

UNIVERSITI PUTRA MALAYSIA

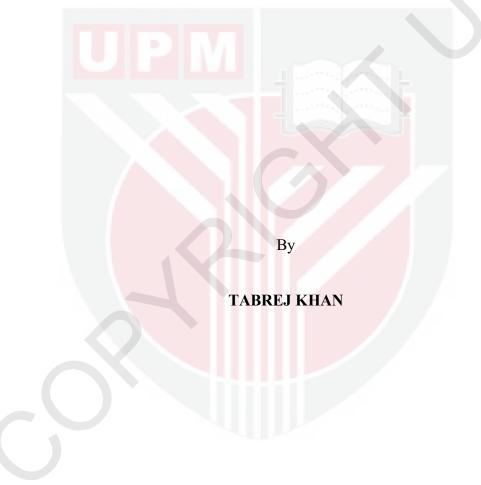
AERODYNAMIC CHARACTERISTIC ASSESSMENT OF AN AIRFOIL USING OPEN CIRCUIT WIND TUNNEL AND COMPUTATIONAL FLUID DYNAMICS

TABREJ KHAN

FK 2015 109



AERODYNAMIC CHARACTERISTIC ASSESSMENT OF AN AIRFOIL USING OPEN CIRCUIT WIND TUNNEL AND COMPUTATIONAL FLUID DYNAMICS



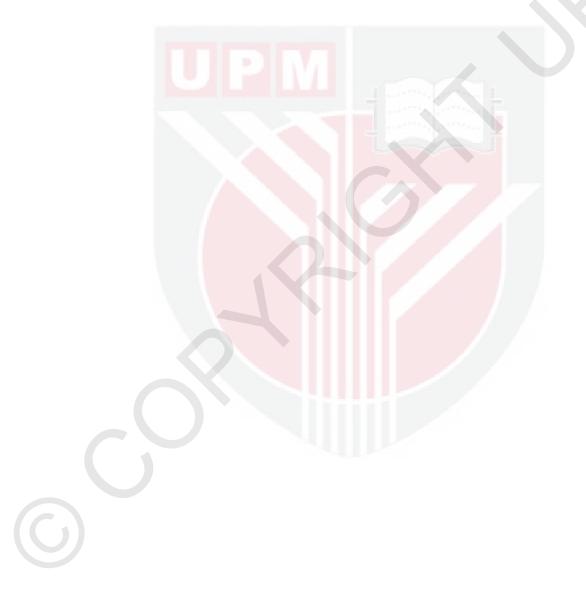
Thesis Submitted to the School of Graduate Studies, Univesiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science

September 2015

COPYRIGHT

All material contained within the thesis, including without limitation text, logos, icons, photographs and all other works, is copyright material of Universiti Putra Malaysia unless otherwise stated. Use may be made any material contained within the thesis for non-commercial purposes from the copyright. Commercial use of material may only be made with express, prior, written permission of Univesiti putra Malaysia.

Copyright © Univesiti Putra Malaysia



Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Master of Science

AERODYNAMIC CHARACTERISTIC ASSESSMENT OF AN AIRFOIL USING OPEN CIRCUIT WIND TUNNEL AND COMPUTATIONAL FLUID DYNAMICS

By

TABREJ KHAN

September 2015

Chairman: Associate Professor Surjatin Wiriadidjaja, PhDFaculty: Engineering

This work is an attempt to investigate the airflow characteristics around an airfoil by using the existing wind tunnel of the University Putra Malaysia (UPM) and Computational Fluid Dynamics (CFD) methods. These results are compared to the available trusted experimental result of the University of Illinois at Urbana-Champaign UIUC (UIUC wind tunnel) for validity and assessment. A Clark Y airfoil was available at the laboratory and used therefore as the airfoil to be investigated. This airfoil was subjected to tests in the low-speed, open-circuit wind tunnel at different test-section velocities (7 m/s - 14 m/s). In order to be able to verify the investigation, the same airfoil definition with the same flow conditions as used in the wind tunnel test was also used for CFD's calculation by using the PHOENICS software, which was available as supplementary joint work elaborated in a companion thesis work as listed in the references. The results of the above two methods were compared and analyzed. The data obtained were further verified by comparing it to the standard data of the UIUC wind tunnel, yielding to an impression that the UPM wind tunnel test results and CFD data exhibited considerable differences. However, both methods shared characteristics that are almost similar to UIUC wind tunnel. Further, the CFD data were found to have more similarity with the UIUC wind tunnel data if compared to those of the UPM wind tunnel data. Some differences that are exhibited by the wind tunnel results are assessed in view of uncertainties and accuracy. Overall, a systematic procedure has been followed that can be used as a basis for further.



Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

PENILAIAN CIRI-CIRI AERODINAMIK KE ATAS AIRFOIL DENGAN MENGGUNAKAN TEROWONG ANGIN LITAR TERBUKA DAN PENGIRAAN CFD.

Oleh

TABREJ KHAN

September 2015

Pengerusi : Profesor Madya Surjatin Wiriadidjaja, PhD Fakulti : Kejuruteraan

Kerja ini cuba menyiasat sifat aliran udara di sekeliling aerofoil dengan menggunakan terowong angin sedia ada di Universiti Putra Malaysia (UPM) dan kaedah pengiraan dinamik bendalir (CFD). Keputusan tersebut dibandingkan dengan keputusan ujikaji daripada University of Illinois at Urbana-Champaign UIUC (terowong angin UIUC) yang boleh dipercayai, untuk pengesahan dan penilaian. Satu aerofoil Clark Y yang terdapat di makmal digunakan sebagai aerofoil untuk dikaji. Aerofoil ini digunakan di dalam ujian terowong angin litar terbuka pada halaju rendah, di pelbagai bahagian ujian halaju (7 m/s – 14 m/s). Untuk mengesahkan siasatan, aerofoil yang sama dengan keadaan aliran seperti di dalam ujikaji terowong angin digunakan di dalam pengiraan CFD melalui perisian PHOENICS yang terdapat di dalam kerjsama tambahan yang diulas lanjut di dalam tesis seperti di dalam senarai rujukan. Keputusan daripada kedua-dua kaedah dibanding dan dianalisa. Data yang diperolehi disahkan melalui perbandingan dengan data piawai dari terowong angin UIUC, yang memberi gambaran bahawa keputusan terowong angin UPM dan CFD sangat berbeza. Tetapi, kedua-dua kaedah mempunyai sifat yang sama dengan terowong angin UIUC. Dalam pada itu, data CFD didapati hampir sama dangan data terowong angin UIUC berbanding data terowong angin UPM. Beberapa perbezaan yang ditunjukkan oleh keputusan terowong angin dinilai dari segi ketidakpastian dan ketepatan. Pada keseluruhan, satu prosedur yang sistematik telah diikuti sebagai asas.



ACKNOWLEDGEMENTS

Thank you, the almighty, Allah S.W.T for giving me the strength and will power to complete the thesis.

I would like to express my sincere gratitude to Prof. Ir. Dr. Surjatin Wiriadidjaja, my teacher and dissertation advisor, for his patience, his encouragement and his support throughout the research period. His delightful personality and detailed knowledge of this research topic has guided me until the very end. I would not be here without all that he has done.

I would also like to thank Assoc. Prof. Dr. Azmin Shakrine Mohd Rafie and Dr. Dayang Laila Abang Abdul Majid, for their thorough review of this thesis and for their valuable comments.

I am grateful to those who are very helpful and supportive in any way, from or shape but shall not be named here; you all are true gems, which I will always remember, cherish and treasure for years and years to come. Without any of you, my work will not be as good as it is now, for that thank you very much.

Finally, I would like to thank my parents and relatives for their continued support throughout my education at Universiti Putra Malaysia. I would like to acknowledge the warm support and caring for my mother and father, Ms. Darakash Khan and Mr. Alam Khan. Without their encouragement and enthusiasm, this work could not have been completed.

Thank you all again for your support, help, and encouragement throughout this study.

I certify that a Thesis Examination Committee has met on 11 September 2015 to conduct the final examination of Tabrej Khan on his thesis entitled "Aerodynamic Characteristic Assessment of an Airfoil Using Open Circuit Wind Tunnel and Computational Fluid Dynamics" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

Members of the Thesis Examination Committee were as follows:

Harijono Djojodihardjo, PhD Professor Ir. Faculty of Engineering Universiti Putra Malaysia (Chairman)

Kamarul Arifin Ahmad, PhD Associate Professor Ir. Faculty of Engineering Universiti Putra Malaysia (Internal Examiner)

Shuhaimi Mansor, PhD Associate Professor Universiti Teknologi Malaysia Malaysia (External Examiner)

ZULKARNAIN ZAINAL, PhD Professor and Deputy Dean School of Graduate Studies Universiti Putra Malaysia

Date: 5 November 2015

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Surjatin Wiriadidjaja, PhD

Associate Professor Faculty of Engineering Universiti Putra Malaysia (Chairman)

