

**EXPERIMENTAL AND COMPUTATIONAL
STUDY OF FLOW OVER A ROTATING
CYLINDER WITH SURFACE ROUGHNESS**

MOHAMAD TARMIZI BIN ABU SEMAN

UNIVERSITI SAINS MALAYSIA

2016

**EXPERIMENTAL AND COMPUTATIONAL STUDY OF FLOW OVER A
ROTATING CYLINDER WITH SURFACE ROUGHNESS**

by

MOHAMAD TARMIZI BIN ABU SEMAN

**Thesis submitted in fulfilment of the requirements
for the degree of
Doctor of Philosophy**

March 2016

DECLARATION

I hereby declare that the work reported in this thesis is the result of my own investigation and that no part of the thesis has been plagiarized from external sources. Materials taken from other sources are duly acknowledged by giving explicit references.

Signature:

Name of student: MOHAMAD TARMIZI BIN ABU SEMAN

Matrix number: P-CD0074

Date: 01 March 2016

APPENDICES

Appendix A: Calibration data.

Table B1 below presents the load cell calibration data to ensure the constants of load cell for measure lift and drag. The experiments were repeated thrice to get accurate measurements and minimum error. They were found to be linear and quite repeatable.

Table B1: Calibration factor for lift and drag measurement

Test 1		
Calibration factor		
Applied force (Newton)	Lift	Drag
1	3.4	3.5
2	3.1	3.1
3	3.7	3.8
4	3.4	3.6
5	3.1	3.2
6	3.8	4.0
Test 2		
Calibration factor		
Applied force (Newton)	Lift	Drag
1	3.5	3.6
2	3.1	3.2
3	3.8	3.9
4	3.4	3.5
5	3.0	3.1
6	3.7	3.9
Test3		
Calibration factor		
Applied force (Newton)	Lift	Drag
1	3.5	3.6
2	3.1	3.2
3	3.8	3.9
4	3.5	3.6
5	3.1	3.1
6	3.7	3.9

The data from **Table B1**, the values were averaged and entered into **Table B2**.

Table B2: Averaged values of calibration data

Applied force (Newton)	Calibration factor	
	Lift	Drag
1	3.48	3.58
2	3.14	3.18
3	3.80	3.84
4	3.44	3.54
5	3.04	3.14
6	3.76	3.92

LIST OF PUBLICATIONS

Journal publications:

1. **M.T. ABU SEMAN¹, F. ISMAIL², H. YUSOFF³**, 2015. Rotational effects on vortex shedding behaviour of a cylinder with surface roughness – An experimental PIV and computational approach, *International Journal of Mechanical And Production Engineering*, Volume3, Issue-4. (Scopus Index)
2. **M.T. ABU SEMAN¹, F. ISMAIL², H. YUSOFF³, M.A. ISMAIL²**, 2015. Effect of counter-rotating cylinder with surface roughness on stagnation and separation point – A Computational Approach, *Indian Journal of Science & Technology*, Vo 8(30), DOI:10.17485. (ISI Index List)
3. **M.T. ABU SEMAN¹, F. ISMAIL², M.Z. ABDULLAH¹**, 2014. Rotational effects on aerodynamics of a cylinder with surface roughness – An experimental and computational approach, *ScienceAsia Journal*. (ISI Index - Under review)
4. **M.T. ABU SEMAN¹, F. ISMAIL², M.Z. ABDULLAH¹, M.N.A. HAMID³**, 2015. Investigation of Aerodynamic Performances on a Rotating Cylinder with Surface Roughness using Light Weight Smart Motor (LWSM), *Iranian Journal of SCIENCE AND TECHNOLOGY Transaction of Mechanical Engineering*. (ISI Index List- Under review)

Conference proceedings:

