AIRFOIL WITH MEMBRANE AT LOW REYNOLDS NUMBER

by

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ENDORSEMENT

I, Abdul Qayyum bin Roslan hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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Date: 18 June 2019

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AIRFOIL WITH MEMBRANE AT LOW REYNOLDS NUMBER

ABSTRACT

In this project, an experiment was carried out to study the aerodynamic performance on NACA 2412. The airfoil is divided into two parts which are airfoil with flexible membrane and rigid airfoil. The airfoils were fabricated using aluminium. A medical rubber sheet was used as the flexible membrane. By using flexible membrane, the airfoils have the ability to adapt to the incoming flows by changing their camber automatically, thus balancing the pressure differences on the upper and lower part of the airfoils to reduce the flow separation. The airfoils were tested in a wind tunnel. The velocities of the air flow are 6m/s, 9m/s, 12m/s and 15m/s. The test was carried out with angles of attack ranging from -5 degree to 25 degree. The airfoil section has a chord of 10cm and length of 30cm. The surface area is 0.03 square metre. Detailed descriptions of the experimental design, fabrication, setup and testing are included in the thesis. The data was analysed using PCD30A software. The results show that airfoil with flexible membrane has the better aerodynamic performance compared to the rigid airfoil. Airfoil with flexible membrane produces the highest aerodynamic efficiency which is 17.27. Flexible membrane airfoil also produces higher maximum lift coefficient and higher stall angle compared to rigid airfoil

AEROFOIL DENGAN MEMBRANE DI NOMBOR REYNOLDS RENDAH

ABSTRAK

Dalam projek ini, satu eksperimen telah dijalankan untuk mengkaji prestasi aerodinamik pada NACA 2412. Aerofoil tersebut dibahagikan kepada dua bahagian iaitu airfoil dengan membran fleksibel dan aerofoil tegar. Aerofoil tersebut direka dengan menggunakan aluminium. Lembaran getah perubatan digunakan sebagai membrane fleksibel. Dengan menggunakan membran yang fleksibel, aerofoil mempunyai keupayaan untuk menyesuaikan diri dengan arus masuk dengan menukar camber mereka secara automatik, dengan itu mengimbangi perbezaan tekanan pada bahagian atas dan bawah aerofoil untuk mengurangkan pemisahan aliran. Aerofoil telah diuji dalam terowong angin. Halaju aliran udara adalah 6m/s, 9m/s, 12m/s dan 15m/s. Ujian ini dijalankan dengan sudut serangan dari -5 darjah hingga 25 darjah. Bahagian aerofoil mempunyai kord 10 cm dan panjang 30cm. Kawasan permukaan adalah 0.03-meter persegi. Deskripsi terperinci mengenai reka bentuk eksperimen, fabrikasi, persediaan dan ujian disertakan dalam tesis. Data dianalisis menggunakan perisian PCD30A. Hasilnya menunjukkan bahawa aerofoil dengan fleksibel membran fleksibel mempunyai prestasi aerodinamik yang lebih baik berbanding dengan aerofoil tegar. Hasilnya menunjukkan bahawa aerofoil dengan fleksibel membran fleksibel mempunyai prestasi aerodinamik yang lebih baik berbanding dengan aerofoil tegar. Aerofoil membrane fleksibel menghasilkan kecekapan aerodinamik yang paling tinggi iaitu 17.27. Aerofoil membran fleksibel menghasilkan koefisien daya angkat maksimum dan sudut stall yang lebih tinggi berbanding dengan aerofoil tegar.

ACKNOWLEDGEMENT

This work would not have been possible without the support and guidance that have been showed by my supervisor, Prof. Ir. Dr. Mohd Zulkifly Abdullah. I would like to express my sincere gratitude to him. His continuous support, patience, motivation and immense knowledge have been the backbone to this Final Year Project. I could not have imagined having a better supervisor than him. I would like to thank to the fellow technicians: Mr Zulkhairi and Mr Mahmud for their willingness to share knowledge with me. They are the best in term of fabricating and machining. Without them, my project would have been so difficult. My sincere thanks also goes to Mr Najib, who provided me with the material and tools needed to complete this project. I thank my fellow coursemates for giving me morale support and knowledge in completing this project. Last but not least, I would like to thank the biggest deserver which is my family especially my parents. There is no word that could express how thankful I am for having them in giving me support throughout writing this thesis.

DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

(Signature of Student)

Date: 18 June 2019

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LIST OF SYMBOLS

$C_d : Drag\ Coefficient$

$C_l : Lift\ Coefficient$

$\propto: Angle\ of\ Attack$

$L : Lift\ force$

$D : Drag\ force$

$\rho : Density\ of\ air$

$\mu : Viscosity\ of\ air$

$V : Free\ stream\ velocity$

$c : Chord$

$Re : Reynolds\ number$

$S : Area\ of\ wing$

$\frac{L}{D} : Lift\ to\ Drag\ ratio$

CHAPTER 1 INTRODUCTION

1.1 General Overview

Every aircraft requires wing to fly on the air. Every wing has a fundamental shape called an airfoil. To make it clearer and simpler, the cross section of the wing is the airfoil. As air flows around an airfoil, the action of aerodynamic forces affects this body. The most significant forces affecting the airfoil directly are lift and drag forces.

Resistance is encountered by the body when a solid body moves through the fluid. In either case, a force in the direction of relative motion must be exerted to maintain steady motion. So, when an aircraft flies through the atmosphere, the propulsion force exerted must be sufficient to balance the dragging force.

Lift on an airfoil is described as the force on the body in the direction normal to the freestream. The velocity above the body is increased, thereby reducing the static pressure, while the velocity below is slowed down, causing the static pressure to increase. The difference in pressure distribution will create an upward force called lift. For an aircraft to operate efficiently, the lift force should be high and the drag force should be low.

An airfoil is the wing's two-dimensional cross-sectional shape with the purpose of either generating lift or minimizing drag when exposed to a moving fluid. The airfoil lift is mainly caused by the angle of attack and shape of airfoil. The resulting airfoil flow has a higher average velocity on the upper surface than the lower surface. This difference in velocity is necessarily accompanied by a difference in pressure (via the principle of Bernoulli), which in turn produces lifting force. An important aspect of aerodynamics is the airfoil design. Any object with an angle of attack and moving in air or fluid, for example, a flat plate, generates an aerodynamic lifting force. Airfoils are more efficient lifting shapes that can generate more lift with less drag. This must be considered the most primary and basic features when designing a wing-span airfoil. Asymmetric airfoils may generate lift at a zero angle of attack, while a symmetry airfoil is more suitable for aerobatics flight for frequent reverse flights.

