CHAPTER 1
INTRODUCTION

1.1 BACKGROUND OF STUDY

Aircraft generates a wake which is caused by a pair of counter rotating vortices trailing from the wing tips. The vortices from aircraft pose problems to encounter a following aircraft. For instance, the wake of these aircraft can impose rolling moments exceeding the roll control capability of some aircraft. Further, turbulence generated within the vortices, if encountered at close range, can damage aircraft components and equipment leading to fatal accidents and personal injuries.

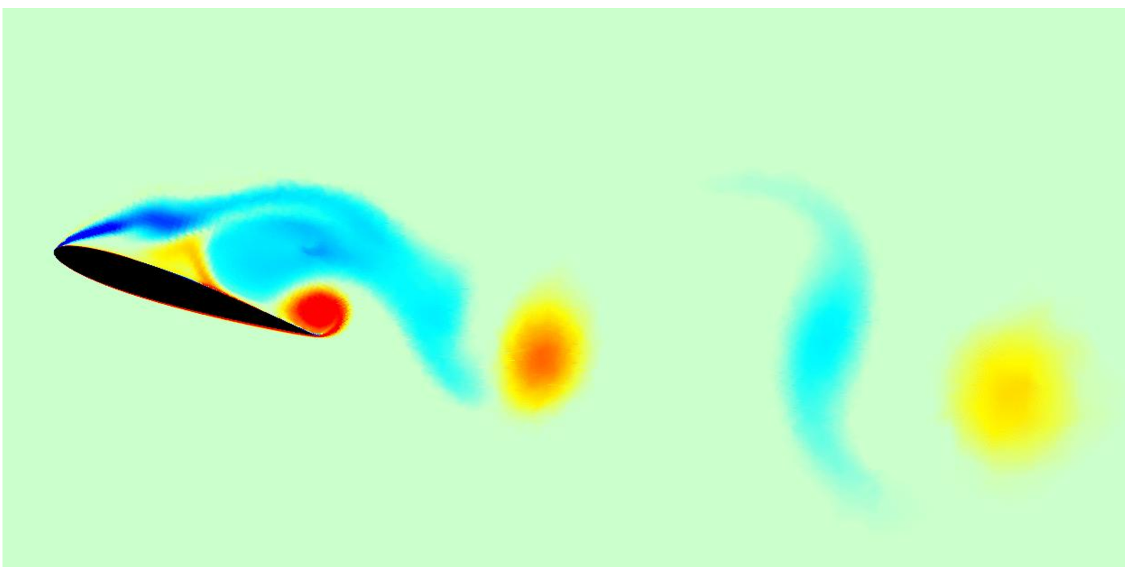


Figure 1: Wake turbulence produced behind wingtip [1].

Wake is especially hazardous during the landing and take-off phases of flight. The reason is that during take-off and landing, aircraft operate at low speeds and high angle of attack. This flight attitude maximises the formation of dangerous wingtip vortices. The other reason is that take-off and landing are the times when a plane is operating closest to its stall speed and to the ground - meaning there is little margin for recovery in the event of encountering another aircraft's wake turbulence. The pilot must learn to envision the location of the vortex wake generated by aircraft and adjust his flight path accordingly.

CHAPTER 2
PROBLEM STATEMENT

2.1 PROBLEM IDENTIFICATION

The wake is a big threat on the safety of an aircraft. Many accidents happened due to the aircraft entering the wake field of a preceding aircraft. Investigation on the effects of the wake field on a following aircraft is the matter of this project. The regulations and instructions of the aircraft can be conducted from the findings of this study.

2.2 SIGNIFICANCE OF THE PROJECT

Wake vortices can have considerable influence on following aircrafts if these encounter the wake vortices directly. Some accidents of recent years, mainly involving small private airplanes, have shown the possible severity of the effect of wake vortices.

An aircraft entering a wake vortex field will momentarily encounter quite large additional aerodynamic forces and moments of rapidly changing sign and magnitude. These may pose considerable hazard if the pilot reaction is inadequate or if the available control forces are insufficient.

In order to minimise any possible threats to air transport safety due to wake vortex, minimum separation distances behind trailing aircraft are enforced within controlled airspace since many years. Separation rules are based solely on the certified Maximum Take-Off Mass (MTOM) of both the leading and following aircraft. The MTOM is a parameter that is part of the Type Design Standard of an aircraft. A change to the MTOM is a design change (modification) and must be approved by the relevant regulatory authority through the auspices of the aircraft manufacturer, or another suitably approved design organisation. No other effects influencing the wake vortex development, movement and decay are considered by the current rules.

CHAPTER 3
OBJECTIVE AND SCOPE OF STUDY

3.1 THE RELEVANCY OF THE PROJECT

In order to do the project perfectly, clear and precise objectives are required. Among the objectives are:

(a) To study the aerodynamics of an aircraft.
(b) To study the aerodynamics effects of the wake field on a following aircraft.
(c) To define safety considerations and limitations to be taken when an aircraft is following another.

The scope of this project is to undergo a thorough literature research to gather information regarding the effects of wake on an aircraft and discussion of experimental results collected during the experiments performed in the wind tunnel. All the findings from this research are hoped to be used in future in preventing the fatal accident due to wake turbulence.

3.2 FEASIBILITY OF THE PROJECT WITHIN SCOPE AND TIME FRAME

A number of studies and simulations using powerful software on the effects of the wake of an aircraft on a following aircraft have been carried out, so that many information about the project can be obtained from the studies especially journals, articles, news reports and also reference books. With all the resources provided, this project can be considered a feasible project within the time frame given.