5. **M.T. ABU SEMAN¹, F. ISMAIL², N.I. ISMAIL³, M.A. ISMAIL², H. YUSOFF³**, 2015, Effect of counter-rotating cylinder with surface roughness on stagnation and separation point – A Computational Approach. *The 4th International Conference on Computer Science & Computational Mathematics ICCSCM 2015, May 7th-8th, 2015, Langkawi, Malaysia.*
6. **M.T. ABU SEMAN¹, F. ISMAIL², H. YUSOFF³**, 2015. Rotational effects on vortex shedding behaviour of a cylinder with surface roughness – an experimental PIV and computational approach. *IIER International Conference on Mechanical, Aeronautics and Production Engineering (ICMAPE-2015), Kuala Lumpur, Malaysia, February 12, 2015*
7. **M.T. ABU SEMAN¹, F. ISMAIL², M.Z. ABDULLAH¹**, 2012. Experimental and Computation analysis on vortex shedding behavior behind a counter-rotating circular cylinder with surface roughness. *2nd Mechanical and Aerospace Engineering Research Colloquium (MAERC). University Sains Malaysia, Malaysia (2012).*

ACKNOWLEDGMENTS

In the name of ALLAH, The Most Beneficent and The Most Merciful
*Praise is exclusively to Allah, the Lord of the universe and peace is upon
the Master of the Messengers, his family and companions.*

First of all, I want to give my humble gratitude to Dr. Farzad Ismail and Prof. Dr. Mohd Zulkifly Abdullah for their guidance, continuous support and advice throughout this study. I am profoundly grateful to my wife, my sons, my parent and my family for all the support they have given.

I would also like to thank University Sains Malaysia (USM), Polytechnic Seberang Perai (PSP) and its staff, my friends and all of my colleagues at the School of Mechanical Engineering, the School of Aerospace Engineering, and the Institute of Postgraduate Studies. Special thanks to my research group members Mr. Najib, Mr. Azmi, Mr. Zafran, Mr. Kamal, Mr. Sharizal, Mr. Andry, Mr. Khalil, Miss Nisa and my lab mates Mr. Akmal, Miss Nadiah, Mr. Fauzy, and to lab technicians Mr. Azhar, Mr. Amri, Mr. Najib, Mr. Ahmad Fadzil and Mr. Nasaruddin, all of which are also my dear friends.

I am deeply indebted to Higher Ministry of Education, especially Department of Mechanical Engineering, Polytechnic Seberang Perai, Penang, Malaysia for the opportunity to pursue this endeavour. I am thankful as well to all my colleagues at the department for all their advice and encouragement. Also many thanks to all other parties that I have not mentioned their names here, whose have helped me directly or indirectly throughout my study. May Allah S.W.T bless all of you.

Finally, I am grateful to the University Sains Malaysia for giving opportunity for this postgraduate study. Praise is exclusively to Allah.

MOHAMAD TARMIZI BIN ABU SEMAN
2016

TABLE OF CONTENTS

Acknowledgments.....	ii
Table of Contents.....	iv
List of Tables.....	viii
List of Figures.....	x
List of Abbreviations.....	xvi
List of Symbols.....	xvii
Abstrak.....	xix
Abstract.....	xx

CHAPTER 1 - INTRODUCTION

1.1 Background.....	1
1.2 Problem statement.....	3
1.3 Objective of the Research.....	6
1.4 Contribution the current research.....	6
1.5 Scope of the Research.....	7
1.6 Thesis outline.....	8

CHAPTER 2 - LITERATURE REVIEW

2.1 Overview.....	10
2.2 Circular cylinder with analytical method.....	10
2.3 The flow Around a Two-Dimensional Circular Cylinder.....	13
2.3.1 Experimental Non-rotating smooth cylinder.....	13
2.3.2 Computational Non-rotating smooth cylinder.....	17

2.3.3	Experimental Rotating smooth cylinder.....	24
2.3.4	Computational Rotating smooth cylinder	27
2.3.5	Experimental Non-rotating cylinder with surface roughness.....	33
2.3.6	Computational Non-rotating cylinder with Surface Roughness	36
2.4	Summary	41