1.2 Problem Statement

Lift and drag coefficient are the most fundamentals for an aircraft to fly. The wing must be able to generate enough lift without ignoring other important parameters. The lift of a wing may be varied depending on the angle of attack, airfoil shape, airspeed, wing size and air density. Airfoil may have different shape based on the aircraft's functions, but does the membrane of the airfoil could affect the aerodynamic performance of the aircraft?

Flow over a membrane and a rigid body is completely different in various aspects. The interaction between the membrane or the body with the fluid determines the nature of the aerodynamic properties of both wings.

Micro aerial vehicles (MAV) are facing a common problem which is to fly at relatively low Reynolds number. This is because MAV has a very small size. It is very important for this vehicle to fly at maximum possible lift to drag ratio.

Thus, the project will be focusing on solving the problem faced by MAV, whether using an airfoil with flexible membrane could increase the aerodynamic efficiency and delay stall.

1.3 Objective

The objectives of this project are:

1. To design and fabricate two different models of NACA 2412 airfoil; rigid model and wrapped with flexible membrane model.
2. To study the aerodynamics characteristics on the airfoil models fabricated at different Reynolds number.
3. To study the manufacturing processes required to fabricate the airfoil models.

1.4 Scope of work

The fabrication of two airfoil models from the beginning stage required a lot of time and processes to be done. The project must be planned wisely to avoid time overdue. There are many processes such as designing, fabricating and testing needed to be done by the time constraint. Therefore, this project has been divided into four stages so that it can be completed before the dateline of thesis submission. The stages are crucial as it can create a guideline for this project to run smoothly and accordingly. The stages mentioned are planning, fabrication, testing and analysis. There are some limitations in this project. One of them is the machines and tools needed to be used for the fabrication purposes must be shared with other students and may require the process to be dragging longer than the actual plan. Some of the machines also involved in laboratory education in certain days in a week, so the fabrication stage must be planned wisely. Other than that, the material must be ordered from a company with the correct required dimension and the waiting time should be long.

1.5 Thesis Outline

This thesis consists of five chapters that describe every detail from introduction to conclusion. Chapter one gives a general overview on the lift force, drag force, airfoil and aircraft wing. This chapter also describe the problem statement, project objectives and project scope. Chapter two consists of literature review and theoretical background related to this project. In chapter three, the methodology of the project is explained. The overall project flow is shown in this chapter. The details of the project flow are then explained further in this chapter. The flow includes design, fabrication, testing, simulating and material involved. Chapter four provides the results of the project. Graphical results and detailed discussions are discussed in this chapter. Chapter five is the conclusion of this project. This chapter also concludes the project with some recommendations for future development of this project.

CHAPTER 2 LITERATURE REVIEW

2.1 Experimental Wind Tunnel

Currently, wind tunnel is certainly the best method to study and investigate flowing fluid properties. There are some disadvantages of using and buying wind tunnel commercially however. One of them is cost. Commercial wind tunnel is very expensive that most of them are used by highly-focus researchers or exclusive institutions only (Reinke, 2017).

Leonardo Da Vinci is believed to be one of the entrepreneurs to be attracted to turbulent flows. Basic dynamic equations were developed by him after some profound research, but the knowledge is too wide and therefore it is still fairly immature until now. Some limitations on the numerical approach such as the approximations and the physical understanding make the observations difficult to researchers. The researchers can get some idea on the flow's behavior in actual after the invention of wind tunnel (H. Bell & D. Mehta, 1988).

A single wind tunnel cannot function for various of purposes, therefore the design types of wind tunnel is variety. There are two classifications of wind tunnel; they are based on air flow speed or on the design of the wind tunnel (Howell, Qin, Edwards, & Durrani, 2010). The classifications can be seen clearly in Table 2.1 below:

Wind Tunnel Types	**Examples**
Design	1. Open-typed 2. Close-typed
Air Flow	1. Subsonic 2. Transonic 3. Supersonic 4. Hypersonic

Table 2.1: Types of wind tunnel and its examples

The open-typed wind tunnel takes the air from atmosphere and rejects them to a vacuum chamber, while the closed-typed wind tunnel recirculated the same air in the closed-circuit wind tunnel. it is preferred to run high speed wind tunnels for a short duration and gather all the experimental data in this short time period (one to five seconds)(J. Kubesh & W. Allie, 2009).

Because of the viscosity effects, the cross-section of a wind tunnel is typically circular rather than square, because in the corners of a square tunnel there will be greater flow constriction that can make the flow turbulent. A smoother flow is provided by a circular tunnel (J. Kubesh & W. Allie, 2009).

Some data can be retrieved from wind tunnel testing. For example, visualization of drag polar, pressure and flow. Drag polar represents induced drag and lift on the wing efficiency. Pressure can be used to determine surface flow separation, calculate local forces, and provide numerical test validation

2.2 Flexible Membrane Airfoil at Low Reynolds Number

For flying and gliding mammals such as bats, flying squirrels and sugar gliders, thin and flexible membrane wings are unique. These animals display extraordinary maneuvering and agility flight capabilities that are not observed in other species of comparable size. Birds, which have been extensively studied, have relatively rigid wings with limited movement, while insects flying at much lower numbers of Reynolds are typically characterized by rigid wings moving with a relatively simple flapping movement. On the other hand, bats have very high levels of wing articulation (elbows, wrists and finger joints). More importantly, the wing surface is made up of a thin, flexible membrane in bats (Tamai, T Murphy, & Hu, 2008).

This observation indicates that the incorporation of flexible membranes as lifting surfaces may be a potentially useful feature for engineered MAVs. MAV team from University of Florida (UF) is the first team to adopt flexible membrane airfoil technique. Unidirectional carbon fiber is used as the leading-edge spar and chordwise battens. The skin of the wing is then formed when the membrane material is bonded to the spar and battens (Tamai et al., 2008).

The flexible membrane-wing-based structures have been found to absorb incoherence in the air currents, thus providing the vehicle a whole improved stability in a turbulent air which is typical for low Reynolds number flight (Tamai et al., 2008)

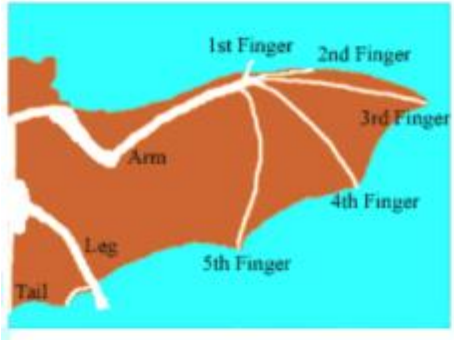
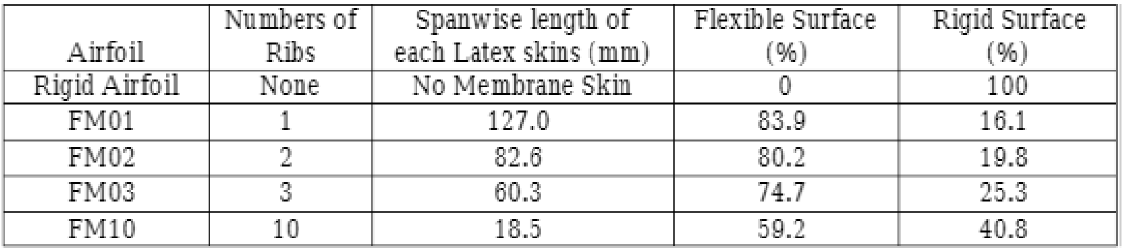


Figure 2.1 Flexible membrane wing of a bat (Tamai et al., 2008).