CHAPTER 4
LITERATURE REVIEW

An airplane experiences four types of forces when moving. The forces include lift, drag, thrust and weight. Lift and Drag are considered aerodynamic forces because they exist due to the movement of the aircraft through the air. The weight pulls down on the plane opposing the lift created by air flowing over the wing. Thrust is generated by the propeller and opposes drag caused by air resistance to the frontal area of the airplane. During take off, thrust must overcome drag and lift must overcome the weight before the airplane can become airborne. In level flight at constant speed, thrust exactly equals drag and lift exactly equals the weight or gravity force. For landings thrust must be reduced below the level of drag and lift below the level of the gravity force or weight.

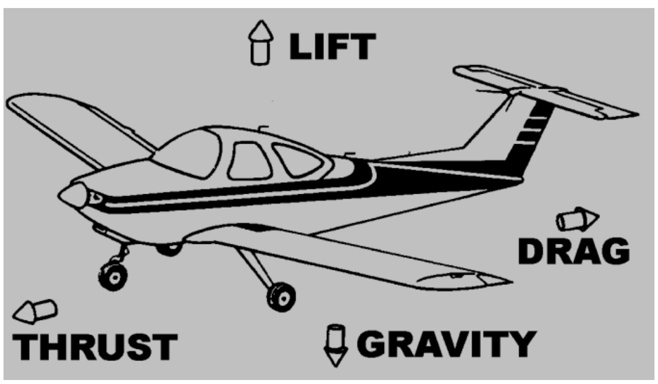


Figure 2: Illustration of lift, drag, thrust and gravity of an aircraft [2].

Lift is produced by a lower pressure created on the upper surface of an airplane's wing compared to the pressure on the wing's lower surface, causing the wing to be "lifted" upward. The special shape of the airplane wing (airfoil) is designed so that air flowing over it will have to travel a greater distance faster, resulting in a lower pressure area thus lifting the wing upward. Lift is that force which opposes the force of gravity (or weight). Drag is the force which delays or slows the forward movement of an airplane through the air when the airflow direction is opposite to the direction of motion of the airplane. It is the friction of the air as it meets and passes over and about an airplane and its components. The more surface area exposed to rushing air, the greater the drag. An airplane's streamlined shape helps it pass through the air more easily.

Every aircraft in flight generates a wake. The important safety issue that concerned in this research is to study the effects of the wake of an aircraft on a following aircraft. This is because the flow field contains strong velocity gradients and rotational flow components which have been known to upset following aircraft. Trailing vortices are potentially hazardous because they can persist for many miles and the breakup of these structures is difficult to predict.

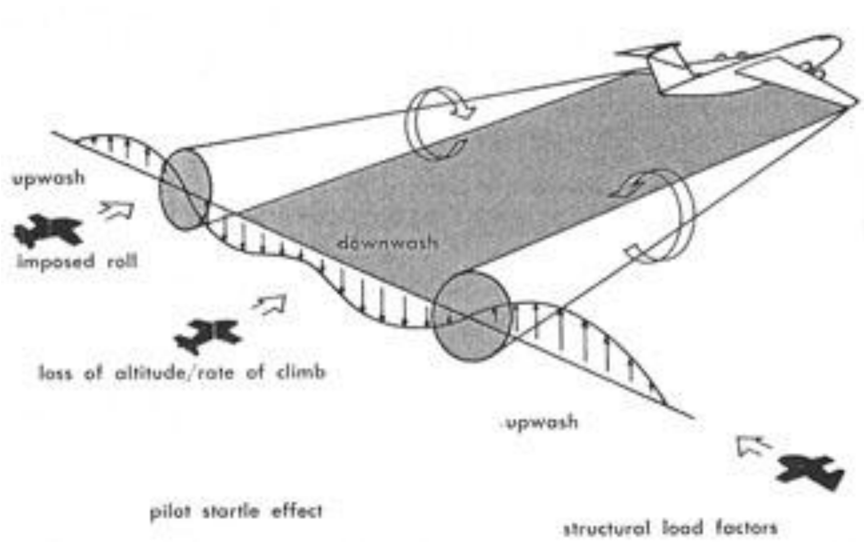


Figure 3: Illustration of hazardous trailing vortices [3].

Heavier aircraft generate stronger flows. The Federal Aviation Administration of United States Department of Transportation (FAA) currently restricts the distance that a small aircraft (<12,500 lb) may follow a heavy aircraft (>300,000 lb) to 6 miles [4]. The distance between planes directly affects the amount of air traffic that airports can handle. With air traffic predicted to triple within the next 20 years [4], air traffic and airport capacity limits could be substantially increased if a means were found to safely and reliably disperse these vortex structures in a shorter time frame.

Many researches and studies have been done and came out with various techniques to reduce the strength of the tip vortex and its subsequent downstream impact. One of the solutions is the introduction of the concept of generating additional circulation to alter the strength of the tip vortex such that it behaves in a manner characteristic of a delta wing vortex. The delta wing is a wing platform in the form of a triangle and it function is to increase the angle of attack in order to generate a vortex which remains attached to the upper surface of the wing, giving the delta a very high stall angle.