CHAPTER 3 - METHODOLOGY

3.1	Overview.....	44
3.2	Experimental setup and procedure.....	45
3.2.1	Vibration of rotating cylinder.....	59
3.2.2	Error analyses.....	62
3.2.3	Experimental uncertainty analysis	64
3.2.4	Uncertainty of load-cell.....	65
3.2.5	Uncertainty for instantaneous lift and drag.....	68
3.2.6	Previous Experimental data.....	71
3.3	Numerical setup and procedure.....	73
3.3.1	Simulation procedure	73
3.3.2	Mesh generation	77
3.3.3	Boundary layer	78
3.3.4	Governing equation.....	80
3.3.5	Turbulence models.....	84
3.3.6	Numerical solver method.....	87
3.3.7	Verification and Validation (V & V) Tests.....	89
3.3.8	Verification and Validation procedures	91

CHAPTER 4 - RESULTS AND DISCUSSION

4.1	Overview	94
4.2	Experimental results and discussion	95
4.2.1	Comparison with past study: non-rotating smooth cylinder	95
4.2.2	Effect of Reynolds number in lift and drag coefficient..... performance	96
4.3	Effect of roughness at low and high Re for present experiment.....	102
4.4	Effect of rotation at low and high Re for present experiment.....	105
4.5	Comparison of lift and drag performance with varying roughness at low..... Reynolds number	109
4.6	CFD results and discussion	113
4.6.1	Comparison of simulation and experiment	113
4.7	Velocity profile by CFD	116
4.7.1	Comparison of velocity at low and high Reynolds number	116
4.8	Pressure coefficient	122
4.8.1	Comparison of pressure profile at low and high Reynolds	122
	number	
4.9	Turbulence Kinetic Energy (TKE).....	125
4.9.1	Comparison of TKE at low and high Reynolds number	125
4.10	Discussion on flow field	128
4.10.1	Velocity field.....	128
4.10.2	Turbulence Kinetic Energy (TKE).....	134
4.10.3	Shear stress.....	134

CHAPTER 5 - CONCLUSIONS AND FUTURE RESEARCH

5.1	Summary	143
5.2	Conclusion	143
5.3	Future research recommendations	146
	References.....	148

Appendices

List of Publications

LIST OF TABLES

	Page
Table 2.1 Non-rotating smooth cylinder base on experiment	17
Table 2.2 Non-rotating smooth cylinder base on CFD	23
Table 2.3 Rotating smooth cylinder base on experiment	26
Table 2.4 Rotating smooth cylinder base on CFD	32
Table 2.5 Non-rotating cylinder with surface roughness base on experiment	36
Table 2.6 Non-rotating cylinder with surface roughness base on CFD	40
Table 3.1 Detail of the average roughness of profile attached at a circular cylinder	48
Table 3.2 Detail of rough surface profile by commercial sandpaper	51
Table 3.3 Rotating cylinder range	59
Table 3.4 Natural Frequency measurement on motor	60
Table 3.5 Error analysis for load cell on drag calibration factor	67
Table 3.6 Error analysis for load cell on lift calibration factor	67
Table 3.7 Uncertainty error for instantaneous C_D	69
Table 3.8 Uncertainty error for instantaneous C_L	69
Table 3.9 Comparison for C_D from the present experimental with value from (Schlichting and Gersten, 2000); Non-rotating with smooth cylinder	72
Table 3.10 Comparison for C_D from the present experimental with value from (Babu and Mahesh, 2008); Non-rotating with roughness cylinder	72
Table 3.11 Details for the meshes used in the grid-independency study on smooth cylinder without rotation required in Verification and	92

Validation assessment

Table 3.12	Verification & Validation analysis data of CFD	92
Table 4.1	Present % difference of C_L for cylinder $e/D=0.0015$ with on-rotating and rotating between present experimental and CFD simulation	98
Table 4.2	Present % difference of C_D for cylinder $e/D=0.0015$ with non-rotating and rotating between present experimental and CFD simulation	98
Table 4.3	% Lift reduction compared to a Cylinder $e/D=0.0001$	111
Table 4.4	% Drag reduction compared to a Cylinder $e/D=0.0001$	111

