Flow Control of Tandem Cylinders Using Plasma Actuators

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FLOW CONTROL OF TANDEM CYLINDERS USING PLASMA ACTUATORS

by

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A thesis submitted in partial fulfillment of the requirements for the Honors in the Major Program in Mechanical Engineering in the College of Engineering and Computer Science and in the Burnett Honors College at the University of Central Florida Orlando, Florida

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ABSTRACT

The flow over a set of tandem cylinders at a moderate Reynolds numbers (Re), and with different separation lengths has been studied. Two dimensional (2D) and three-dimensional (3D) plasma actuators were used to control the flow over the leading cylinder to change the vortex shedding, and subsequently the flow on the second cylinder. The 3D plasma actuator was segmented along the length of the cylinder with a spacing of $\lambda = 4$ while the 2D actuator simply ran straight down the span of the cylinder. Particle image velocimetry (PIV) measurements were used to investigate the flow along the central plane in the wake of the cylinders. The image pairs were processed into velocity grids which were then averaged. Plots of the shear, vorticity, and turbulent kinetic energy were created. These plots are used to understand how the character of vortex shedding from the upstream cylinder changes the same from the downstream one.
ACKNOWLEDGEMENTS

The CATER research facility has made this research possible. They have been the home to my work. In addition to space, they provided the equipment that cost more than most cars to perform my experiment. The staff has been incredibly helpful in technical problems that arose during the process. Thank you, Dr. Erik, for your expertise in the PIV process. I wish I could absorb all the knowledge that you drop in a normal conversation.

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# TABLE OF CONTENTS

LIST OF FIGURES ........................................................................................................... v

LIST OF TABLES .............................................................................................................. vii

INTRODUCTION ............................................................................................................... 1

EXPERIMENTAL SETUP ................................................................................................. 4

A. Wind tunnel ............................................................................................................... 5

B. Acrylic test section ................................................................................................... 5

C. Tandem cylinders ...................................................................................................... 5

D. Plasma Actuator ......................................................................................................... 6

E. PIV setup .................................................................................................................... 9

F. Test Parameters ......................................................................................................... 9

RESULTS .......................................................................................................................... 11

CONCLUSION ................................................................................................................ 23

APPENDIX A: SETUP PHOTOS ...................................................................................... 26

LIST OF REFERENCES .................................................................................................... 31
LIST OF FIGURES

Figure 1: Sketches of four flow structures [11] ........................................................................... 2
Figure 2: Wind Tunnel and PIV Setup .......................................................................................... 4
Figure 3: Test Section .................................................................................................................. 4
Figure 4: No Actuation, Straight Actuation, Segmented Actuation .............................................. 7
Figure 5 Plasma Actuator Installation Angle ................................................................................... 8
Figure 6: Circuit Diagram for Plasma Actuator .............................................................................. 8
Figure 7: Typical Image Capture .................................................................................................... 12
Figure 8: Typical Image with Processing ....................................................................................... 12
Figure 9: Typical Vector Field for Processed Image Pair ................................................................ 12
Figure 10: Typical Vector Field for Processed Faulty Image Pair ..................................................... 12
Figure 11: L=3, No Actuation, Shear Plot ..................................................................................... 15
Figure 12: L=3, No Actuation, Vorticity ....................................................................................... 15
Figure 13: L=3, No Actuation, Turbulent Kinetic Energy ............................................................... 16
Figure 14: L=4, Actuation, Shear .................................................................................................. 16
Figure 15: L=4, Actuation, Vorticity ............................................................................................ 17
Figure 16: L=4, Actuation, Turbulent Kinetic Energy .................................................................... 17
Figure 17: L=4, Segmented Actuation, Shear ............................................................................... 18
Figure 18: L=4, Segmented Actuation, Vorticity ........................................................................... 18
Figure 19: L=4, Segmented Actuation, Turbulent Kinetic Energy .................................................. 19
Figure 20: L=5, Actuation, Shear .................................................................................................. 19
Figure 21: L=5, Actuation, Vorticity ............................................................................................ 20
Figure 22: L=5, Actuation, Turbulent Kinetic Energy .................................................................... 20
Figure 23: L=5, Segmented Actuation, Shear................................................................. 21
Figure 24: L=5, Segmented Actuation, Vorticity .......................................................... 21
Figure 25: L=5, Segmented Actuation, Turbulent Kinetic Energy................................. 22
LIST OF TABLES