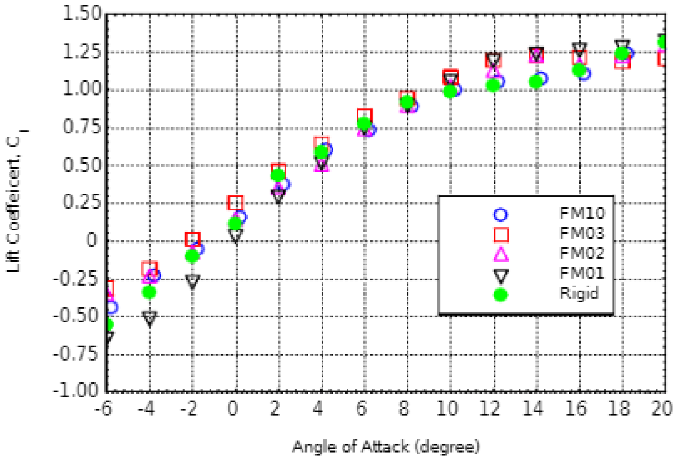
Flexible membrane airfoils have been suggested to reduce gust wind, delay airfoil stall and provide additional benefits to enhance agility and storage compared to rigid airfoils for MAV applications. However, it is still not well understood why and how flexible membrane airfoils could provide those advantages. Most previous experimental studies on flexible membrane airfoils were carried out based primarily on the measurement of total aerodynamic forces and/or moments on flexible membrane airfoils. The transient behavior of unstable vortex and turbulent flow structures around flexible membrane skins and their effects on the overall aerodynamic performance of flexible membrane airfoils / wings can be found to be very limited in literature (Tamai et al., 2008).

This study focuses on investigating the benefits of using flexible membrane airfoil compared to conventional rigid airfoil at low Reynolds number for MAV applications. A high-resolution Particle Image Velocimetry (PIV) system was used to conduct quantitative flow field measurements to visualize the transient behavior of vortex and turbulent flow structures around the flexible membrane airfoils / wings at different angles of attack (Tamai et al., 2008).

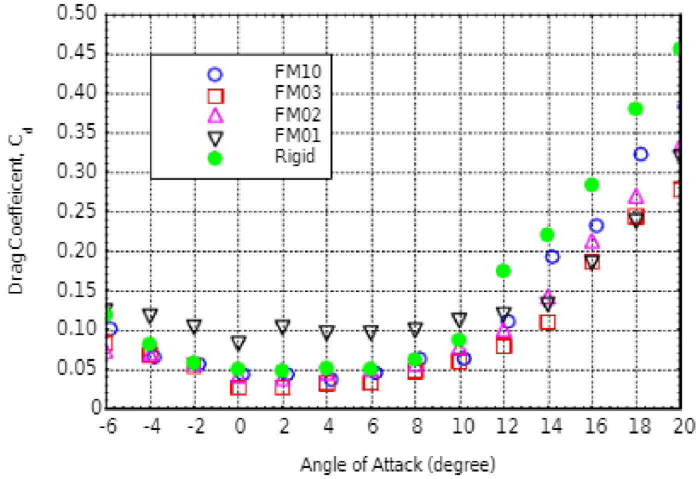


Airfoil	Numbers of Ribs	Spanwise length of each Latex skins (mm)	Flexible Surface (%)	Rigid Surface (%)
Rigid Airfoil	None	No Membrane Skin	0	100
FM01	1	127.0	83.9	16.1
FM02	2	82.6	80.2	19.8
FM03	3	60.3	74.7	25.3
FM10	10	18.5	59.2	40.8

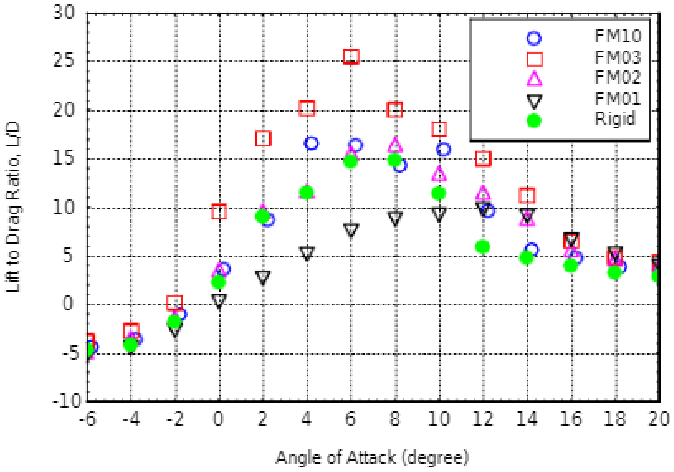
Table 2.2: The design parameters of the test airfoils (Tamai et al., 2008).



a. Lift coefficient vs. angle of attack



b. Drag coefficient vs. angle of attack



c. Lift to drag ratio vs. angle of attack

Figure 2.2 Aerodynamic performance of the airfoils (Tamai et al., 2008).

The drag coefficient is reasonably small when the angle of attack is relatively low (AOA<10.0 degrees) for the rigid thin airfoil, while the lift coefficient was found to increase almost linearly with the increasing angle of attack as expected. The lift coefficient's rate of increase was found to flatten out at a relatively high attack angle. The rigid thin airfoil drag coefficient was found to significantly increase at AOA > 10.0 degrees. Such features revealed in the profiles of the lift and drag coefficient indicate that airfoil stall occurred at AOA > 10.0 degrees for the rigid thin airfoil (Tamai et al., 2008).

Compared to the rigid thin airfoil, it was found that the flexible membrane airfoils FM02, FM03 and FM10 had a very comparable or slightly larger lift coefficient. At relatively high angle of attack (AOA>10.0 degrees), the drag coefficient of the flexible membrane airfoils was found to be significantly lower than that of the rigid thin airfoil (Tamai et al., 2008).

Compared to the rigid thin airfoil, the airfoil stall was found to occur at higher angles of attack for flexible membrane airfoils. Such measurement results confirmed the fact that, as suggested by previous studies, flexible membrane airfoils could delay airfoil stall (Tamai et al., 2008).

