Experiment and Computational Analysis on Effect of Plasma Actuation Incompressible Flow around Tandem Cylinders

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TITLE PAGE

EXPERIMENT AND COMPUTATIONAL ANALYSIS ON EFFECT OF PLASMA ACTUATION IN INCOMPRESSIBLE FLOW AROUND TANDEM CYLINDERS

By

EMMANUEL GABRIEL-OHANU

A dissertation submitted in partial fulfillment of the requirements for the Honors in Major in the Department of Mechanical and Aerospace Engineering in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

Fall Term 2019

Major Professor: Samik Bhattacharya, PhD
ABSTRACT

The utilization of steady state flow of air over tandem circular cylinders has several applications in engineering systems. Incompressible flow over circular cylinders in tandem at different spacing with and without plasma actuation on the leading cylinder will be investigated in this paper to understand the effects of plasma actuation on flow properties and wake region of the two cylinders in cross flow. The principal focus of the research is on the use of experimental and computational methods to study and provide valid results, the research will analyze the wake region, the effect of Reynolds number and the longitudinal spacing between cylinder on vortex shedding, aerodynamic parameters i.e. lift, drag, pressure differential, etc. The research will be conducted for steady flow at Reynold number, \( Re = \frac{U_\infty L}{\nu} \) between 5000 and 8000 for air. The turbulence of the wake and dynamic instability of the experimental is characterized by the Strouhal number, \( St = \frac{f L}{U_\infty} \) frequency of the vortex shedding in the wake which is directly proportional to the spacing, \( \lambda \) from center to center of cylinders between 3 to 5 inches. The dependencies on critical values of \( Re \) and \( St \) in symmetric flow over cylinders to show the instability of the flow regime in previous research. At \( Re = 5000 \) the vortex co-shedding on the second cylinder would occur at critical spacing, \( \lambda_c \) characterized by the \( Re - St \) relationship at \( 3 \leq \lambda \leq 5 \) in the flow regime.

The use of plasma actuation in fluid dynamics to control flow velocity by generating momentum to force atmospheric pressure and velocity in external flow with Single-Dielectric Barrier Discharge(SDBD) for both two and three-dimensional, 2D and 3D actuator (straight and segmented actuator). The SDBD actuators are mounted spanwise on
the leading cylinder for both 2D and 3D to impact momentum, therefore, forcing the wake regime. Computational Analysis is utilized for result and data pre-processing. The steady three-dimensional flow of tandem cylinders can be studied through Large Eddy Simulation (LES) using a subgrid-scale model to compare numerical and experimental results for the same setup and physical conditions. Particle Image Velocimetry (PIV) is used to resolve time series images from flow visualization of the experiment, the images are processed to visualize velocity vectors of the flow regimes. The velocity profile of the flow can be averaged and plotted for all instantaneous time-series images processed in PIV by Dynamic Mode Decomposition (DMD) or Proper Orthogonal Decomposition (POD) to generate common eigenvalues and eigenvector of the large dimension PIV data which shows the average properties of the flow properties.
ACKNOWLEDGEMENT

I would like to thank my thesis chair Dr. Samik Bhattacharya, the members Fluid Mechanics Lab and SIEMENS CATER Lab for providing funding and resources for the completion of this project.
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INTRODUCTION

Flow over cylinders has many application in engineering as isolated cylinders, tandem cylinder and staggered cylinders structures as classified in (Suehiro, 2005) flow around cylinder have been comprehensively researched and discussed in fluid mechanics and dynamics with application ranging from thermal, mechanical and aerospace engineering. Cylindrical structures are used in engineering design such as buildings, heat exchanger, nuclear reactors, power cable, large marine vessel, Turbines, etc. The vortex shedding in flow was first studied by Von Karman as Karman Vortex street over a range of Reynolds number which creates a swirling of fluid (air) downstream of the flow in the turbulent flow regime, this effect is referred to as eddy in fluid dynamics. Karman vortex and eddies result in the failure of several engineering systems due to problems with flow-induced vibration, instability, and noise. (Sumner, 2010) A complete understanding of the fluid dynamics for the flow around a circular cylinder includes such fundamental subjects as the boundary layer, separation, the free shear layer, the wake, and the dynamics of vortices. Vortex shedding due to Karman turbulence create problems in engineering system i.e. the Ferrybridge power station cylindrical towers collapsed due to vortex interaction.