Table 1: Test Parameters............................................................................................................. 10

Table 2 Images Collected for each Test Case............................................................................... 11
INTRODUCTION

Flow over a cylinder has been studied thoroughly for many years. Many researchers have focused on the wake properties of the cylinders at various Reynolds numbers and spacing [9]. The existence of these vortex structures is characterized by the Strouhal number which is based on the vortex-shedding frequencies. Flow control is used to change this vortex shedding of these flows and cancel it in some cases. Many noteworthy experiments have been carried out on the effect of forcing the wake of circular cylinders. The primary instability in the wake of a circular cylinder is vortex shedding, in which the separating shear layers on either side of the cylinder roll up to form alternating Von Kármán vortices that are shed into the wake [8]. These large-scale structures are responsible for structural loading and drag, but active flow control offers strong possibilities for reducing the unsteady loading. Thus, it is useful to study how these flow structures respond under different forcing conditions. In particular, the response of the shear layers to any type of disturbance depends on a number of parameters, with frequency and amplitude of the disturbance being most important. In some of the experiments with controlled excitation, it was found that an excitation frequency close to the natural shedding frequency, or twice its value, strengthened the natural shedding due to the existence of a resonance condition. This phenomenon is commonly known as vortex shedding lock-on. A vortex “formation length” as that point downstream of the body where the velocity fluctuation level has grown to a maximum (and thereafter decays downstream) [4].

Plasma actuators are a growing technology for flow control. They are favorable for many applications for their relatively simple construction and lack of moving parts. They are essentially a plate capacitor with offset electrodes being fed high voltage and frequencies. The effect when powered is like a wall jet in larger flow scenarios. The structure of plasma actuators
is complex and unsteady in nature [6]. However, the formation and excitation of these structures is not a concern for this paper. The induced momentum on the air directly above a surface at certain power levels is key. Selection of the exact configuration was made to optimize this wall jet effect with altering the base flow significantly [10].

![Figure 1: Sketches of four flow structures [11]](image)

As suggested by Zhou [11] the reattachment region ranges from \( L/d \) 2 to 5. In this region a bi-stable flow has been observed at \( L/d=2–3 \), where two stable flow states may co-exist at the same \( L/d \) and \( Re \), though not necessarily in time, i.e. the shear layer rolls up behind and reattaches on the downstream cylinder [12]. This flow will be the target for recreation and change using the flow control. From the study of Bhattacharya Effect of Three-Dimensional Plasma Actuation on the Wake of Circular Cylinder [1], we know that plasma actuation has positive effects on the drag coefficient. For simple 2D actuation at +/- 80° from the leading stagnation point, there was a decrease of 3.6%. While with 3D actuation vortex shedding could be canceled and the drag coefficient drop by 33%. This research builds on the study of S. Bhattacharya “Effect of Three-Dimensional Plasma Actuation on the Wake of a Circular Cylinder.” [1] This gives an idea as to what happens to trailing edge vortices of the leading cylinder and the effects that it has on the wake of the trailing cylinder. This also presents a comparison to other research for the effects of flow control at various Reynolds number. This will open up a new area of research for flow control using plasma actuation in repeated
geometries that often show up in heat transfer situations. For heat sinks that have fixed geometric constraints, heat transfer may be able to be improved with increased turbulence in the flow. This research will give insight into the conditions of certain flows. Flow control using a single dielectric barrier discharge is a relevant topic to aerodynamic manufacturers. The technology is to be studied for potential applications.
EXPERIMENTAL SETUP

Figure 2: Wind Tunnel and PIV Setup

Figure 3: Test Section
A. Wind tunnel

An open-end low-speed wind tunnel was used to run all the test cases. The tunnel was leveled at the inlet and outlet and then matched to ensure the flow was horizontal. The exit of the tunnel just before the fan was partially blocked off to lower the flow speed in the test section. The blockage was kept constant to maintain a flow speed of roughly 3 m/s for a Reynolds number of 5000. The inlet of the tunnel is filled with straight tubes to help achieve a more uniform flow. Part of the table was removed to allow the laser plane to be projected from the bottom of the test section as seen in Figure 2.