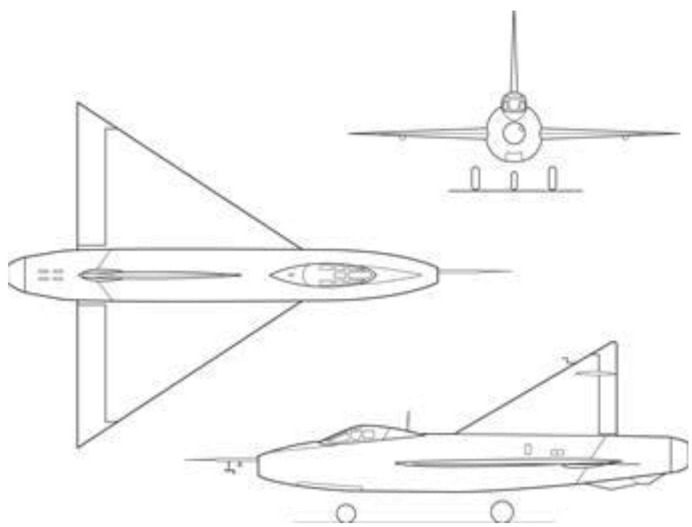


Figure 4: Illustration of delta wing [3].

Studies have shown that the vortices from a delta wing can breakdown, or "bursting", which is characterised by an increase in vortex diameter followed by large scale turbulent dissipation, and a decrease in the core's axial and circumferential velocity. In short, the vortices from a delta wing can disperse because they are too powerful.

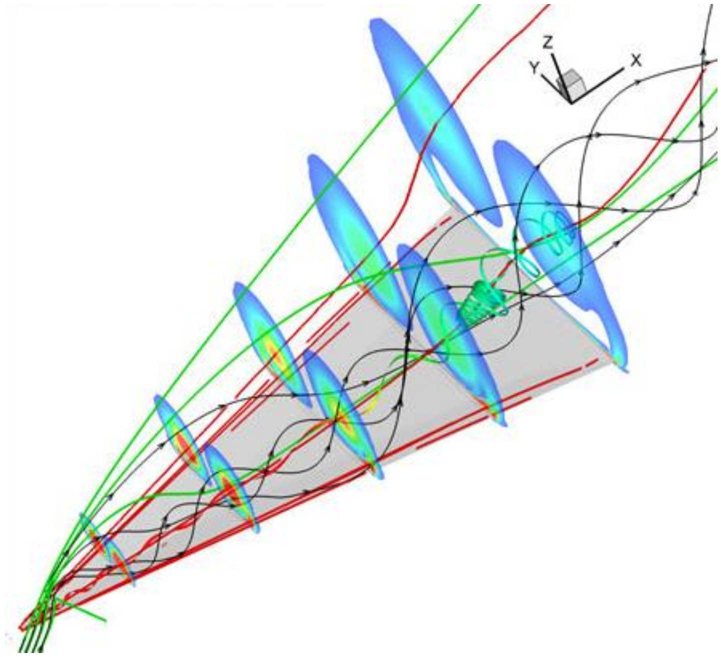


Figure 5: Delta wing vortices [5]

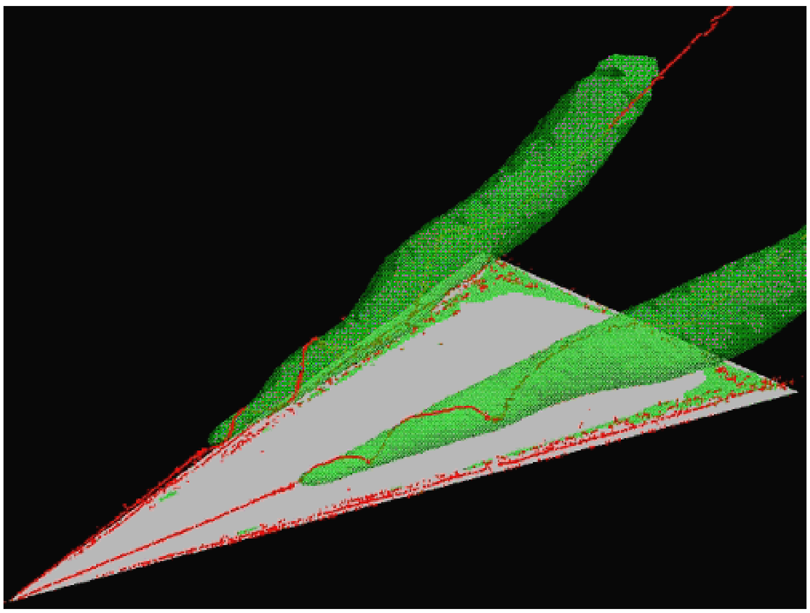


Figure 6: Breakdown of delta wing vortices [6].

CHAPTER 5
METHODOLOGY / PROJECT WORK

5.1 PROCEDURE IDENTIFICATION

This project will involve a few options in order to gather all the required information. These options below will be used with regards to study the effects of wake of an aircraft on the following aircraft perfectly:

(a) Own research on previous available case studies.
- Sample case studies are gathered from journals and paper works

(b) Testing models in wind tunnel.
(i). Aerofoil models are tested in UTP wind tunnel. The experiment is to observe the drag and lift forces around the aerofoil models at variable air stream velocity.
(ii). Experiments to observe the relation between Reynold's Number with drag and lift coefficient at variable air stream velocity.

(c) Perform the similarity calculation between prototype and model of an aerofoil wing.

(d) Discussion on results collected from experiments in wind tunnel.
The measurements are recorded and graphs are plotted. Observation and discussion are done based on the results collected.

5.2 TOOLS REQUIRED

This project required a Wind Tunnel calibrated equipment and at least two wing models for experimental purposes. A new test section is to be fabricated and installed specially for this study.

CHAPTER 6
RESULTS AND DISCUSSION

6.1 DESCRIPTIONS OF WT04 SUB-SONIC WIND TUNNEL

Tabulated below are the specifications and capabilities of WT04 Sub-Sonic Wind Tunnel Demonstration Unit [7].