LIST OF FIGURES

	Page
Figure 1.1 Cylinder definition	2
Figure 1.2 Magnus effect concept on rotating cylinder. Adapted from source: (Marsh,October 2015)	2
Figure 1.3 Model of a sailing boat, using a Savonius-rotor	4
Figure 1.4 Monoplano Rotor. Courtesy of Deutsches	5
Figure 2.1 Visualisation of low Reynolds number flows around a circular cylinder. (a) Laminar flow; $Re=1.54$ (b) Separation flow; $Re=26$. Flow directed from left to right. Adapted from (Van Dyke, 1982).	14
Figure 3.1 Flow chart of the experimental procedure	46
Figure 3.2 Friction force experiment apparatus	49
Figure 3.3 Friction force (N/m) versus speed (rev/m) for smooth and rough cylinder	50
Figure 3.4 RPM versus velocity in the test section of wind tunnel	53
Figure 3.5 Experimental apparatus	54
Figure 3.6 Schematic of the experimental setup	55
Figure 3.7 Schematic of four beam strain gage balance with LWSM	57
Figure 3.8 Four beam strain gage balance for lift and drag measurement	57
Figure 3.9 (a) 3D Isometric view for LWSM; (b) Complete LWSM set	58
Figure 3.10 Cylinder displacement of rotating	60
Figure 3.11 Vibration on light weight motor	61
Figure 3.12 Load cell calibration test set-up	66

Figure 3.13	Uncertainty curve for cylinder with roughness ($e/D=0.0015$) at rotation (400rev/m)	70
Figure 3.14	Contour pressure for cylinder with roughness ($e/D=0.0015$) at rotation (400 rev/m), $Re < 20000$; C_P in Zone A $>$ C_P in Zone B	70
Figure 3.15	Contour pressure for cylinder with roughness ($e/D=0.0015$) at rotation (400 rev/m), $Re > 40000$; C_P in Zone A $<$ C_P in Zone B	71
Figure 3.16	Flow chart CFD and numerical procedures	74
Figure 3.17	Principal schemes of roughness	75
Figure 3.18	Meshed model and boundary condition of the computation domain	77
Figure 3.19	Velocity (m/s) on cylinder surface	79
Figure 3.20	Flow pattern on boundary layer; (a) Smooth surface ($e/D=0.0001$), (b) Rough surface ($e/D=0.0015$)	80
Figure 3.21	Velocity contour (a) K-epsilon model; (b) Reynolds stress model; (c) Spalart –Allmaras model	86
Figure 3.22	Flow chart of pressure based segregated solver	88
Figure 3.23	L1 error of simulation and experimental solution for the C_D	93
Figure 4.1	Comparison of C_D (non-rotating cylinder) data from Schlichting and Gersten (2000), Zhou et al. (2015) and the present experiment	96
Figure 4.2	Coefficient of lift (C_L) comparison for non-rotating and rotating cylinder for Cylinder $e/D=0.0015$, experimental versus CFD simulation	99
Figure 4.3	Coefficient of drag (C_D) comparison for non-rotating and rotating cylinder for Cylinder $e/D=0.0015$, experimental versus CFD simulation	99