A complete understanding of the fluid dynamics for the flow around a circular cylinder includes such fundamental subjects as the boundary layer, separation, the free shear layer, the wake, and the dynamics of vortices (Sumner, 2010). The flow around two cylinders in tandem has not been adequately studied and there has been no research for
the application of plasma actuators for flow control over tandem cylinder to investigate the flow separation on the downstream cylinder.

![Figure 1: Tandem cylinder configuration adapted from (Sumner, 2010)](image)

The flow pattern and characteristics of the wake regime for tandem cylinders have been investigated by using Large Eddy Simulation by several researchers in the journal of fluid dynamic, in (Mia Abrahamsen Prsic, 2014) it validated the used of LES model is chosen due to its capability of modeling the moderate-high Re flow and resolving the 3D bluff body flow in a less numerically costly manner, by using a subgrid scale due to turbulence in incompressible flow. LES simulation is used visualize eddies in the flow regime not affected by Vortex Induced Vibrations (VIV). Several studies have been performed on the flow over a single circular cylinder and tandem cylinder to understand the aerodynamic parameters and flow properties for different experimental and simulation setup, over the past 30 years research has been conducted to create adaptive technology and methods to control the flow around cylinder from the use of rotating cylinder, helical projections, staggered configuration, heat application, etc. A relatively new method for flow control is the use of plasma actuators in the form of SDBD straight and segmented mounting on the surface of the cylinder. The use of Dielectric Barrier Discharge (DBD) plasma actuator is a fast growing technology, in accordance with (Thomas C. Corke,
2010) DBD plasma are fully electronic with no moving parts, have a fast time response for unsteady applications and very low mass.

Figure 2: Morphology of SDBD plasma actuator showing structure and ion transport and Ionized plasma electrode (C. L. Enloe, 2004) (Thomas C. Corke, 2010)

The structure, specification, and physics of the plasma actuators is not reviewed in this paper the experiment and simulation will use the study of (Gregory, Effect of Three-Dimensional Plasma Actuation on the Wake of a Circular Cylinder, 2015) (Gregory, Investigation of the cylinder wake under spanwise periodic forcing with a segmented plasma actuator, 2015) (Dmitriy M. Orlov, 2006) to understand the physics of the plasma but the experiment will focus on the application of plasma actuation in flow control and application in industry and engineering systems.
CHAPTER 2: LITERATURE REVIEW AND VALIDATION

In 1981 a study on flow over tandem cylinder done by (Igarashi, 1981) showed several properties for flow tandem cylinder at subcritical Reynold number $8.7 \times 10^3 \leq Re \leq 5.2 \times 10^4$ and spacing $L/d$ between 1 and 5 showed that vortex generation depended on the Reynolds number, Igarashi investigated the aerodynamic force and quantities which helped understand the point and angle at which flow separation occurs ($\phi$) from the cylinder which matches the angle from (Gregory, Effect of Three-Dimensional Plasma Actuation on the Wake of a Circular Cylinder, 2015)

![Figure 3: Plot showing pressure differential coefficient at the different circumference angle for tandem cylinder](image)

In Figure 3 the upstream cylinder plot shows that pressure unifies after approximately 80 degrees which is the point at which separation occurs which is the point of attaching the plasma. (Samik Bhattacharya, 2018) And (Flint O. Thomas, 2009) showed a method for
plasma induced body forcing modeling applicable for experimental setup for aerodynamic control. The use of plasma actuation is the primary focus but in other to understand its effect in forcing the wake of the flow understanding the characteristics of the flow around cylinders is important and can be understood through (Sumner, 2010) for the configuration of the tandem cylinder.

Sumner (2010) discussed the many approaches in understanding the fluid dynamics for flow over multiple cylinders based on experimental observation, numerical methods, and simulations were done by several researchers, according to (Sumner, 2010) Zdravkovich studied and classified the fluid behavior into two basic types of interference, based on the location of the downstream cylinder with respect to the upstream one. Sumner (2010) review showed two types of interference; wake interference and proximity interference. In (Igarashi, 1981) he identified eight different flow patterns for two tandem circular cylinders of equal diameter in steady cross-flow, The reattachment regime can be subdivided into two basic flow regimes based on the behavior of the Strouhal number (Zhou, 2006) and the wake flow structure and vortex dynamics. The four resulting flow regimes for the tandem configuration, based on these more recent studies (BRUNO S. CARMO1, 2010) shown in figure 4.

![Figure 4: (Zhou, 2006) studied flow pattern for tandem cylinder configuration](image-url)
The downstream cylinder sits inside the vortex formation region of the upstream cylinder (Sumner, 2010) and the separated shear layers from the upstream cylinder are forced to enclose or wrap around the downstream cylinder, without any reattachment onto its surface, before rolling up alternately into Karman vortices behind the downstream cylinder.