B. Acrylic test section

The acrylic test section panels were cut out by a laser cutter based on DXF file exports. The cross-section of the test section was made to be 0.3175 m square. The total length of the test section was made to be the maximum allowable by the wind tunnel at 0.572 m. This gives an aspect ratio of 13D which is comparable with the studies of many researchers as shown by the review of Sumner [9]. After some initial testing, the rear panel was painted flat black to minimize reflections seen by the camera. All other panels were kept clear to allow the laser to dissipate. The front and rear mount of the test section were installed with a foam layer between them and the wind tunnel to seal the mount. On the inside of this connection, tape was applied over the joint to help smooth out the boundary layer. This kept the boundary layer less than 10% from the walls at any face.

C. Tandem cylinders

The cylinders were mounted in a unique way in the test section. The leading cylinder protrudes from a hole in the rear panel that was centered vertically and cut out 0.165 m from the start of the test section. Using this hole and a special jig, the near side of the leading cylinder was
aligned and pressed into the viewing window. This connection was held by double-sided tape to a pair of strong magnets and then double-sided tape to the viewing window. This allowed for the viewing window to be removed by splitting the magnets. When reinstalling the viewing window the magnet re-aligned the leading cylinder.

The same procedure was followed for the trailing cylinder. The cylinder was positioned by a jig that referenced the leading cylinder. The viewing window was installed and pressed into place to stick the magnets. Magnets were used on both sides of the acrylic tube to allow the cylinder to be completely removed. To change the spacing of the cylinders the magnets of the trailing cylinder were removed and reinstalled using the jig once again. This allowed the camera view to remain clean.

D. Plasma Actuator

Plasma actuators will be made based on the studies of Corke [5] and Thomas [10]. The base material will be the acrylic tube that is to be tested. In his research, Corke found that some of the strongest forces come from materials like Teflon, Delrin, and quartz as you could send more voltage through the system. The cost for that extra power is added thickness to the base material up to 6 mm. To avoid changing the aerodynamic properties of a base cylinder, three layers of 0.051 mm Kapton tape will be used for its overall thinness as the dielectric. The plasma actuators were made with a 0.0127 m buried copper electrode and a 0.0064 m exposed electrode [10]. The corners of the copper tapes were cut off at a radius of 10 mm to avoid concentration in the magnetic field. For the straight actuator, the electrodes spanned the maximum length of the tube. This ensured that the effects of the actuators were to be captured in the plane of the PIV. The effects out of the plane are not noticeable outside of 3 diameters from the plane. For the
segmented case, the buried electrode was broken into segments that were set at an optimal wavelength of $\lambda = 4$ [2].

![Figure 4: No Actuation, Straight Actuation, Segmented Actuation](image)

To adjust for the radius of the corners, the copper electrodes were longer in the segmented case. The Kapton tape was installed so that there were no air bubbles near the seam of the electrodes to avoid a burnout. The electrodes in both cases were placed on the cylinders so that were $\pm 80^\circ$ from the leading stagnation point [1]. The electrodes were wired with two separate 16 ga wires that ran through a hole in the tube and back to the transformer to avoid interference with each other.

The operating conditions of the actuators were set to optimal values [10]. A sinusoidal signal of 6 kHz and 6 V peak to peak is sent to an audio amplifier and checked with a signal analyzer. The amplifier boosts the signal to a voltage of 60 V peak to peak which is also checked using the signal analyzer. The signal is stepped up with a transformer to the final voltage of 6 kV peak to peak with the same frequency. A capacitor is placed in the circuit to measure the power delivered.
Figure 5 Plasma Actuator Installation Angle

Figure 6: Circuit Diagram for Plasma Actuator
E. **PIV setup**

The PIV equipment was set up carefully to reduce errors [7]. The laser beam was concentrated using a convex lens with a focal point of one meter. This focused the beam from a 5 mm diameter to a near focal point. This lens was positioned just under a meter from the top of the tunnel so that the region of interest had a thickness of less than 2 mm. This minimized the particle movement seen by the camera normal to the plane. Shortly after the convex lens, a planoconvex lens was used to spread the beam to cover the region of interest. This plane created by the laser was aligned perpendicular to the flow top to bottom and front to back within half a degree. This made the error from the alignment of the plane less than 1%.