Table 1: WT04 Sub-Sonic Wind Tunnel Demonstration Unit specifications

No	Item	Specifications
1	Type of Tunnel	Low speed, open circuit, suction type
2	Test Section	300H x 300D x 1500L mm (inside)
3	Air Speed	Up to 60 m/s (continuously variable)
4	Contraction Ration	25:1
5	Drive	Axial flow fan by DC motor with digital type DC drive controller
6	Motor	11Kw, 2800rpm DC motor
7	Overall Size	6.4L x 2.5H x 1.7W meter approx.
8	Power Requirement	AC, 3ph 415 volts, 30 Amps Electrical supply with neutral and earth connection
9	Material of construction	Effuser and Diffuser: Mild Steel Blower and supporting frame: Mild Steel

Table 2: WT04 Sub-Sonic Wind Tunnel Demonstration Unit experimental capabilities

No	Experiment	Capabilities
1	Study of lift and drag on aerofoil	Symmetrical, cambered and special shapes
2	Study of drag on bluff bodies	Spherical, hemispherical, flat disc, automobile models
3	Study of pressure distribution	Symmetrical aerofoil, cylindrical
4	Study of smoke pattern around	Aerofoil, automobile models

Figure 7:WT04 Sub-sonic Wind Tunnel Demonstration Unit.

6.2 EXPERIMENTAL RESULTS

6.2.1 Effect of Free stream Velocity on the Drag and Lift Forces.

An experiment is conducted to test the capabilities of the wind tunnel unit. For the experiment, a symmetrical aerofoil model is used and the measurement of drag and lift forces are taken at variable Free Stream Velocity. Throughout this experiment, the symmetrical model is fixed at 15 degree angle of attack.

Table 3: Experimental results for the effect of Free Stream Velocity on the drag and lift forces

Free Stream Velocity (m/s)	**Velocity pressure (mmH2O)**	**Drag (Newton)**	**Lift (Newton)**
10.36	6.43	2.26	0.76
20.86	25.99	4.59	4.39
30.96	56.72	6.66	10.12
40.32	98.09	9.31	17.78
50.90	155.31	13.01	25.40
57.90	200.25	20.20	32.61

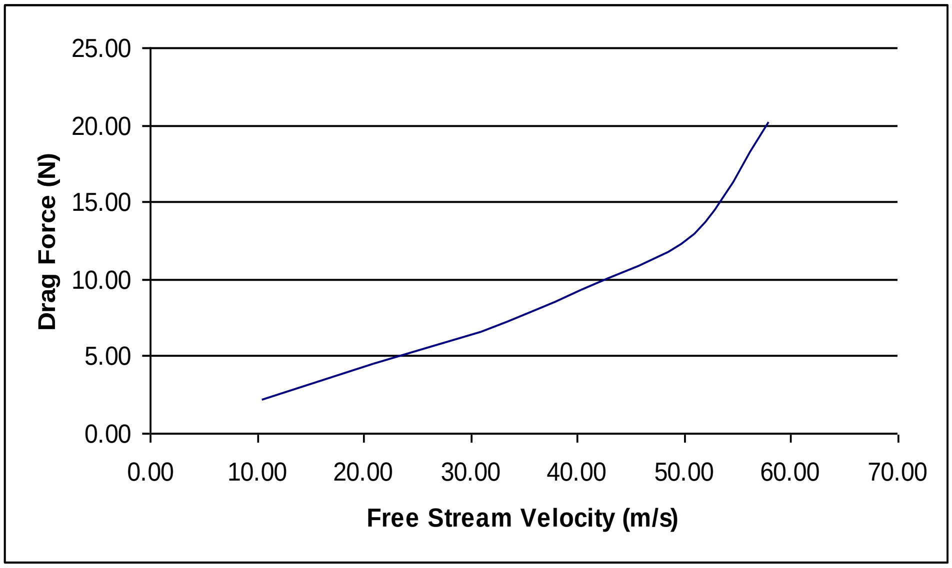


Figure 8: Free Stream Velocity vs. Drag Force

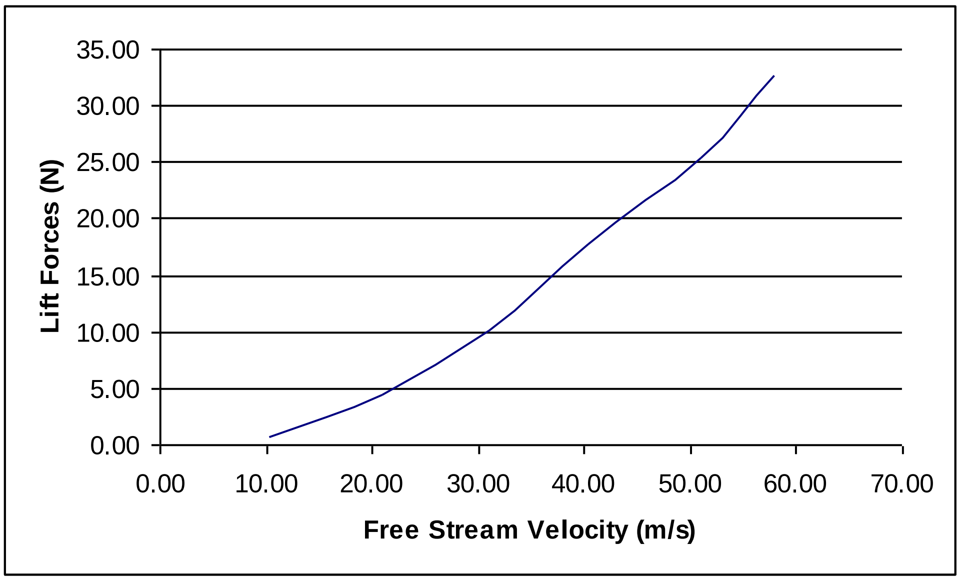


Figure 9: Free Stream Velocity vs. Lift

As shown in the results above, lift and drag forces are proportionally related to the free stream velocity. Further experiments will be carried out to achieve reliable results.