Azmin Shakrine Mohd Rafie, PhD

Associate Professor Faculty of Engineering Universiti Putra Malaysia (Member)

Dayang Laila Abang Abdul Majid, PhD Senior Lecturer

Faculty of Engineering Universiti Putra Malaysia (Member)

BUJANG BIN KIM HUAT, PhD Professor and Dean School of Graduate Studies

Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software

Signature:	Date:

Name and Matric No.: Tabrej Khan (GS38558)

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

Signatura	
Signature:	
Name of Chairman	
of Supervisory	
Committee:	Associate Professor Dr. Surjatin Wiriadidjaja
Signature:	
Name of Member	
of Supervisory	
Committee	Associate Professor Dr. Azmin Shakrine Mohd Rafie
Committee:	Associate Professor Dr. Azmin Shakrine Mohd Rafie
Committee:	Associate Professor Dr. Azmin Shakrine Mohd Rafie
Committee:	Associate Professor Dr. Azmin Shakrine Mohd Rafie
Committee:	Associate Professor Dr. Azmin Shakrine Mohd Rafie
Committee:	Associate Professor Dr. Azmin Shakrine Mohd Rafie
	Associate Professor Dr. Azmin Shakrine Mohd Rafie
Signature:	Associate Professor Dr. Azmin Shakrine Mohd Rafie
Signature: Name of Member	Associate Professor Dr. Azmin Shakrine Mohd Rafie
Signature: Name of Member of Supervisory	
Signature: Name of Member	Associate Professor Dr. Azmin Shakrine Mohd Rafie
Signature: Name of Member of Supervisory	
Signature: Name of Member of Supervisory	