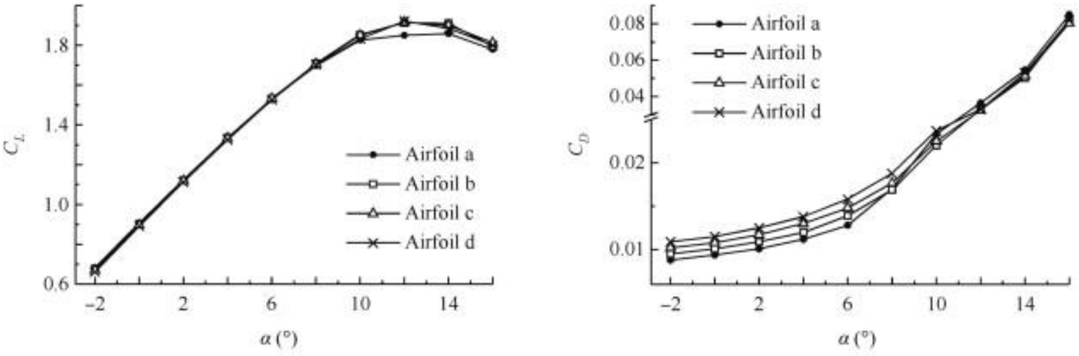
The FM01 flexible membrane airfoil has been found to have the lowest aerodynamic performance (the lowest lifting coefficient and the largest drag coefficient) among all airfoils tested at relatively low angle of attack (AOA<10.0 degrees). Remarkably, the FM01 airfoil was found to have nearly the best aerodynamic performance (i.e., lowest drag coefficient and highest lifting coefficient) among all the airfoils tested at a relatively high angle of attack (i.e., AOA>14.0 degrees). This is because of the fluttering that happens at low angle of attack and seems to be disappearing at high angle of attack (Tamai et al., 2008).

The flexible membrane airfoils have been designed to have the same cross-sectional form as the thin rigid airfoils but the flexible membrane skins enable the membrane airfoils to adjust the form of their shape automatically in order to balance the differences of pressure acting at different angles of the top and bottom surfaces of the flexible membrane airfoils (Tamai et al., 2008).

2.3 Effect of Relative Thickness on Aerodynamics Performance

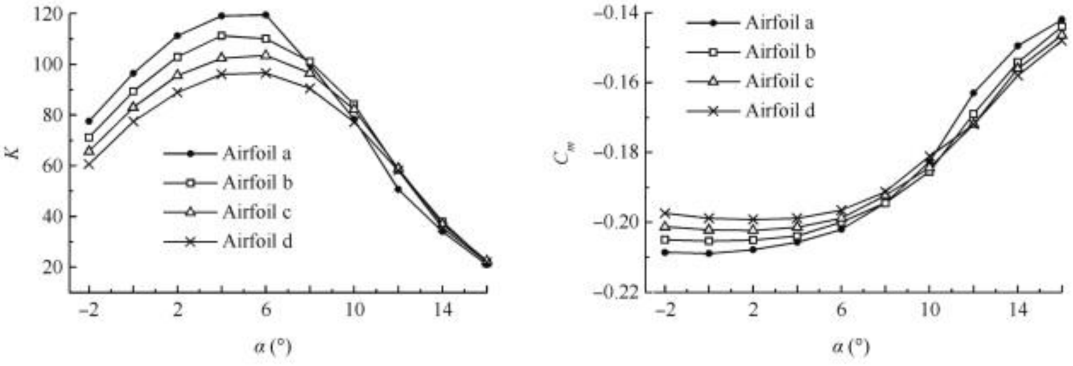
A high-altitude unmanned aerial vehicles (HAUAVs) airfoil is used in this experiment. The characteristics of low Reynolds number flow around the HAUAVs airfoil is observed. Water tunnel model is used to test and validate the accuracy and effectiveness of the numerical method. The method is used to investigate the low Reynolds number flow. The method then simulate the flows around the airfoil with different relative thickness (12%, 14%, 16%, 18%) and different relative thickness (x/c = 22%, 26%, 30%, 34%) at a low Reynolds number of 5 x 10^5. The effects of the relative thickness of the airfoil on the aerodynamics performance is studied after that (Ma, Zhao, Qiao, & Li, 2015).

The experiment concludes that the aerodynamics performance is mainly affected by the laminar separation bubble. For a good airfoil performance, the value of maximum relative thickness should be as small as possible, and the location of the maximum relative thickness must be closer to the trailing edge.



(a) Lift coefficients

(b) Drag coefficients



(c) Lift-drag ratio

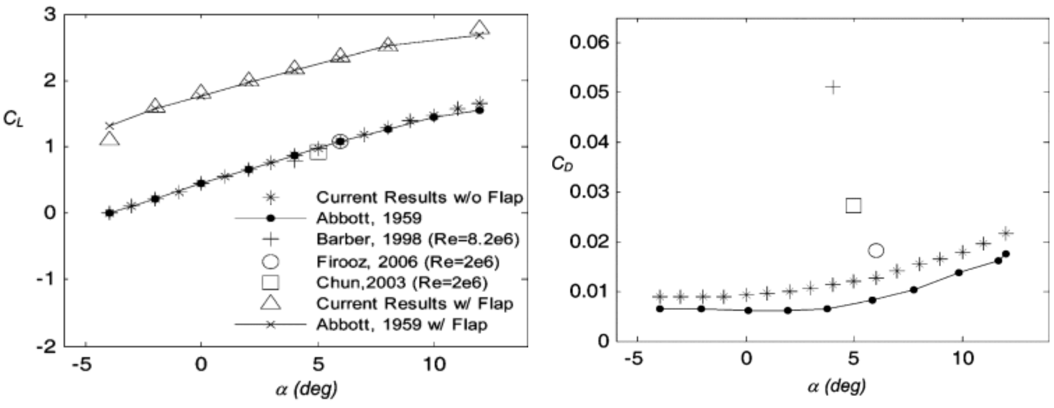
(d) Pitching moment coefficients

Figure 2.3: The effect of different thickness from airfoil a (12%), b (14%), c (16%) and d (18%) on the aerodynamics performance (Ma et al., 2015).

Based on Figure 2.1, it is clearly shown that increasing the maximum relative thickness value leads to the increase in maximum lift but larger drag forces. Thus, to obtain a higher maximum lift-drag ratio, the airfoil ought to be thinner. A thicker airfoil can reach higher maximum lift and the stall happens slower, but the differences are not so obvious. At small angle of attack, thicker airfoil produces more drag but the trend for all airfoils starts to intersect as the angle of attack increases. Maximum lift to drag ratio for all airfoils occurs at angle of attack from 4° to 6°. Thicker airfoils perform better than thinner airfoils at large angle of attacks. This can be seen on graph (c) where the lift-drag ratios of thinner airfoil descend steeply while the thicker airfoils descend gradually. In conclusion, the aerodynamics performance can be affected by different relative thickness. The change mainly affected by laminar separation bubbles and transition. Therefore, it is important to study the best thickness during designing an airfoil based on the aircraft functionality.