6.2.2 Sensitivity of Results to Reynold's Number.

The objective of this experiment is to investigate the relation of Reynold's Number with Drag and lift Coefficient. The experiment is carried out at 10 m/s, 20 m/s, 30 m/s, 40 m/s, 50 m/s and 57 m/s (maximum) Free Stream Velocity. An aerofoil model is used for this experiment and fixed at 20 degree angle of attack. Before running the experiment, it is a need to perform similarity calculation between a prototype and a model of an aircraft to fulfill a few requirements of the experiment. The requirements include the minimum speed of an aircraft during take-off and in-flight.

Similarity equation:

$Re_p = Re_m$ ……………………………………………… (1)

Re_p = Reynold's Number for prototype

Re_m = Reynold's Number for model

$Re_p = [(\rho_{air}) \times (V_p) \times (L_p)] / (\mu_{air})$ …………………….….. (2)

$Re_m = [(\rho_{air}) \times (V_m) \times (L_m)] / (\mu_{air})$ ……………………….. (3)

ρ_{air} = Density of air in Kg/m^3

V_p = Required Velocity of prototype in m/s

V_m = Required Velocity of model in m/s

L_p = Length of prototype in m

L_m = Length of model in m

μ_{air} = Viscosity of air in Kg/m s

The objective is to find V_m, the required Velocity for model to be tested in wind tunnel. So by re-arranging the equation (1), (2) and (3),

$V_m = [(\rho_{air}) \times (V_p) \times (L_p) \times (\mu_{air})] / [(\mu_{air}) \times (\rho_{air}) \times (L_m)]$…. (4)

$V_m = [(V_p) \times (L_p)] / (L_m)$………………………………….……….. (5)

Similarity calculation:

For the similarity calculation, the same density and viscosity are used because both model and prototype experienced the same medium which is air. So, from equation (4), density and viscosity values can be eliminated. Scaled model can be used to define the length of a model and its real prototype. For this experiment, 1: 42 scaled is used, means that 1 unit length of a model is equal to 42 unit length of its prototype [8]. For a small private aircraft required 15 m/s speed for take-off and up to 70 m/s maximum speed during in-flight. As the WT04 Sub-sonic wind tunnel only can produce 57 m/s maximum Free Stream Velocity, it is acceptable to use 50 m/s as the in-flight for this similarity calculation.

Table 4: Model scaled at 1: 42

Model	Prototype
1	42

Table 5: Take-off and in-flight speed required for a prototype

Take-off	15 m/s
In-flight	50 m/s

Table 6: Results obtained from calculations

V_m for Take-off	630 m/s
V_m for In-flight	2100 m/s

The results obtained as shown in the Table 6 can be used to calculate and define the characteristics of Mach Number, Ma.

$Ma = V_m / C$……………………………………………….. (6)

V_m = Required Velocity of model in m/s
C = Speed of sound in m/s
For this calculation, the speed of sound used is 343 m/s.

Table 7: Mach Number obtained from calculation for both take-off and in-flight

Take-off	1.836735
In-flight	6.122449

From the results obtained of the similarity calculation, obviously shown that the requirement speed of an aircraft model V_m, is much more higher than the capability of WT04 Sub-sonic Wind Tunnel which can only produced 57 m/s Free Stream Velocity. The calculated Mach Number also shown that both take-off and in-flight requirement speed for the model required a supersonic flow since Ma > 1 and it is beyond the capability of WT04 Sub-sonic Wind Tunnel. This is because the WT04 Sub-sonic Wind Tunnel can only produced sub-sonic flow or flow with Ma < 1.

The similarity analysis has shown the need of high velocity as requirement to test a model in WT04 Sub-sonic Wind Tunnel Demonstration Unit. The requirement will not be fulfilled due to constraint of capability of the wind tunnel. The solution of this problem is by defining the sensitivity of Reynold’s Number on drag and lift coefficient. Reynold’s Number increases proportionally with velocity. The study on sensitivity of Reynold’s Number will help solving problem due to high requirement of velocity.

Table 8: Data for experiment on Sensitivity of Results to Reynold’s Number

Model	Symmetrical aerofoil
Length of model	0.1003 m
Drag area	0.0099 m^2
Lift area	0.0278 m^2
Density of air	1.18 Kg/ m^3
Viscosity of air	1.8395×10^{-5} Kg/m s
Angle of attack	20^o

Figure 10: Symmetrical aerofoil model tested in WT04 Sub-sonic Wind Tunnel

Table 9: Experimental results for Sensitivity of Results to Reynold’s Number

Free Stream Velocity, V (m/s)	Drag Force, D (N)	Lift Force, L (N)	Drag Coefficient, C_D	Lift Coefficient, C_L	Reynold's Number
10	3.34	20.83	5.718199	12.699670	64340.31
20	7.61	36.86	3.257148	5.618217	128680.60
30	13.44	60.57	2.556640	4.103158	193020.90
40	16.94	81.56	1.812618	3.107853	257361.20
50	19.69	98.33	1.348399	2.398000	321701.50
57(Max)	24.27	122.88	1.278889	2.305869	366739.80