TABLE OF CONTENTS

ABSTRACT

CHAPTER 1 INTRODUCTION 1 1.1 Overview 1 1.2 Problem Statement 1 1.3 Objective 2 2 LITERATURE REVIEW 3 2.1 Overview 3 2.1 Overview 3 2.1 Wind Tunnel Classification 8 2.1.1 Wind Tunnel Classification 8 2.2.2 Wind Tunnel Classification 8 2.2.2 Wind Tunnel Classification 8 2.2.3 Basic Components of Low Subsonic Wind Tunnel 12 2.3.4 Design Philosophy 16 2.3.3 Clark Y airfoil 20 2.4.1 Phoenics CFD software 22 2.4.2 Turbulence model 23 2.4.3 Standard K-c Model 23 3.1 Introduction 26 3.2.1 General Flow Chart 26	ACK APP DECI LIST LIST	ROVAL LARAT OF TA OF FIC	ION BLES	ii iii iv vi x xi xiii
1.1 Overview 1 1.2 Problem Statement 1 1.3 Objective 2 2 LITERATURE REVIEW 3 2.1 Overview 3 2.2 Wind Tunnel 7 2.2.1 Wind Tunnel Classification 8 2.2.2 Wind Tunnel Design 11 2.2.3 Basic Components of Low Subsonic Wind Tunnel 12 2.2.4 Design Philosophy 16 2.3 Airfoil nomenclature 17 2.3.1 Aerodynamic forces 18 2.3.2 Coefficients of lift, drag, moment and pressure 19 2.3.3 Clark Y airfoil 20 2.4 Overview of computational fluid dynamics (CFD) 21 2.4.1 Phoenics CFD software 22 2.4.2 Turbulence model 23 2.4.3 Standard K-€ Model 23 3.4 Methodology Flow Chart 26 3.2.1 General Flow Chart 26 3.2.1 General Flow Chart 26 3.2.1 General Flow Chart <t< th=""><th>CHA</th><th>PTER</th><th></th><th></th></t<>	CHA	PTER		
1.3 Objective 2 2 LITERATURE REVIEW 3 2.1 Overview 3 2.2 Wind Tunnel 7 2.2.1 Wind Tunnel Classification 8 2.2.2 Wind Tunnel Design 11 2.2.3 Basic Components of Low Subsonic Wind Tunnel 12 2.2.4 Design Philosophy 16 2.3 Airfoil nomenclature 17 2.3.1 Aerodynamic forces 18 2.3.2 Coefficients of lift, drag, moment and pressure 19 2.3.3 Clark Y airfoil 20 2.4 Overview of computational fluid dynamics (CFD) 21 2.4.2 Turbulence model 23 2.4.3 Standard K-c Model 23 2.4.3 Standard K-c Model 23 3.1 Introduction 26 3.2 Methodology Flow Chart 26 3.2 Experimental Flow Chart 26 3.3.1 Description of the UPM Wind Tunnel 28 3.3.2 UPM Low Speed Wind Tunnel 28 3.3.3 T	1	1.1	Overview	1
2.1Overview32.2Wind Tunnel72.2.1Wind Tunnel Classification82.2.2Wind Tunnel Design112.2.3Basic Components of Low Subsonic Wind Tunnel122.2.4Design Philosophy162.3Airfoil nomenclature172.3.1Aerodynamic forces182.3.2Coefficients of lift, drag, moment and pressure192.3.3Clark Y airfoil202.4Overview of computational fluid dynamics (CFD)212.4.1Phoenics CFD software222.4.2Turbulence model232.4.3Standard K-€ Model232.4.3Standard K-€ Model263.1Introduction263.2.1General Flow Chart263.2.2Experimental Flow Chart273.3Filed Observation283.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5.1Types of Calibration323.5.2Full Calibration33				
2.2.1Wind Tunnel Classification82.2.2Wind Tunnel Design112.2.3Basic Components of Low Subsonic Wind Tunnel122.2.4Design Philosophy162.3Airfoil nomenclature172.3.1Aerodynamic forces182.3.2Coefficients of lift, drag, moment and pressure192.3.3Clark Y airfoil202.4Overview of computational fluid dynamics (CFD)212.4.1Phoenics CFD software222.4.2Turbulence model232.4.3Standard K-€ Model232.4.3Standard K-€ Model233.1Introduction263.2Methodology Flow Chart263.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5.1Types of Calibration33	2	LIT	ERATURE REVIEW	3
2.2.1Wind Tunnel Classification82.2.2Wind Tunnel Design112.2.3Basic Components of Low Subsonic Wind Tunnel122.2.4Design Philosophy162.3Airfoil nomenclature172.3.1Aerodynamic forces182.3.2Coefficients of lift, drag, moment and pressure192.3.3Clark Y airfoil202.4Overview of computational fluid dynamics (CFD)212.4.1Phoenics CFD software222.4.2Turbulence model232.4.3Standard K-€ Model232.4.3Standard K-€ Model233.1Introduction263.2Methodology Flow Chart263.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5.1Types of Calibration33				3
2.2.2Wind Tunnel Design112.2.3Basic Components of Low Subsonic Wind Tunnel122.2.4Design Philosophy162.3Airfoil nomenclature172.3.1Aerodynamic forces182.3.2Coefficients of lift, drag, moment and pressure192.3.3Clark Y airfoil202.4Overview of computational fluid dynamics (CFD)212.4.1Phoenics CFD software222.4.2Turbulence model232.4.3Standard K-€ Model233METHODOLOGY263.1Introduction263.2.1General Flow Chart263.2.2Experimental Flow Chart263.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5.1Types of Calibration313.5.2Full Calibration33		2.2		
2.2.3Basic Components of Low Subsonic Wind Tunnel122.2.4Design Philosophy162.3Airfoil nomenclature172.3.1Aerodynamic forces182.3.2Coefficients of lift, drag, moment and pressure192.3.3Clark Y airfoil202.4Overview of computational fluid dynamics (CFD)212.4.1Phoenics CFD software222.4.2Turbulence model232.4.3Standard K- ϵ Model232.4.3Standard K- ϵ Model263.1Introduction263.2Methodology Flow Chart263.3Filed Observation283.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3Technical Drawing303.4Experimental Approach303.5Wind tunnel Calibration313.5.1Types of Calibration323.5.2Full Calibration33				
$\begin{array}{cccccccccccccccccccccccccccccccccccc$				
2.3Airfoil nomenclature172.3.1Aerodynamic forces182.3.2Coefficients of lift, drag, moment and pressure192.3.3Clark Y airfoil202.4Overview of computational fluid dynamics (CFD)212.4.1Phoenics CFD software222.4.2Turbulence model232.4.3Standard K- ϵ Model233METHODOLOGY263.1Introduction263.2Methodology Flow Chart263.2Experimental Flow Chart263.2.1General Flow Chart263.2.2Experimental Flow Chart263.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33				
$\begin{array}{cccccccccccccccccccccccccccccccccccc$		2.2		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$		2.3		
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$				
2.4Overview of computational fluid dynamics (CFD)212.4.1Phoenics CFD software222.4.2Turbulence model232.4.3Standard K-€ Model233METHODOLOGY263.1Introduction263.2Methodology Flow Chart263.2.1General Flow Chart263.2.2Experimental Flow Chart263.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33				
$\begin{array}{cccccccccccccccccccccccccccccccccccc$		2.1		
2.4.2Turbulence model232.4.3Standard K-ε Model233METHODOLOGY263.1Introduction263.2Methodology Flow Chart263.2.1General Flow Chart263.2.2Experimental Flow Chart263.3Filed Observation283.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33		2.4		
$\begin{array}{c ccccc} 2.4.3 & \text{Standard K-} \in \text{Model} & 23 \\ \hline \textbf{3} & \textbf{METHODOLOGY} & 26 \\ \hline 3.1 & \text{Introduction} & 26 \\ \hline 3.2 & \text{Methodology Flow Chart} & 26 \\ \hline 3.2.1 & \text{General Flow Chart} & 26 \\ \hline 3.2.2 & \text{Experimental Flow Chart} & 26 \\ \hline 3.2.2 & \text{Experimental Flow Chart} & 27 \\ \hline 3.3 & \text{Filed Observation} & 28 \\ \hline 3.3.1 & \text{Description of the UPM Wind Tunnel} & 28 \\ \hline 3.3.2 & \text{UPM Low Speed Wind Tunnel} & 29 \\ \hline 3.3.3 & \text{Technical Drawing} & 30 \\ \hline 3.4 & \text{Experimental Approach} & 30 \\ \hline 3.5 & \text{Wind tunnel Calibration Basic} & 31 \\ \hline 3.5.1 & \text{Types of Calibration} & 32 \\ \hline 3.5.2 & \text{Full Calibration} & 33 \\ \hline \end{array}$				
3METHODOLOGY263.1Introduction263.2Methodology Flow Chart263.2.1General Flow Chart263.2.2Experimental Flow Chart263.3.4Filed Observation283.3.3Technical Drawing303.4Experimental Approach303.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33				
3.1Introduction263.2Methodology Flow Chart263.2.1General Flow Chart263.2.2Experimental Flow Chart273.3Filed Observation283.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33				
3.2Methodology Flow Chart263.2.1General Flow Chart263.2.2Experimental Flow Chart273.3Filed Observation283.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33	3	MET	THODOLOGY	
3.2.1General Flow Chart263.2.2Experimental Flow Chart273.3Filed Observation283.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33				
3.2.2Experimental Flow Chart273.3Filed Observation283.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33		3.2		
3.3Filed Observation283.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33				
3.3.1Description of the UPM Wind Tunnel283.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33				
3.3.2UPM Low Speed Wind Tunnel293.3.3Technical Drawing303.4Experimental Approach303.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33		3.3		
3.3.3Technical Drawing303.4Experimental Approach303.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33				
3.4Experimental Approach303.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33			1	
3.5Wind tunnel Calibration Basic313.5.1Types of Calibration323.5.2Full Calibration33		2 4	6	
3.5.1Types of Calibration323.5.2Full Calibration33				
3.5.2 Full Calibration 33		5.5		