2.4 High Lift Devices

A flap at the wing trailing edge can increase the aerodynamics lift at relatively low speeds. Numerical method is used to investigate the effects of flap on NACA 4412 airfoil in viscous ground-effect flow. An experiment is then set up to validate the method. The data for aerodynamics forces are collected. The effects of angle of attack, Reynolds number, ground height and flap deflection are observed for a split and plain flap (Pecora, Barbarino, Concilio, Lecce, & Russo, 2011).



(a) lift coefficient

(b) drag coefficient

Figure 2.4: Experimental validation at Reynold number 600000 (Pecora et al., 2011)

Adding flap increases both lift and drag but increment in lift is much higher as compared to drag. When the flap is deflected, the flow is trapped at the lower part of the airfoil. The flow velocities decrease, and pressure is built up below the airfoil. At the same time, adverse pressure gradient increases yield a larger flow separation behind the flap. On the other hand, drag coefficient also increases as the flap is deflected. The pressure drag below the airfoil increases because the pressure below the airfoil is large and the separation zone on the upper surface of the flap is growing lead to increase in drag. Lift and drag seems to be increasing with angle of attack (Myose, Heron, & Papadakis, 1998).

In conclusion, using high lift devices can reduce takeoff and landing distance as the stall speed of the aircraft is reduced.

CHAPTER 3 METHODOLOGY

This chapter presents about the methods applied throughout the project. The main project objective is to focus on the study of aerodynamics characteristics on different thickness of an airfoil. To achieve the objectives of this project, there are four stages needed to follow which are planning, fabricating, testing and analysis.

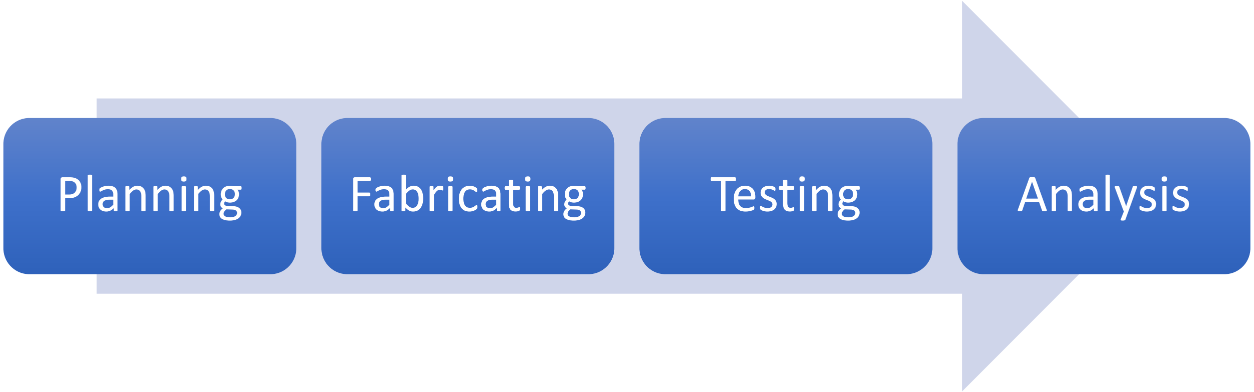


Figure 3.1: Project methodology stages in sequential order

3.1 Planning

3.1.1 Flow Chart

A flow chart was created in the planning stage of this project. Flow chart is a crucial step that will show the process throughout the project in a graphical presentation. The sequential order of the flow chart is important to display and idealize how the process functions and to prepare for the upcoming process.

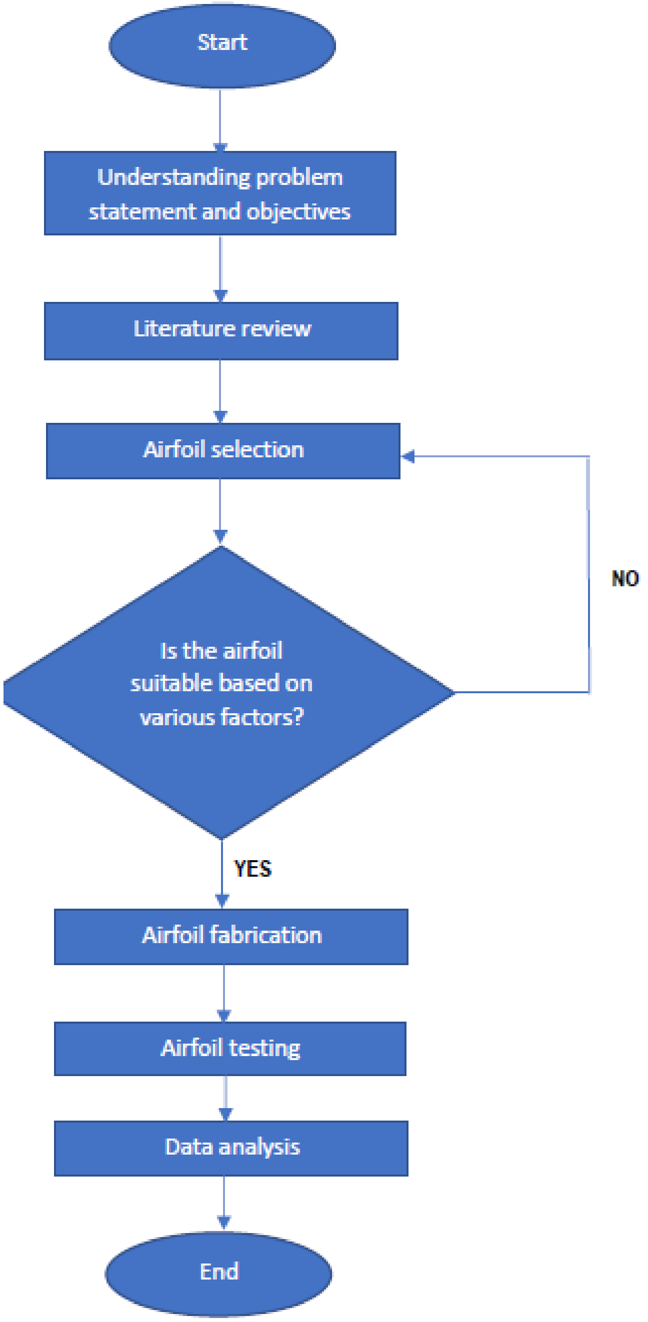


Figure 3.2: Flow chart used in this project

3.1.2 Gantt Chart

A Gantt chart was created alongside the flow chart in this planning stage. The Gantt chart is used to display the project milestones over time. It provides a clear guide of activities with its respective start and end dates.