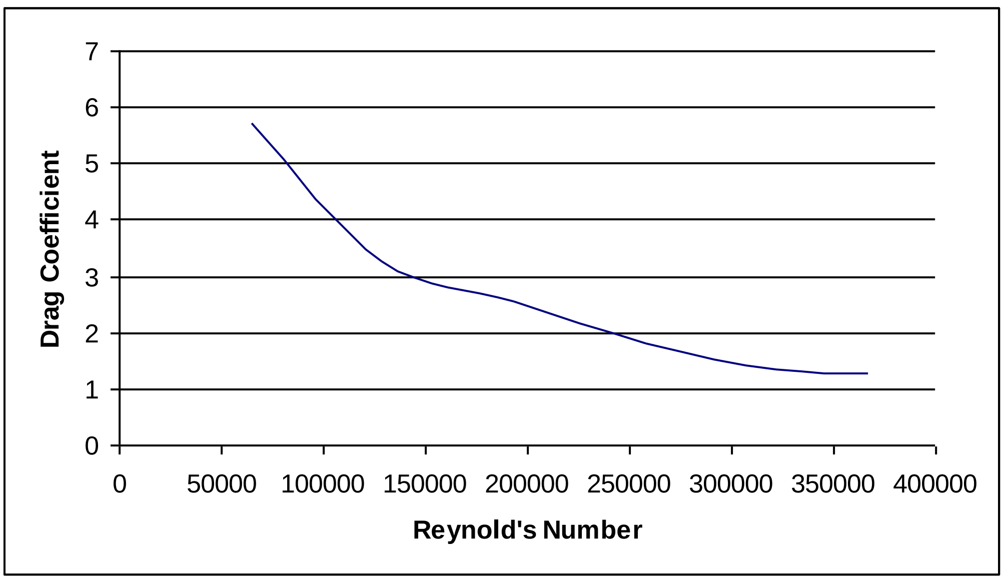


Figure 11: Reynold's Number vs. Drag Coefficient

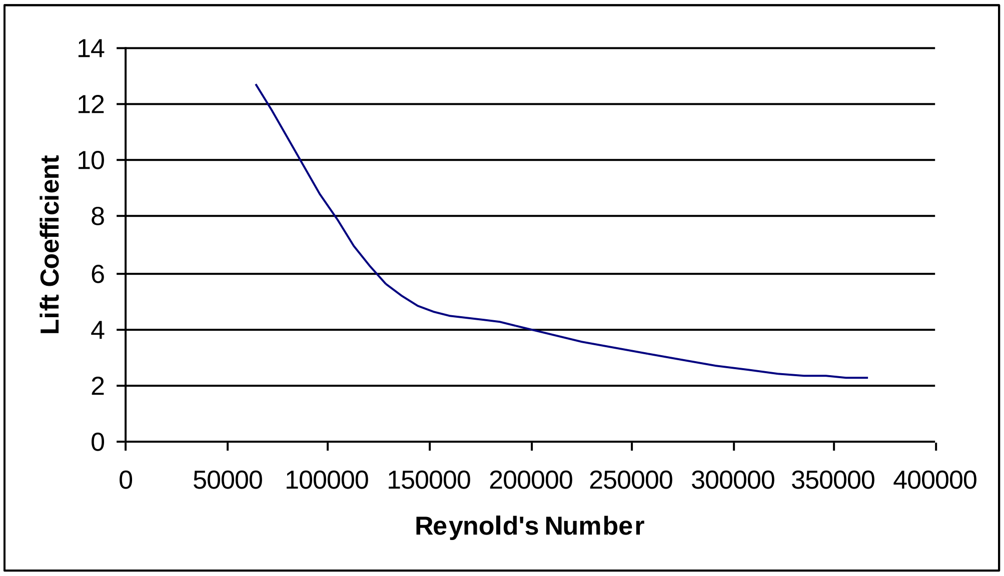


Figure 12: Reynold's Number vs. Lift Coefficient

As shown in Figure 11 and Figure 12, both Drag Coefficient (C_D) and Lift Coefficient (C_L) are independent variable. For Drag Coefficient (C_D), the value is approaching 1 while for the Lift Coefficient (C_L), the value is approaching 2. These values are applicable for determination of Drag and Lift force at high Free Stream Velocity.

6.3 SELECTION OF AEROFOIL WING TYPE.

NACA0012 aerofoil wing type is commonly used in aircraft industry especially for small private aircraft such as CESSNA 152(Figure 13). NACA0012 aerofoil type is selected to be tested through out completing this project.

Figure 13: CESSNA 152 aircraft [9]

The purposes of selecting NACA0012 aerofoil type is because it is significant with the problem statement of this research. Most of the fatal aircraft accident due to effect of wake turbulence involved small private aircraft and most of them used NACA0012 aerofoil type for their wing section. Furthermore, NACA0012 aerofoil type is easy to be fabricated because it is symmetrical shape. Many journals and books of NACA0012 aerofoil type are published and can be used as references.