i

	3.6	Clark Y airfoil characteristics	35
	3.7	General procedures of wind tunnel test	36
	3.8	The experimental set up	36
	3.9	Data acquisition system	37
	3.10	CFD supplementary joint work	38
	3.11	General procedures of CFD simulation with free interference	38
	3.12	-	41
	3.13	-	42
4	RES	ULT AND DISCUSSION	44
	4.1	Introduction	44
		4.1.1 Calibration of the UPM low speed wind tunnel	44
		4.1.2 Data for boundary layer condition	47
		4.1.3 Velocities stability test	47
	4.2	Convergence of solution	48
		4.2.1 Visualization results for free interference	49
		4.2.2 Data validation	53
	4.3	Finding and discussion of an airfoil measurement	57
5	CON	CLUSION AND RECOMMENDATIONS FOR FUTURE	60
	RESI	EARCH	
	5.1	Conclusion	60
	5.2	Recommendation	60
	ERENCI		61
	NDICE		65
		F STUDENT	92
PUBL	JCATI	ON	93

G

LIST OF TABLES

Table		Page	
3.1	UPM Low Speed Wind Tunnel Specification	29	
3.2	Main specification of the reviewed wind tunnels	29	
3.3	Clark y airfoil characteristics	35	
3.4	UPM Wind Tunnel and UIUC Wind Tunnel Characteristics.	43	
4.1	Data for Calibration Test	44	
4.2	Comparison of UIUC, UPM and CFD data (Cl against α)	58	
4.3	Comparison of UIUC, UPM and CFD data (Cd against α)	58	
4.4	Percentage error (UIUC and UPM)	59	
4.5	Percentage error (UIUC and CFD)	59	