![Flow pattern and Classification based on Reynolds number and spacing](image)

Figure 5: Flow pattern and Classification based on Reynolds number and spacing

(G. Xu, 2004) (S. Bhattacharyya, 2008) Studied the effects of Reynold and Strouhal number on the flow over the cylinders beyond the flow pattern boundary at critical values and experimental effect on the vortex dynamics and wake structure in the flow pattern. (Sumner, 2010) Review attempt to summarize several works from publications for flow over cylinder showing all measured parameters and physical conditions in previous studies. It summarizes the method of data collection used such as Constant temperature
anemometry (CTA), Flow Visualization (FV), Laser-Induced Fluorescence (LIF). The table below shows the summary of selected experiments.

<table>
<thead>
<tr>
<th>Re</th>
<th>L/D</th>
<th>AR</th>
<th>Blockage ratio (%)</th>
<th>Turbulence intensity (%)</th>
<th>Test facility</th>
<th>Technique</th>
<th>Measurements</th>
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<tr>
<td>$6.5 \times 10^4$</td>
<td>1.1-9</td>
<td>8</td>
<td>8</td>
<td>0.19</td>
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<td>St, CD, CP, C_D, CD, CP, C_D'</td>
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<td>11</td>
<td>9</td>
<td>0.3</td>
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<td>Pressure</td>
<td>St, CP, C_P, C_D, C_D'</td>
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<td>48-120</td>
<td>1.2-3</td>
<td>Not given</td>
<td>Wind tunnel</td>
<td>Force</td>
<td>Interference drag</td>
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<td>8, 20</td>
<td>7, 13</td>
<td>0.2</td>
<td>Wind tunnel</td>
<td>FV, CTA, pressure, temperature</td>
<td>St, CD, CP, Sh, Nu</td>
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<td>$200-1.2 \times 10^6$</td>
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<td>120</td>
<td>1</td>
<td>0.03</td>
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<td>CTA, pressure</td>
<td>St, CP, CPb, velocity profiles</td>
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<td>30</td>
<td>2</td>
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<td>6</td>
<td>0.6</td>
<td>Wind tunnel</td>
<td>FV, CTA, pressure</td>
<td>St, CP, C_P, CD</td>
</tr>
<tr>
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<td>3</td>
<td>13</td>
<td>0.6</td>
<td>Wind tunnel</td>
<td>FV, CTA, pressure</td>
<td>St, CP, C_P, CD</td>
</tr>
<tr>
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<td>1-5</td>
<td>11</td>
<td>9</td>
<td>Not given</td>
<td>Wind tunnel</td>
<td>FV, CTA, pressure</td>
<td>St, CD, CP</td>
</tr>
<tr>
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<td>9</td>
<td>1-11</td>
<td>Water tunnel</td>
<td>Force</td>
<td>St, C_D', C_D'</td>
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<td>11</td>
<td>10</td>
<td>0.1-10</td>
<td>Wind tunnel</td>
<td>CTA, pressure</td>
<td>–</td>
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<td>5</td>
<td>20</td>
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<tr>
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<td>2.5</td>
<td>Water channel</td>
<td>PIW</td>
<td>Velocity field</td>
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<td>6.3</td>
<td>0.35</td>
<td>Wind tunnel</td>
<td>FV, CTA, pressure</td>
<td>St, CP</td>
</tr>
<tr>
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<td>2.3-2</td>
<td>20</td>
<td>5</td>
<td>0.35</td>
<td>Wind tunnel</td>
<td>CTA, FV, CTA, pressure</td>
<td>St, CP, CP</td>
</tr>
<tr>
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<td>1.15-5.1</td>
<td>8.3</td>
<td>10</td>
<td>Not given</td>
<td>Water channel</td>
<td>PIW</td>
<td>Velocity field</td>
</tr>
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<td>$3.3 \times 10^3-4 \times 10^5$</td>
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<td>16</td>
<td>6</td>
<td>0.1</td>
<td>Wind tunnel</td>
<td>FV, pressure</td>
<td>St, CP, CP'</td>
</tr>
<tr>
<td>$2 \times 10^6$</td>
<td>1.25-5</td>
<td>16</td>
<td>6</td>
<td>0.1-3.2</td>
<td>Wind tunnel</td>
<td>FV, pressure</td>
<td>St, CP, CP', CD</td>
</tr>
<tr>
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<td>1.2-7.2</td>
<td>5</td>
<td>9</td>
<td>0.6</td>
<td>Water channel</td>
<td>FV</td>
<td>Sh</td>
</tr>
<tr>
<td>$4 \times 10^6-6.2 \times 10^5$</td>
<td>1.1-6.3</td>
<td>7</td>
<td>8</td>
<td>0.1</td>
<td>Wind tunnel</td>
<td>FV</td>
<td>St, C_D</td>
</tr>
<tr>
<td>$3.25 \times 10^5-6.5 \times 10^5$</td>
<td>2.2-4</td>
<td>15</td>
<td>5</td>
<td>0.12</td>
<td>Wind tunnel</td>
<td>Pressure</td>
<td>C_D, C_D'</td>
</tr>
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<td>16, 16</td>
<td>2.5, 6.7</td>
<td>Not given</td>
<td>Wind tunnel</td>
<td>FV, CTA, pressure, wind tunnel</td>
<td>St, CD, CP, C_D</td>
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<td>24, 20</td>
<td>4, 5</td>
<td>0.1, 0.15</td>
<td>Not given</td>
<td>FV, CTA, pressure</td>
<td>St</td>
</tr>
<tr>
<td>$6 \times 10^6$</td>
<td>2.5-7</td>
<td>33</td>
<td>2</td>
<td>0.1</td>
<td>Wind tunnel</td>
<td>CTA, pressure</td>
<td>CP, CPb, CD</td>
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<tr>
<td>$1.11 \times 10^5$</td>
<td>2-10</td>
<td>8</td>
<td>5</td>
<td>0.4-11.5</td>
<td>Wind tunnel</td>
<td>Pressure, force</td>
<td>CP, CP', CD, C_D, C_D', C_D'</td>
</tr>
<tr>
<td>$7 \times 10^3$</td>
<td>1.3-6</td>
<td>40</td>
<td>2.5</td>
<td>0.4</td>
<td>Wind tunnel</td>
<td>CTA</td>
<td>Velocity, temperature</td>
</tr>
</tbody>
</table>