Figure 4.4	Coefficient of drag (C_D) comparison for non-rotating and rotating cylinder for Cylinder $e/D=0.0001$ (Experiment)	100
Figure 4.5	Coefficient of drag (C_D) comparison for non-rotating and rotating cylinder for Cylinder $e/D=0.0008$ (Experiment)	100
Figure 4.6	Coefficient of drag (C_D) comparison for non-rotating and rotating cylinder for Cylinder $e/D=0.0012$ (Experiment)	101
Figure 4.7	Coefficient of drag (C_D) comparison for non-rotating and rotating cylinder for Cylinder $e/D=0.0015$ (Experiment)	101
Figure 4.8	Coefficient of drag (C_D) versus Roughness at $Re < 20000$ in various cylinder speeds (Experiment)	102
Figure 4.9	Coefficient of lift (C_L) versus Roughness at $Re < 20000$ in various cylinder speeds (Experiment)	103
Figure 4.10	Coefficient of drag (C_D) versus Roughness at $Re > 20000$ in various cylinder speeds (Experiment)	104
Figure 4.11	Coefficient of lift (C_L) versus Roughness at $Re > 20000$ in various cylinder speeds (Experiment)	105
Figure 4.12	Coefficient of drag (C_D) versus Speed (rev/m) at $Re < 20000$ in various types of cylinder (Experiment)	106
Figure 4.13	Coefficient of lift (C_L) versus Speed (rev/m) at $Re < 20000$ in various types of cylinder (Experiment)	107
Figure 4.14	Coefficient of drag (C_D) versus Speed (rev/m) at $Re > 20000$ in various types of cylinder (Experiment)	108
Figure 4.15	Coefficient of lift (C_L) versus Speed (rev/m) at $Re > 20000$ in various types of cylinder (Experiment)	109
Figure 4.16	Lift coefficient (C_L) based on different roughness levels for non-rotating cylinder at $Re < 20000$	110

Figure 4.17	Drag coefficient (C_D) based on different roughness levels for non-rotating cylinder at $Re < 20000$	111
Figure 4.18	Coefficient of lift (C_L) respect to Reynolds number for various cylinder speeds on $e/D=0.0015$	114
Figure 4.19	Coefficient of drag (C_D) respect to Reynolds number for various cylinder speeds on $e/D=0.0015$	115
Figure 4.20	Location of velocity taps	118
Figure 4.21	Velocity profile against y/D at azimuth angle $+30^\circ$, $+60^\circ$ and $+90^\circ$ for non-rotating cylinder in Reynolds number between 10000 to 20000 (negative angles not included due to symmetry)	118
Figure 4.22	Velocity profile against y/D at azimuth angle $+30^\circ$, $+60^\circ$ and $+90^\circ$ for non-rotating cylinder in Reynolds number between 20000 to 42000 (negative angles are not included due to symmetry)	119
Figure 4.23	(a) Comparison of non-rotating and rotating cylinders in velocity profile against y/D at angle $\pm 90^\circ$ within Reynolds number 10000 to 20000 (b) U-shaped profile graph enlarged	120
Figure 4.24	Comparison of non-rotating and rotating cylinders in velocity profile against y/D at angle $\pm 60^\circ$ within Reynolds number 10000 to 20000	121
Figure 4.25	Comparison of non-rotating and rotating cylinders in velocity profile against y/D at angle $\pm 30^\circ$ within Reynolds number 10000 to 20000	121
Figure 4.26	Pressure coefficient distribution for non-rotating and rotating cylinder in CFD	123
Figure 4.27	Pressure distribution for non-rotating cylinder at low and high Reynolds number in CFD	124