C

LIST OF FIGURES

Figure		Page
2.1	Low Speed Wind Tunnel Test Section UPM	5
2.2	Wind tunnel classification	8
2.3	A Schematic of open circuit wind tunnel	11
2.4	A Schematic of closed circuit wind tunnel	11
2.5	UPM Open Circuit Wind tunnel	17
2.6	Basic nomenclature of an airfoil.	18
2.7	Sketch showing aerodynamic forces.	18
3.1	General Flow Chart for research	27
3.2	Experimental Flow Chart for research	28
3.3	Definitions of point, planar, and volume calibrations with respect to test section	33
3.4	Clark Y airfoil mounted in Wind tunnel test section	37
3.5	Schematic diagram of wind tunnel experiment.	37
3.6	Six component internal balance DARCS.	38
3.7	Velocities measuring equipment and Pitot tube	38
3.8	Grid Mesh Settings with free interference	39
3.9	Mesh Setting in X direction	40
3.10	Mesh Setting in Y direction	40
3.11	Mesh Setting in Z direction	40
3.12	Airfoil in the domain after meshing	41
3.13	Grid mesh setting with closed walls	42
3.14	Airfoil in the domain with closed walls	42
4.1	Calibrated total pressure test section vs total pressure settling chamber	45

4.2	dp vs V ∞ true Frequency	45
4.3	Motor (kW) versus Frequency (Hz)	46
4.4	Power (m/s) versus Velocity (kW)	46
4.5	Velocity (m/s) versus position along z-axis.	47
4.6	Velocity (m/s) versus Time (s) for stability test at 5 m/s	48
4.7	Velocity (m/s) versus Time (s) for stability test at 40 m/s	48
4.8	Checking the convergence of the solution	49
4.9	Pressure Contour, Velocity Contour and streamline at a velocity 7m/s and Angle of attack -4 degree	50
4.10	Pressure Contour, Velocity Contour and streamline at a velocity 14m/s and Angle of attack -4 degree	52
4.11	Coefficient of lift versus angle of attack at velocity 7m/s	53
4.12	Coefficient of drag versus angle of attack at velocity 7m/s	53
4.13	Coefficient of lift versus angle of attack at velocity 14m/s	54
4.14	Coefficient of drag versus angle of attack at velocity 14m/s	54
4.15	Block diagram of experiment and error analysis	58

G

LIST OF ABBREVIATIONS

С	chord
Н	Test Section Height
S	Platform Area
t	Time
Т	Temperature
AOA	Angle of Attack
Cd	Coefficient of Drag
C ₁	Coefficient of lift
Re	Reynolds Number
Cm	Moment Coefficient for an Airfoil
N	Normal Force
A	Axial Force
СР	Pressure Coefficient
Q	Dynamic Pressure
Pt	Total Pressure
Р	Pressure
Ps	Static Pressure
Р	Free stream Pressure
Р	Density
V	Velocity
В	Tunnel Width
В	Wing Span
С	Test Section Cross-sectional Area
Δ	Boundary Layer Thickness

G

CFDComputational fluid dynamicsUIUCUniversity of Illinois at Urbana- Champaign



CHAPTER 1

INTRODUCTION

1.1 Overview

Successful aircraft are developed by selecting appropriate wing design and airfoil design.

Nowadays, the aircraft industries have their own way to design aircraft by developing by using computational fluid dynamics codes, and validated in a wind tunnel. There is another analytical method, which can be used only for special simple case but not for arbitrary.

This work is an attempt to study the airfoil and to investigate the appropriate flow mechanism at UPM (Universiti Putra Malaysia) open circuit wind tunnel and computational fluid dynamics.

Limitation in this work is some of the wind tunnel flow qualities are not known, such as turbulence etc. the available Clark Y model (chord ± 0.50) is about too big related to wind tunnel test section (1×1 m). 2D airfoil should relay on balance to avoid too many interference. (Actually C <25% wind tunnel width).

However, by looking into those limitations, it is hoped that by combining experimental efforts supported computational fluid dynamics calculation would still give sufficient evidence for making conclusions about the airfoil characteristics.

This research strongly support by comparison with other available wind tunnel test data (UIUC wind tunnel) which are trustworthy. Thus this investigation results in an acceptable conclusion, conducted results on this airfoil may be considered as a proof of "calibration" of the wind tunnel.