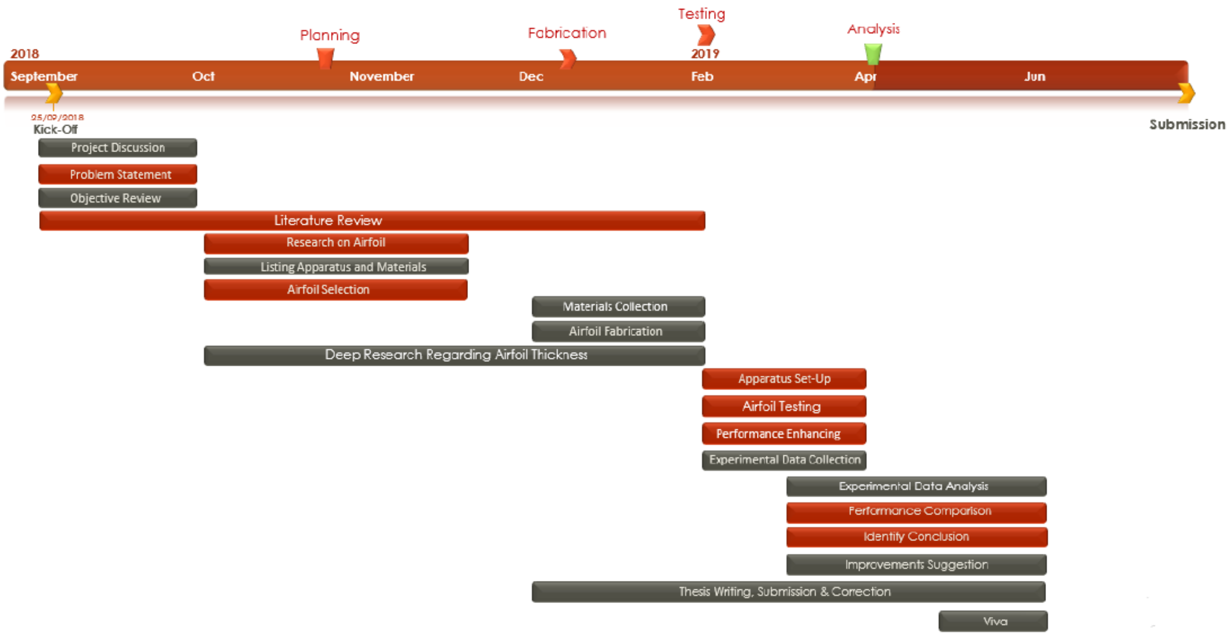


Figure 3.3: Gantt chart for this project

From Figure 3.3, the project was expected to be started on September 2018 and ended with thesis submission on Jun 2019. The Gantt chart also divides the activities into four stages that involve in the methodology which are planning, fabrication, testing and analysis

3.1.3 Design

The NACA 2412 was designed by using SolidWorks, a solid modelling computer-aided design software. These are the steps of designing the airfoil models:

Every airfoil has their own coordinates that distinguish its profile from other airfoil. The NACA 2412 coordinates was imported from an airfoil plotter website (Airfoil Tools, 2019). The coordinates were then saved into text file.

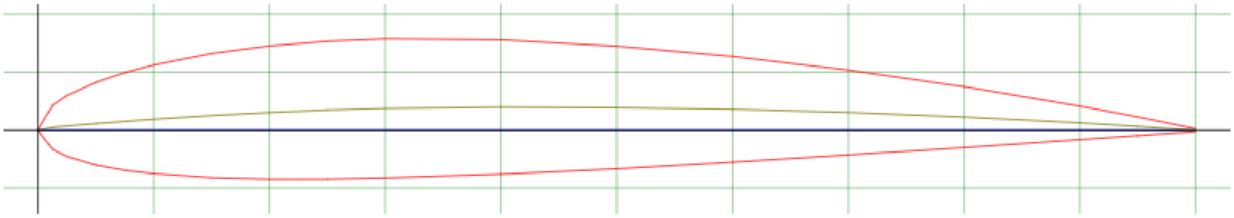


Figure 3.4: NACA 2412 profile (Airfoil Tools, 2019)

X(mm)	Y(mm)
100	0.13
95	1.14
90	2.08
80	3.75
70	5.18
60	6.36
50	7.24
40	7.8
30	7.88
25	7.67
20	7.26
15	6.61
10	5.63
7.5	4.96
5	4.13
2.5	2.99
1.25	2.15
0	0
1.25	-1.65
2.5	-2.27
5	-3.01
7.5	-3.46
10	-3.75
15	-4.1
20	-4.23
25	-4.22
30	-4.12
40	-3.8
50	-3.34
60	-2.76
70	-2.14
80	-1.5
90	-0.82
95	-0.48
100	-0.13

Table 3.1: NACA 2412 coordinates (Airfoil Tools, 2019)