6.4 DESIGN OF NACA 0012 AEROFOIL TYPE MODEL

Two units of NACA 0012 aerofoil type wing models are designed using CATIA V5R6 software. The designs are as shown in figures below:

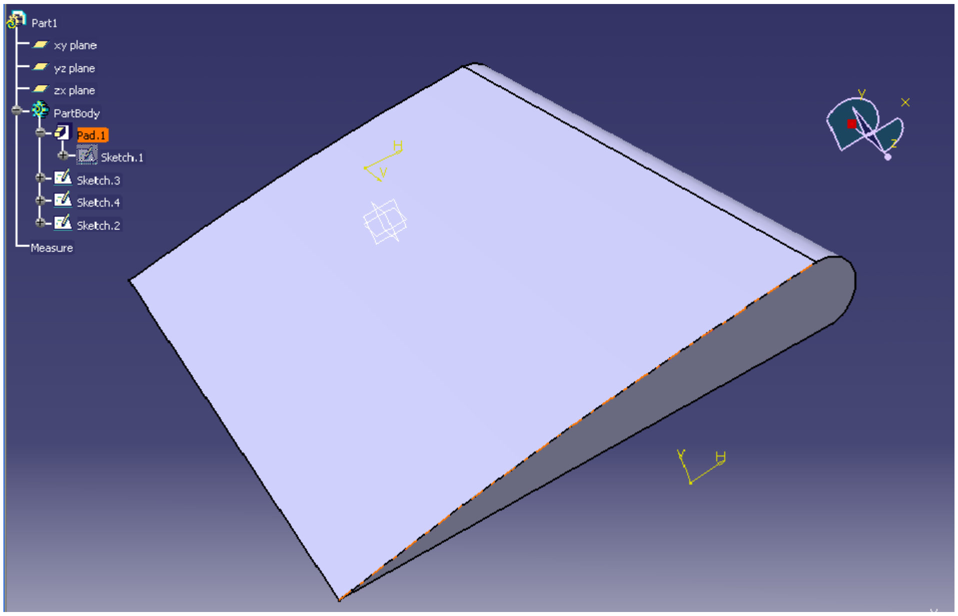


Figure 14: NACA 0012 Aerofoil wing type model

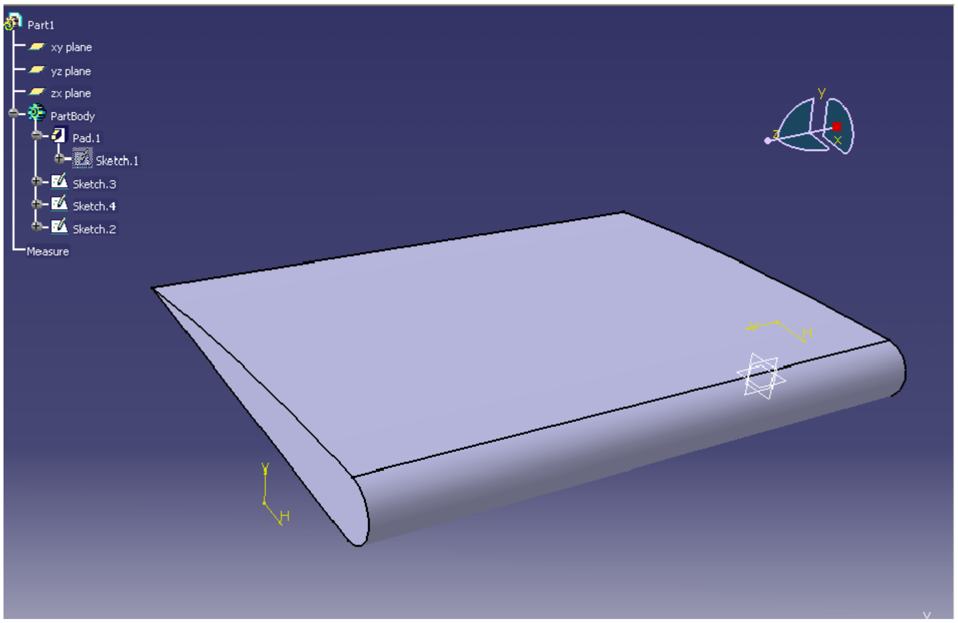


Figure 15: NACA 0012 Aerofoil wing type model

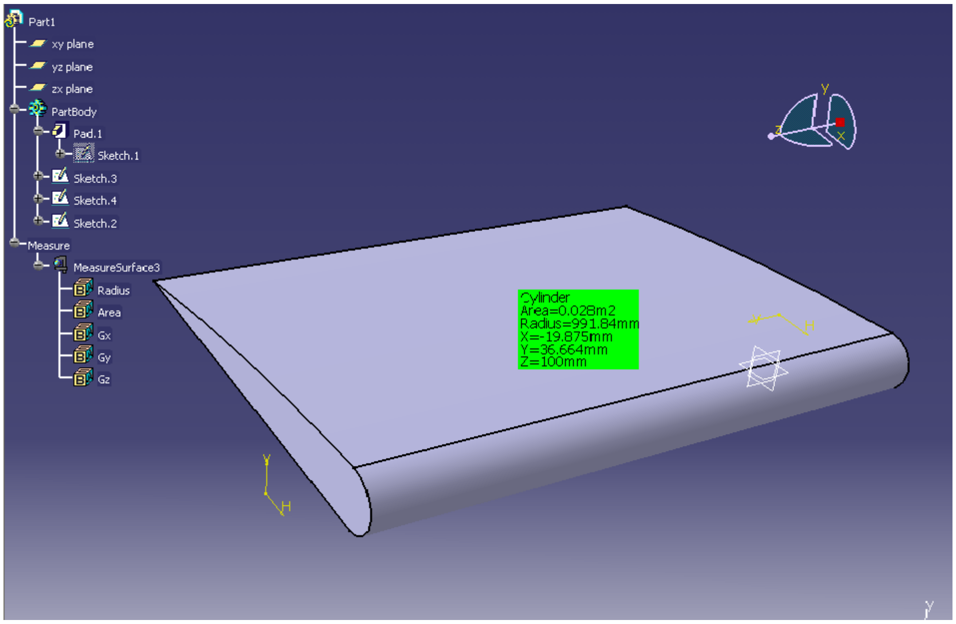


Figure 16: NACA 0012 Aerofoil wing type model

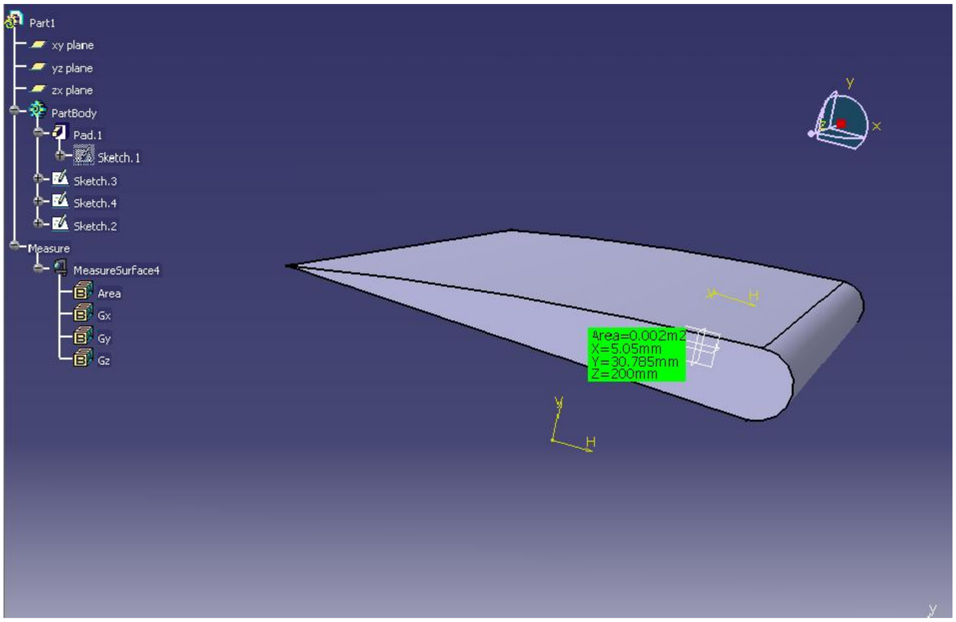


Figure 17: NACA 0012 Aerofoil wing type model