This v experim lead to

This work is therefore composed of literature reviews (theory), methodology, experimental reports, and computational fluid dynamics work. Which is all together lead to discussion and conclusion.

1.2 Problem Statement

There are several variable that can be used in this research. The problem which would be face in this research related to the model, wind tunnel, measuring equipment and computational fluid dynamic (CFD). Wind tunnel experiment has constraints by mean

of model accuracy in terms of material and size, wind tunnel flow qualities (Uniformity and turbulence), measuring equipment (rack and balance). Computational technique also has some constraints by means of insufficient computational power of computers, time limitation and incorrect selection of flow models and boundary conditions (mesh density and turbulence model). We cannot say that every output result is always true as the simulation can generate the result whatever input we enter. It would lead to sufficient acceptable results for understanding.

1.3 Objective

The main objective of this research is to:

- 1. To investigate flow mechanism around an airfoil.
- 2. To use the available facilities, for testing an airfoil in,
 - a) An open circuit wind tunnel experiment of UPM open-circuit and using available model (Clark Y).
 - b) Conducting Computational fluid dynamics calculation by using Phoenics software.
- 3. To analyze and compare the experimental and the computational fluid dynamic and to validate by using the UIUC wind tunnel.

REFERENCES

- [1] Dodson, MG (2005). "An Historical and Applied Aerodynamic Study of the Wright Brothers' Wind Tunnel Test Program and Application to Successful Manned Flight". US Naval Academy Technical Report. USNA-334. Retrieved.
- [2] "US Navy Experimental wind Tunnel" Jan (1916). Aerial Age Weekly.
- [3] Man Made Hurricane Tests Full Size Planes, Jan (1936) "Popular Mechanics.
- [4] Anderson, J.D. (1991). Fundamental of aerodynamics, 2nd Edition, Mcgraw hill, Inc.
- [5] Surjatin Wiriadidjaja, Fadilah Hasim, Shuhaimi Mansor, Waqar Asrar, Azmin Shakrine Mohd Rafie, Ermira Junita Abdullah, (2012) Subsonic Wind Tunnels In Malaysia: A Review Applied Mechanics and Materials Vol. 225 pp 566-571, TransTech Publications, Switzerland.
- [6] http://www.grc.nasa.gov/WWW/k-12/airplane/tunoret.html
- [7] Barlow, Jewel B., William H. Rae, and Alan Pope, (1999) Low-Speed Wind Tunnel Testing. 3rd Edition. New York: Wiley-Inter science.
- [8] R. D. Mehta, P. Bradshaw, (1979) "Design Rules for Small Low-Speed Wind Tunnels", Aero.Journal, (Royal Aeronautical Society), 73, 443.
- [9] J. C. A. Van Ditshuizen & R. Ross, Construction (1976-1980)", Design Manufacturing Calibration of the German (DNW).
- Bell, J. H., and R. D. Mehta, (1988) Contraction Design for Small Low-Speed Wind Tunnels. [NASA contractor report], NASA CR-177488. Washington, DC: National Aeronautics and Space Administration.
- [11] Norlizaa B. Mohamad, (2012) design and development of wind tunnel for contraction ratio effects to the velocity and boundary layer thickness.
- [12] Ben Goldberg & Tom Carlone (2008)," Building a Wind Tunnel: It Will Blow Your Mind" Carlone.
- [13] Prandtl L. Oct (1933). "Attaining a Steady Stream in Wind Tunnel", NACA TM 726.
- [14] Eckert W., Mort K. W. Pope J. October, (1976). "Aerodynamic Design Guidelines and Computer Program for Estimation of Subsonic Wind Tunnel Performance", National Aeronautics and Space Administration NASA TN D-8243, Washington, D.C.