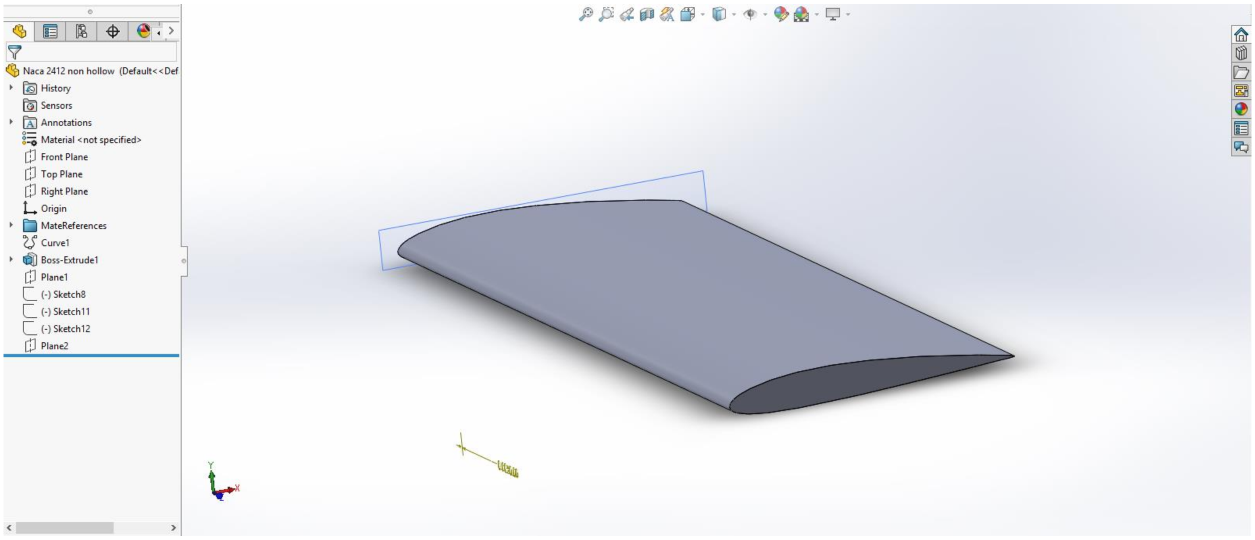


Figure 3.5: The design for NACA 2412 rigid model

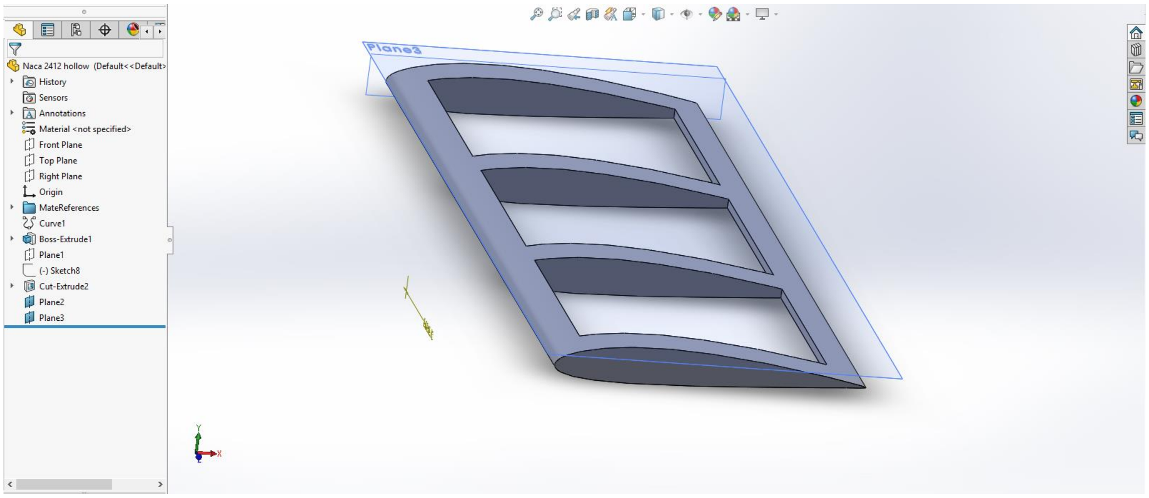


Figure 3.6: The design for NACA 2412 hollow model

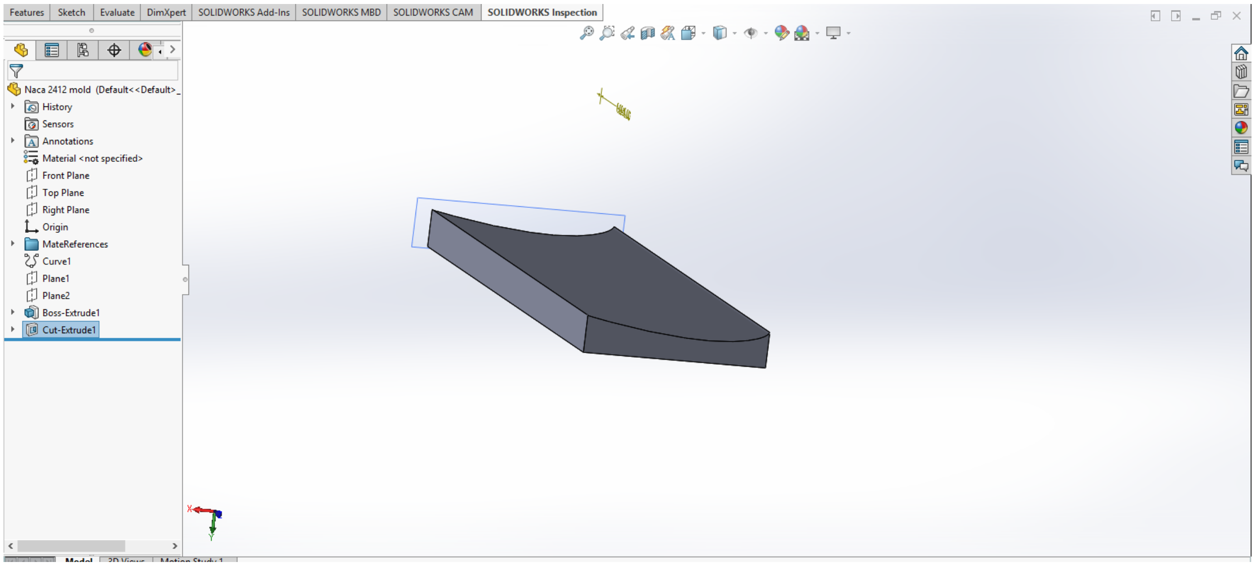


Figure 3.7 The NACA 2412 airfoil mold

3.2 Material

For this project, there are two material needed to complete the objectives. The material for fabrication process is Aluminium 5083 H112 Plate. The material was ordered and bought at Lian Giap & Co located at Bukit Minyak Industrial Park, Bukit Mertajam, Penang. The material stated was ordered for three pieces. Two pieces will be used for the two models of the airfoils and another one is for the mold that will be used during fabrication process. The diameter for all of the three pieces is similar which is 12mm x 140mm x 340mm. The price for each plate is RM33.60. The next material is the Rubber Mackintosh Sheet that will be used as the airfoil membrane

Figure 3.8: Lian Giap & Co building

Figure 3.9: Aluminium 5083 H112 Plate

Figure 3.10: Rubber Mackintosh Sheet

3.3 Fabrication

There are many engineering processes involved in fabrication stage to fabricate the airfoil models. The fabrication process took place after the planning stage.

3.3.1 CNC Milling

The fabrication process started by a machining process called CNC Milling. The designed models were illustrated into drawings to be referred by Mr. Zulkhairi during the machining process. The process of machining both of the models took a week to be finished. This process started with fabricating the mold. The mold is a rigid frame of the particular airfoil models. The mold is very important to hold the machined part of the airfoil during machining the other side of the aluminium. After that, the machining process of the airfoil models can be started. The material was set up to be clamped on both sides. Clamping using vise clamp is easier and more convenient, but this method could not be achieved as the vise clamp was broken. After finishing on the upper side of the aluminium block, the model then was placed on the mold to continue the machining process on the other side. The machine used is Fanuc Robodrill Alpha-T21iFlb, a high speed, high precision and high efficiency machine manufactured in the United States

Figure 3.11: Fanuc Robodrill Alpha-T21iFlb

3.3.2 Cutting Excess Material

After finishing the CNC milling machining process, there was an excess aluminium left on one edge of the airfoil. The excess was cut by using a metal saw,