Figure 4.28	Pressure distribution for rotating cylinder at low and high Reynolds number in CFD	124
Figure 4.29	TKE at range angle (θ) between 30° to 360° for non-rotating and rotating cylinders of Reynolds number 10000 to 20000	126
Figure 4.30	TKE at range angle (θ) between 30° to 360° for non-rotating cylinders at low and high Reynolds number	127
Figure 4.31	TKE at range angle (θ) between 30° to 360° for rotating cylinder at low and high Reynolds number	127
Figure 4.32	Contour of velocity for non-rotating cylinder at range $Re < 10000$ (a) Cylinder $e/D=0.0001$, (b) Cylinder $e/D=0.0015$	130
Figure 4.33	Contour of velocity for non-rotating cylinder at range $Re > 20000$ (a) Cylinder $e/D=0.0001$, (b) Cylinder $e/D=0.0015$	131
Figure 4.34	Contour of velocity for rotating (400rev/m) cylinder at $Re < 10000$ (a) Cylinder $e/D=0.0001$, (b) Cylinder $e/D=0.0015$	132
Figure 4.35	Contour of velocity for rotating (400rev/m) cylinder at $Re > 20000$ (a) Cylinder $e/D=0.0001$, (b) Cylinder $e/D=0.0015$	133
Figure 4.36	Contour of turbulent kinetic energy for non-rotating cylinder at $Re < 10000$	135
Figure 4.37	Contour of turbulent kinetic energy for non-rotating cylinder at $Re > 20000$ (a) Cylinder $e/D=0.0001$, (b) Cylinder $e/D=0.0015$	136
Figure 4.38	Contour of turbulent kinetic energy for rotating (400rev/m) cylinder at $Re < 10000$	137
Figure 4.39	Contour of turbulent kinetic energy for rotating (400rev/m) cylinder at $Re > 20000$ (a) Cylinder $e/D=0.0001$, (b) Cylinder $e/D=0.0015$	138
Figure 4.40	Contour of shear stress for non-rotating cylinder at $Re < 10000$	139

(a) Cylinder $e/D=0.0001$, (b) Cylinder $e/D=0.0015$

Figure 4.41 Contour of shear stress for non-rotating cylinder at $Re > 20000$ 140

(a) Cylinder $e/D=0.0001$, (b) Cylinder $e/D=0.0015$

Figure 4.42 Contour of shear stress for rotating (400rev/m) cylinder at 141

$Re < 10000$ (a) Cylinder $e/D=0.0001$, (b) Cylinder $e/D=0.0015$

Figure 4.43 Contour of shear stress for rotating (400rev/m) cylinder at 142

$Re > 20000$ (a) Cylinder $e/D=0.0001$, (b) Cylinder $e/D=0.0015$

LIST OF ABBREVIATIONS

CFD	Computational Fluid Dynamics
LWSM	Light Weight Smart Motor
PIV	Particle Image Velocimetry
LDA	Laser Doppler Anemometer
RAS	Reynolds Average Simulation
LES	Large Eddy Simulation
RANS	Reynolds Average Navier Stokes
VMS-LES	Variational Multi Scale Large Eddy Simulation
DES	Detached Eddy Simulation
IFEM	Immersed Finite Element Method
FVM	Finite Volume Method
FDM	Finite Difference Method
DAQ	Data Acquisition Board
SA	Spalart Allmaras
TKE	Turbulence Kinetic Energy
VTOL	Vertical Take-off Landing
SIMPLE	Semi-Implicit Pressure-Linked Equations
2D	Two Dimensional
3D	Three Dimensional

LIST OF SYMBOLS

Roman Symbols		Unit
C_D	Drag coefficient	-
C_L	Lift coefficient	-
C_P	Pressure coefficient	-
D	Diameter of cylinder	mm
e_i	error	-
F_D	Drag force	N
F_L	Lift force	N
f_r	Friction force per length of pulley contact	N/m
G_v	Production of Turbulent viscosity	-
J	Moment of inertia	kg.m ²
R^2	Correlation coefficient	-
R_a	Average Roughness	μm
r_2	Position vector of second node	m
SD	Standard deviation	-
S_c	Motor speed (rpm)	Rad/s
T	Torque	N.m
t	Time	sec
U	Dimensionless velocity	-
U_∞	Free stream velocity	ms ⁻¹
u	Velocity	m/s
v	Mean velocity of air	m/s

\vec{v}	Velocity vector	-
\bar{x}	Mean	-
Y_v	Destruction of Turbulent viscosity	

Greek Symbols	Description	Unit
μ	Dynamic viscosity	N.s/m ²
ν	Kinematic viscosity	m ² /s
α	Rotational rate	Hz
σ_x	Standard deviation	-
$\sigma_{\bar{x}}$	Standard error	-
μ	Friction coefficient	-
ρ	Air density	kg/m ³
θ	angle	° degree
ω_N	Natural frequency	Hz