- [15] G. G. Borger, Mar (1976). "The Optimization of Wind Tunnel Contractions for the Subsonic Range", NASA TTF 16899,
- [16] Bradshaw P, Mehta RD., Nov (1979). "Design rules for small low speed wind tunnels", The Aeronautical Journal of the Royal Aeronautical Society.
- [17] Chmielewski, G. E. (1974), Boundary layer considerations in the design of Aerodynamic contractions. J. Aircraft. vol. 11. No. 8, pp. 435-438.
- [18] Stratford, B. S. (1959), The Prediction of separation of the turbulent boundary layer. J. Fluid Mech., Vol. 5, pp. 1-16.
- [19] Miguel A. González Hernández, Ana I. Moreno López, Artur A. Jarzabek, José M. Perales Perales, Yuliang Wu and Sun Xiaoxiaodesign (2013). Methodology for a quick and low cost wind tunnel
- [20] Roland B. Stuall, (1988). An introduction to boundary layer methodology.
- [21] UPM Closed Circuit Low Speed Wind Tunnel (2014). Design Data, ZKK.
- [22] Harold S. Boudreau iii, (2009) design, construction, and testing of an open Atmospheric boundary layer wind tunnel.
- [23] Anderson Jr., J. D. (2012). Introduction to Flight. New York, NY, McGraw Hill Companies, Inc.
- [24] Karna, S. P., Saumil, B. P., Utsav, B. P., & Ankit, P. A. Mar (2014). CFD Analysis of an Aerofoil. In International Journal of Engineering Research (Vol. 3, pp: 154-158).
- [25] Hansen, J. R. (Ed.). (2009). the Wind and Beyond: A Documentary Journey into the History of Aerodynamics in America, V. 2: Reinventing the Airplane. Government Printing Office.
- [26] Simons, M. (2000). Model aircraft aerodynamics. Chris Lloyd Sales & Marketing.
- [27] Piccirillo, A. C. (2000). The Clark Y airfoil: A historical retrospective. SAE transactions, 109(1), 1016-1036.
- [28] Sato, M. & Kobayashi, T., (2012). A fundamental study of the flow past a circular cylinder using Abaqus/CFD
- [29] Sayma, A. (2009). Computational fluid dynamics. Bookboon.
- [30] Chung, T. J. (2010). Computational fluid dynamics. Combridge university press.

- [31] B. E. Launder and D. B. Spalding (1973), Mathematical Models of Turbulence. Journal of Applied Mathematics and Mechanics, Zeitschrift für Angewandte Mathematik und Mechanik Volume 53, Issue 6, page 424,
- [32] T.S.D.Karthik. (2011) Turbulence Models and their Applications, Department of Mechanical Engineering. IIT Madras, 10th Indo German Winter Academy.
- [33] N. A. Ahmed,(2013) Wind Tunnel Designs and Their Diverse Engineering Applications, Janeza Trdine 9, 51000 Rijeka, Croatia
- [34] http://www.nasa.gov/aero/nasa-contribution-chevrons.html.
- [35] Hazardous Industry Planning Advisory Paper No. 8 HAZOP Guidelines Consultation Draft July (2008).
- [36] Anderson, J. D. (2007). Fundamentals of Aerodynamics, 4th Edition. New York City:McGraw-Hill.
- [37] Kasravi, K. (2010). Tec452 body Structures I. Retrieved from http://www.kasravi.com/cmu/tec452/aerodynamics/WindTunnel.html.
- [38] Abbott, I. (1959). Theory of Wing Sections. New York City: Dover Publications.
- [39] G. R. Spedding, M. Rosén and A. Hedenström, apr (2013). A family of vortex wakes generated by a thrush nightingale in free flight in a wind tunnel over its entire natural range of flight speeds.
- [40] N. Findanis and N.A. Ahmed,(2011) Wind Tunnel 'Concept of Proof' Investigations in the Development of Novel Fluid Mechanical Methodologies and Devices.
- [41] Pankhurst, R. C. (1952). Wind Tunnel Technique. London: Pitman
- [42] Abbott, I. (1959). Theory of Wing Sections. New York City: Dover Publications.
- [43] Pope, A. (1984). Low-Speed Wind Tunnel Testing. New York City: John Wiley & Sons.
- [44] Pankhurst, R. C. (1952). Wind Tunnel Technique. London: Pitman.
- [45] Reston Hahn, Philip (2004). American Institute of Aeronautics and Astronautics, NACA 0012 Airfoil Aerodynamics Analysis.
- [46] National Aeronautics and Space Administration (NASA). (2005). Wind Tunnel Hisory.

- [47] Matthew N. Rhode, (2012) Estimation of Uncertainties for a Supersonic Retro Propulsion Model Validation Experiment in a Wind Tunnel.
- [48] Alexander N. May, Clayton R. Green, Clinton J. Kirsop, Jason A. Schupp, June, (2013). Proof of concept for propeller performance testing in the cal poly wind tunnel.
- [49] J.Wehrmeyer, Carl M, J. Sirbaugh, and D. Sinclair, Jan (2010), Orlando, Florida, Planar Doppler Velocimetry Applied in the AEDC 16T Large-Scale Transonic Wind Tunnel.
- [50] Ash Amin, apr (2008), Collective culture and urban public space.
- [51] P.P win jul (2015), experimental and computational studies on aerodynamic characteristics of an airfoil