The laser used double-pulsed Nd-YAG laser at 15 Hz with a delta T of 250 microseconds between flashes. The camera took a photo for each flash to view a displacement of the particles. This displacement measured in pixels was kept to 12 pixels in the free stream and as a result 3 pixels in the turbulent recirculating area. The seeding particles measured approximately three pixels in diameter. This meant that for processing the windows were kept between 24 and 64 pixels square.

The signal to trigger the camera and the laser was generated by lab view signal generator. It was sent through National Instruments 6320 timing card to a timing box that split the signal to their respective inputs. These lines has to kept away from metal that the plasma signal was close to or resting on to avoid interference. The plasma signal acted like a radio signal. The entire plasma circuit was wired to a separate panel than the PIV equipment.

F. **Test Parameters**
Table 1: Test Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds Number</td>
<td>Re</td>
<td>5000</td>
</tr>
<tr>
<td>Diameter</td>
<td>D</td>
<td>25.4 mm</td>
</tr>
<tr>
<td>Longitudinal pitch</td>
<td>λ</td>
<td>3D, 4D, 5D</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>AR</td>
<td>13D</td>
</tr>
<tr>
<td>Actuation</td>
<td>B, A, S</td>
<td>No actuation,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straight Actuation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Segmented Actuation</td>
</tr>
</tbody>
</table>

The test parameters selected added up to three cases of spacing with three types of actuation for a total number of nine cases. The spacing was selected to start at $\lambda = 3D$ because that is when three-dimensional flow occurs between the cylinders [3]. This is the structure that is aimed to be cancelled by the plasma actuator. The three cases of actuation were chosen to compare results with other studies. The no actuation case is important to relate to the larger body of research of flow over tandem cylinders while the actuation cases appeal to another body of research. The diameter of the cylinder was selected because of the availability of acrylic tube in its size. This also gave an aspect ratio that was is acceptable for this type of research. It avoids interference from the boundary layers of the wind tunnel. The Reynolds number was chosen to fill the gap in turbulent flow conditions of tandem cylinders.
RESULTS

Table 2 Images Collected for each Test Case

<table>
<thead>
<tr>
<th>Spacing</th>
<th>3D</th>
<th>4D</th>
<th>5D</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Actuation</td>
<td>6000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Straight Actuation</td>
<td>0</td>
<td>1200, 1600, 3000</td>
<td>250, 400</td>
</tr>
<tr>
<td>Segmented Actuation</td>
<td>0</td>
<td>1500, 2300</td>
<td>1600</td>
</tr>
</tbody>
</table>

Due to some errors in the saving of the images some of the test cases images were not image pairs and thus could not be processed using the PIV software. This was true for the cases that had zero images in Table 2. The vector field of the faulty images can be seen from Figure 10. The velocity vectors of the entire stream are chaotic because there was poor correlation. The computer processing was simply guessing. For successful cases, typical processing can be seen (Figures 7, 8, 9). For the cases that had actuation, the number is images is the total number of usable images collected. The number of images pairs and hence velocity fields for any given case is half the number of images taken. This number was determined by failure of the plasma actuator. These failures usually occurred in the middle of the electrodes along the seam which meant that the Kapton was heating up and losing its dielectric properties. This would burn out and cause a short in the circuit.
Discussion

The 3D case was the only case that successfully ran without actuation (saved properly). Although the spacing differs from the actuated cases the structures of the wakes are similar. Comparing figure 11 and 14 the shear of the first cylinder wake with actuation tightens the shear to the centerline. The vortex structure without actuation are much larger and hence create a shear farther from the centerline. When the spacing is increased to 4, in normal flow the vortex in the first wake have more time to develop and would create a shear layer farther from the centerline. Ever though the spacing is increase to 4, the shear layer tightens. This is a confirmation of the cancellation of the vortex shedding using the plasma actuator. The shear layer of the second
The turbulent kinetic plots of the later cases (Figures 16, 19, 22, 25) all agree that the energy of the first wake is concentrated to the centerline (due to the actuator). The distribution of the second wake is different in some regard than the 4D straight actuated case. Regarding size, the width of the distributions are similar. They have surpassed the width of the cylinder and are energizing the free stream flow. This suggests that turbulence can be increased in repeated structures using flow control. Differing from the 4D straight actuated case, are symmetric structures in the energy that are mirrored about the centerline in the second wake. This is mostly due to low number of images for any given run of these later cases. The 4D straight actuated case was based on the largest run of 3000 images hence the plots are better averaged (smoother) than the latter. In the extreme example of the 5D straight actuated case, the split feature didn’t have time to developed. In the segmented plot of 5, the energy has clear split features.