*Table 1: Comparison of flow over tandem cylinder from (Sumner, 2010)*
CHAPTER 3: EXPERIMENTAL SETUP AND METHOD

The experiment was performed in a subsonic wind tunnel with test section of 24in by 1in by 1in as shown in the figure below. For the computational model I used star come for the analyses with a computational domain similar to that of the experiment in symmetry

For data collection we used Furness Control pressure transducer with a National Instrument Data Acquisition System. This was used alongside the Pitot tube to collect the pressure data for plotting the velocity profile along the x axis

Figure 6: Wind Tunnel CAD and Test Section
The use of plasma for flow control on the surface of the cylinder was applied in the experiment for forced case and unforced case. The setup for the plasma consists of a function generator supplying voltage at 4vpp and 6kHz frequency to an amplifier with a gain of ten and the output voltage is sent to a transformer with a gain of 137 with an output of about 5 to 6 KV.
Figure 9: Circuit diagram of voltage generation for plasma

Plasma
Function Generator = 4Vpp at 6 kHz
Amplifier gain = x10
Transformer = x137
Output voltage to plasma = 5.48 - 6 kV

Figure 10: Cylinder orientation with plasma
CHAPTER 4: COMPUTATIONAL ANALYSIS

The Computational analysis of the experiment was performed to provide insight and validation on the results gotten from the experiment. The Flow analysis is performed using STARCCM+ to visualize flow regime and study the interaction of vortex on downstream cylinder. I analyzed the cylinder spacing, aerodynamic forces, vortex shedding

![Figure 11: CFD Mesh and Grid](image)

Simulation Physics and Boundary Conditions
- Large Eddy Simulation
- Turbulent
- Implicit Unsteady
- Surface Interface between cylinder and plasma region

Simulation Initial Value
- Free Stream Velocity = 3.0m/s
- Reynolds Number=4700
- Segregated Fluid Enthalpy
- Time Step=2.5E-05s and 0.001s
Pressure at Downstream Cylinder (Tandem Cylinder at $\lambda=3D$)

Pressure at Downstream Cylinder (Tandem Cylinder at $\lambda=4D$)
Figure 12: Coefficient of Pressure for spacing 3D, 4D, 5D
CHAPTER 5: PITOT TUBE MEASUREMENTS DATA

Single Cylinder
- Freestream Velocity, $U_\infty = 3.122\text{m/s}$
- Straight forcing has more effect than segmented
- Vortex cancelling

Tandem Cylinder
- Freestream Velocity, $U_\infty = 3.122\text{m/s}$
- Segmented forcing has more effect than straight
- Forcing has no effect at 3D
- 4D is optimum
Tandem Cylinder Pressure Distribution Data

- Freestream Velocity, $U_\infty = 3.122\text{m/s}$
- Ports to measure pressure differential on cylinder surface
- Stagnation point
- Characteristics of the Flow around Two Circular Cylinders Arranged in Tandem (JSME Igarashi)
Pressure was taken over the surface of the second cylinder for both unforced and forced case and compared to the data of JSME Igarashi.

