse velocity at $x/d = 2$ and 5, obtained from a total of 2000 images, was compared with literature.\textsuperscript{34,50} It is to be noted that both these investigations in Ong and Wallace\textsuperscript{34} and Parnaudeau et al.\textsuperscript{50} were carried out at $Re = 3900$. Though the $Re$ of the present investigation was 4700, good match in the mean transverse velocity was obtained as shown in Figure 71 and Figure 72.

![Figure 71. Comparison of normalized mean transverse velocity with literature, $x/d = 5$](image-url)
During the discussion in Section 2.4.2, it was mentioned that perspective errors were encountered in the $yz$ plane PIV data. A representative image showing this error is given in Figure 73. Due to this error, the velocity vectors appeared to be diverging along the image boundary. These diverging velocity vectors have been exaggerated by white arrows for better visibility.
C2. Velocity profiles at other spanwise locations

In Section 3.5, coefficients of drag were computed by numerically integrating the velocity profiles obtained behind the plasma and the no plasma region. It was mentioned that only two velocity profiles were used to incorporate the spanwise variation of $C_d$. Evidence in support of that claim will be presented here with the help of velocity profiles obtained at other spanwise locations. Figure 76 shows the various profiles obtained at $x/d = 40$. It can be observed that changing the spanwise location of the $X$-wire probes did not cause significant change in the velocity profiles.
Figure 74. Mean streamwise velocity profiles obtained in the wake of 6\textit{d} actuator at \(x/d = 40\) at different spanwise locations

C3. Verification of wake profiles with and without actuator

In order to ensure that placement of the actuators on the cylinder surface did not alter the characteristics of the flow, velocity profiles were acquired in the wake with a regular cylinder with no actuators mounted on it. This profile was compared with the unforced case profile. It is to be noted that in the unforced case, the actuators were mounted on the cylinder. The figure below shows the result of this comparison. It is evident that existence of the actuator did not change the flow characteristics considerably.
Figure 75. Comparison of mean streamwise velocity between a cylinder mounted with actuators and a regular cylinder

C4. Streamtraces obtained in $xz$ plane

In this section, streamtraces obtained in $xz$ plane of $\lambda = 2d$, $3d$ and $4d$ actuator will be presented. The main feature of these streamtraces are the location of distinct circulating regions at the edge of buried electrodes of $\lambda = 3d$, $4d$ actuators under high power forcing case (Figure 76). These circulating regions were not observed in the low power forcing case for any of the actuators. A representative plot of streamtraces has been shown in Figure 76(d).
Figure 76. Streamtraces obtained in $xz$ plane ($y/d = 0.5$) of (a) $\lambda = 2d$, (b) $\lambda = 3d$, (c) $\lambda = 4d$ actuator, under high power forcing, (d) $\lambda = 4d$ actuator, low power forcing case.
C5. Phase averaged spanwise vorticity

Figure 77. Phase averaged spanwise vorticity ($\langle \omega_z \rangle d/U_\alpha$, calculated at $x/d = 5$ for $4d$ actuator, high power forcing. (a) probe 1 no plasma region, (b) probe 2, plasma region contour levels are 0.3 to 0.5 (solid) and -0.5 to -0.3 (dashed), with intervals of 0.05.

Figure 78. Phase averaged spanwise vorticity ($\langle \omega_z \rangle d/U_\alpha$, calculated at $x/d = 5$ for $3d$ actuator, high power forcing. (a) probe 1 no plasma region, (b) probe 2, plasma region contour levels are 0.2 to 0.8 (solid) and -0.8 to -0.2 (dashed), with intervals of 0.1.