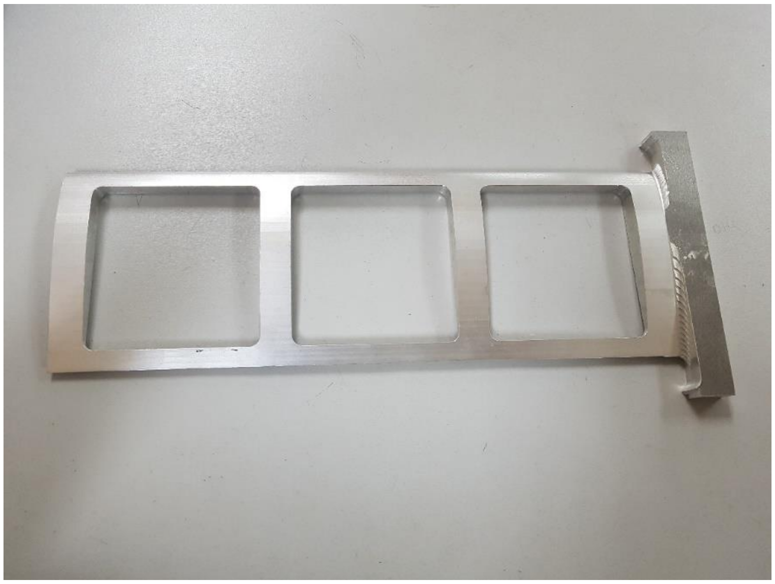


Figure 3.12: The finished hollow airfoil after CNC milling process

Figure 3.13: The excess was clamped before being cut

Figure 3.14: The hollow airfoil after the excess has been cut

3.3.3 Milling

After cutting the excess, the unfinished part must be finished by a milling process. The airfoil was clamped on the milling machines using two clamps as shown in Figure 3.10. The part was then milled until the end edge of the airfoil. The machined part was then deburred using a flat file.

Figure 3.15: Milling process is under process

3.3.4 Milling Drill

As the milling process done, the machining process has entered the final process which is the milling drill process. The purpose of this process is to create a hole on each side of the airfoil. The holes on both edges must be perpendicular to each other to make sure the airfoil is not tilted during the testing stage. Therefore, the holes cannot be drilled manually. Milling drill will make sure the holes are perpendicular to each other as the airfoil will be clamped on the milling table before being drilled by the machine. The dimension set for this process is shown in Table 3.2 below:

Airfoil Type	**Distance from leading edge (mm)**	**Distance from lower part of the airfoil (mm)**	**Hole Depth (mm)**
Hollow	30	6	10
Solid	30	6	15

Table 3.2: Requirements of the milling drill process

Based on Table 3.2, the value for both airfoil types are constant, except for the hole depth. The hole depth for the hollow airfoil is 5mm less than the solid airfoil. This is because the distance between the edge of the airfoil and the inner side of the hollow part is 15mm. Therefore, drilling until 15mm will create a hole that will break through the hollow part.

After the drilling process finished, the holes were then threaded using a cutting tool. The holes were drilled to fit a 5mm screw into each hole.

Figure 3.16: Milling drill machine used for the process

Figure 3.17: Threaded holes on both airfoils

3.3.5 Lathe & Die Threading the Shaft

To hold the airfoils during testing, a shaft is needed. The dimension set for the shaft is 6cm length and 0.9cm in diameter. The material used for the shaft is brass. The brass was provided by the technician, Mr. Zulkhairi. Brass is selected for its durability and easy to machine. Aluminium is not suitable to be selected as the material as it has the tendency to dent or bend when holding the airfoils. The shaft must be strong as it has to withstand the weight of the airfoil and the speed of the airflow simultaneously.

The brass was cut into the desired length before being lathed into 0.9cm diameter. The shaft part was finished. After that, the brass was lathed once again with smaller diameter to create the screw part. The diameter for the screw part should be more than 5mm because the part will be die threaded to exact 5mm diameter. The tool used for die threading is the die casting. The threads were formed across the screw part by winding the die casting.

Figure 3.18: The shaft

Figure 3.19: The shaft fits perfectly into the airfoil

3.4 Testing

1. An experimental wind tunnel in Aerodynamics Laboratory, School of Aerospace Engineering was chosen to test the airfoils. The wind tunnel is an open circuit wind tunnel. The airfoils were placed at the middle of the test section of wind tunnel. The test section of the wind tunnel is a rectangular hollow shaped.
2. The side frame of the test section is opened to set up the airfoil in the test section. The frame on the other side of the test section is attached to a gauge. The gauge will calculate the aerodynamics forces on the airfoils. The rigid airfoil with the shaft attached on it was connected to the gauge. The connection was made by tightening up the gauge after the shaft was correctly placed in the gauge. By doing this, the airfoil will be firmly held in the test section during data collection. The step was repeated after finished testing the rigid airfoil and was replaced with the flexible airfoil.

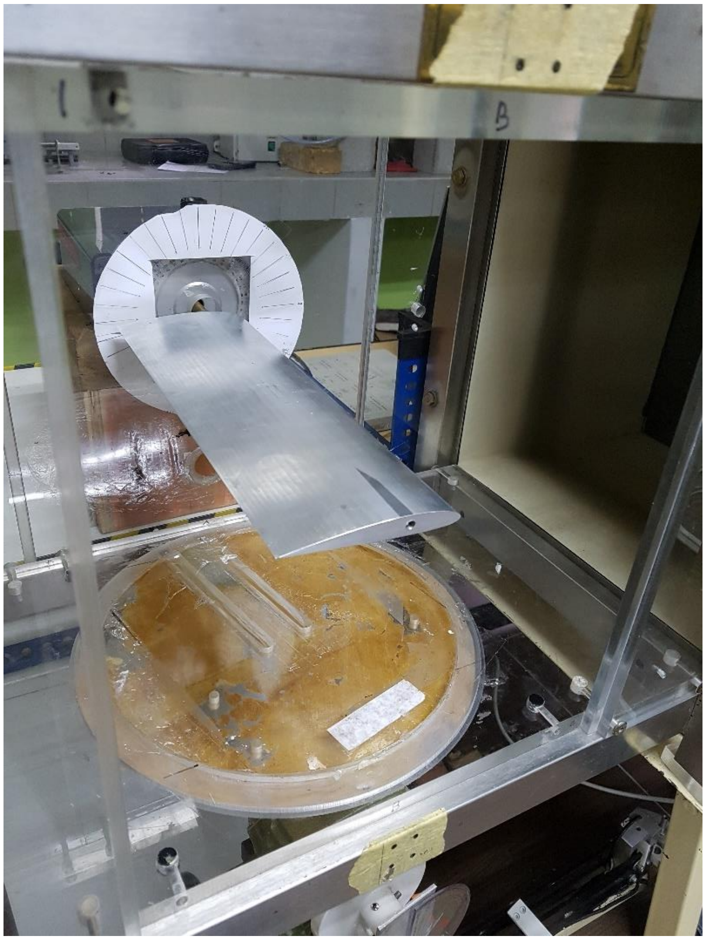


Figure 3.20: Setting up rigid airfoil in test section