The vorticity plots (Figures 12, 16, 18, 21, 24) show one common change. In the 3D case the vorticity of the wake changes from positive to negative. This shows the mode B structure alternates in the set of cylinders. When the actuation is applied, both wakes show a negative vorticity. In the instantaneous case, the vorticity would be split to follow the vortex structure. These time averaged plots show that the flow favors one direction of the vorticity for both wakes.
with actuation. Assuming the strength of the upper and lower electrodes were relatively equal, the wake of the second cylinder matches the wake of the first.

For the 5D cases with either actuation, the shear layer of the first wake was scattered. This is from lack of data points. The structure of the wake is larger because it has more time (distance) to develop. This means the data is more varied further away from the cylinder which is way there is less defined areas compared to prior plots. In either case it can be seen that the shear layer is tight to the centerline for the first wake.

Plots
Figure 11: L=3, No Actuation, Shear Plot

Figure 12: L=3, No Actuation, Vorticity
Figure 13: L=3, No Actuation, Turbulent Kinetic Energy

Figure 14: L=4, Actuation, Shear
Figure 15: L=4, Actuation, Vorticity

Figure 16: L=4, Actuation, Turbulent Kinetic Energy
Figure 17: L=4, Segmented Actuation, Shear

Figure 18: L=4, Segmented Actuation, Vorticity
Figure 19: L=4, Segmented Actuation, Turbulent Kinetic Energy

Figure 20: L=5, Actuation, Shear
Figure 21: L=5, Actuation, Vorticity

Figure 22: L=5, Actuation, Turbulent Kinetic Energy
Figure 23: L=5, Segmented Actuation, Shear

Figure 24: L=5, Segmented Actuation, Vorticity
Figure 25: L=5, Segmented Actuation, Turbulent Kinetic Energy
CONCLUSION

The flow over tandem cylinders with 2D and 3D plasma actuators at a Re of 5000 was studied. The flow over the leading cylinder was forced with actuation to cancel the vortex shedding of the first cylinder. This tightened the first wake and energized it compared to normal. This energized wake had a larger explosion on the second cylinder which widened the wake. The Turbulent Kinetic energy distribution was widened as a result. However, the concentration was much more uniform compared to the first wake and a normal second wake. This direct effect on the wake of the second cylinder is directly related to the forcing of the plasma actuator.

With actuation, the shear boundary was tightened in the first wake, and widened in the second wake. This effect is like a mist of water hitting a bluff body vs a stream of water hitting a bluff body. The mist of water can simply move out of the way of the body. It acts more laminar. While with actuation, or a stream of water hitting a bluff body, the flow explodes. It creates a larger wake as the fluid stream breaks into mist. This effect created a wider, more uniform turbulent region. Also due to the additional space (3D to 4D, 5D) of these plots the wake had more time to recover from first cylinder. It gained energy and that can be seen in the values of the second wake. Even though the second wake is more evenly distributed, the value of the kinetic energy is higher.

To better compare the normal tandem cylinder flow vs actuated flow these missing results need to be retaken. This would allow the energized wakes for a given spacing to be directly compared to normal flow. The second wake also needs to have a larger view in the frame. With one camera maximizing its field of view it and minimizing the particle diameter to the limit the second wake was cut off. To better understand the second wake, future studies
should implement two cameras to widen the field of view and possibly achieve a better resolution.

It is also not certain to what extent the out of plane mode B vortices were affected. As these are related to the in plane Von Kármán vortices which were cancelled there must be an affect for the first cylinder. The second cylinder has not been studied in this unique setup. In the segmented case, the actuator induces vortices in the direction of the flow that cannot be measured with the current plane. To better understand these vortices and their effect on the second wake future research should take PIV data on a plane that rests on both cylinders and distances above.
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