Figure 15: Pressure Distribution over one cylinder

Figure 16: Coefficient of pressure from tandem cylinder (Igarashi, 1981)
Figure 17: Pressure Distribution over tandem cylinder
CHAPTER 6: CONCLUSIONS AND FUTURE WORK

- Particle Image Velocimetry and Dynamic Mode Decomposition: Experimental method to verify simulation in larger scale application.
- Scaling and Improvements:
  - Increase in mesh density and computational power for better simulation results
  - Utilization of LES methods with grid independence for analysis
- Rotating Cylinder
- Variation in blowing ratio and Reynolds number
- Pulsed Plasma
APPENDIX

Codes used in processing
% this code plots the mean velocity after reading the
velocity from individual mat data files
% this code processes data
%------------------------------------------------------
------
clear all;
clc;
close all;
%%%INPUT MODULE%%
Uinf=3.3
file_dir='C:\Users\ohanu\OneDrive\Desktop\Tandem
Cylinder Data\2_Cylinder_pitot';
string1='\Forced\Segmented_Plasma\5D_Spacing\x_d=5';
string2='\Forced\Straight_Plasma\5D_Spacing\x_d=5';
string3='\Unforced\5D_Spacing\x_d=5'

%%
filedir1=[file_dir, string1];%change source
folder1=dir(filedir1);
files=cell(1,length(folder1)-2);
nn=1;
for nfile=3:length(folder1)
    files{1,nn}=[filedir1 '\ folder1(nfile).name];
    nn=nn+1;
end
data1=cellfun(@(x)(importdata(x)),files,'UniformOutput'
,false);

meanP=zeros(1,25);
meanU=zeros(1,25);
ypos=zeros(1,25);
for j=1:25
    meanP(j)=mean(data1{1,j}.data,1);
    meanU(j)=sqrt(2.*10.*meanP(j)./1.184)/Uinf;
    ypos(j)=(6/25)*j;
end
%%
filedir2=[file_dir, string2]; %change source
folder2=dir(filedir2);
files=cell(1,length(folder2)-2);
nn=1;
for nfile=3:length(folder2)
    files{1,nn}=[filedir2 '\ folder2(nfile).name];
    nn=nn+1;
end
data2=cellfun(@(x)(importdata(x)),files,'UniformOutput'
    ,false);
mean2P=zeros(1,25);
mean2U=zeros(1,25);
y2pos=zeros(1,25);
for j=1:25
    mean2P(j)=mean(data2{1,j}.data,1);
    mean2U(j)=sqrt(2.*10*mean2P(j)./1.184)./Uinf;
    y2pos(j)=(6/25)*j;
end

filedir3=[file_dir, string3]; %change source
folder3=dir(filedir3);
files=cell(1,length(folder3)-2);
nn=1;
for nfile=3:length(folder3)
    files{1,nn}=[filedir3 '\ folder3(nfile).name];
    nn=nn+1;
end
data3=cellfun(@(x)(importdata(x)),files,'UniformOutput'
    ,false);
mean3P=zeros(1,25);
mean3U=zeros(1,25);
y3pos=zeros(1,25);
for j=1:25
    mean3P(j)=mean(data3{1,j}.data,1);
    mean3U(j)=sqrt(2.*10*mean3P(j)./1.184)./Uinf;
y3pos(j) = (6/25)*j;
end

meanUi = smooth(meanU)
mean2Ui = smooth(mean2U)
mean3Ui = smooth(mean3U)

plot(meanUi, ypos, '-b*');
hold on
plot(mean2Ui, y2pos, '--mo');
hold on
plot(mean3Ui, y3pos, '-rS');

title('Normalized Velocity Profile at x/d=5 (Tandem Cylinder at \lambda=5D)')
legend('Unforced', 'Segmented Forcing', 'Straight Forcing')
set(gca, 'XMinorTick', 'on', 'YMinorTick', 'on')
set(gca, 'fontweight', 'bold', 'fontsize', 12)
ylabel('y/d')
xlabel('U/U_\infty')
%xlim([0 3.5])
%ylim([-3 3])
REFERENCES