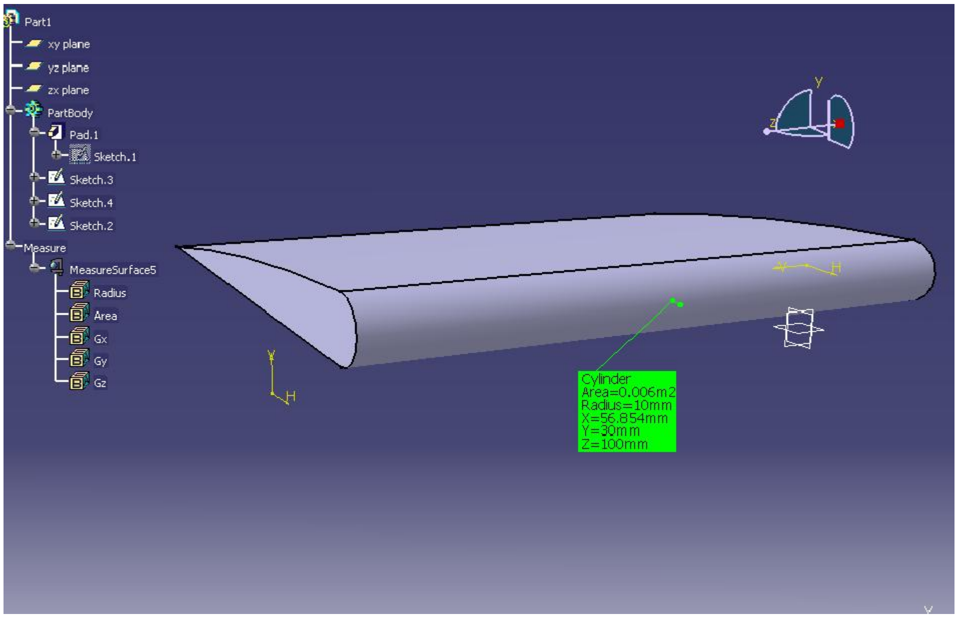


Figure 18: NACA 0012 Aerofoil wing type model

6.5 FABRICATION OF NACA 0012 AEROFOIL TYPE MODEL

The material used for fabrication of the NACA 0012 aerofoil wing type models is wood. The reasons of using wood are because it is cheaper and easy to purchase. The steps involved in the fabrication of the models are shown in the flowchart below.

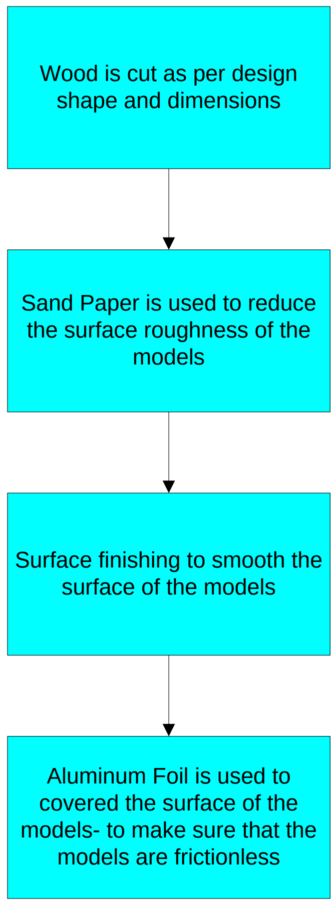


Figure 19: Flowchart of steps involved in fabrication of aerofoil models.

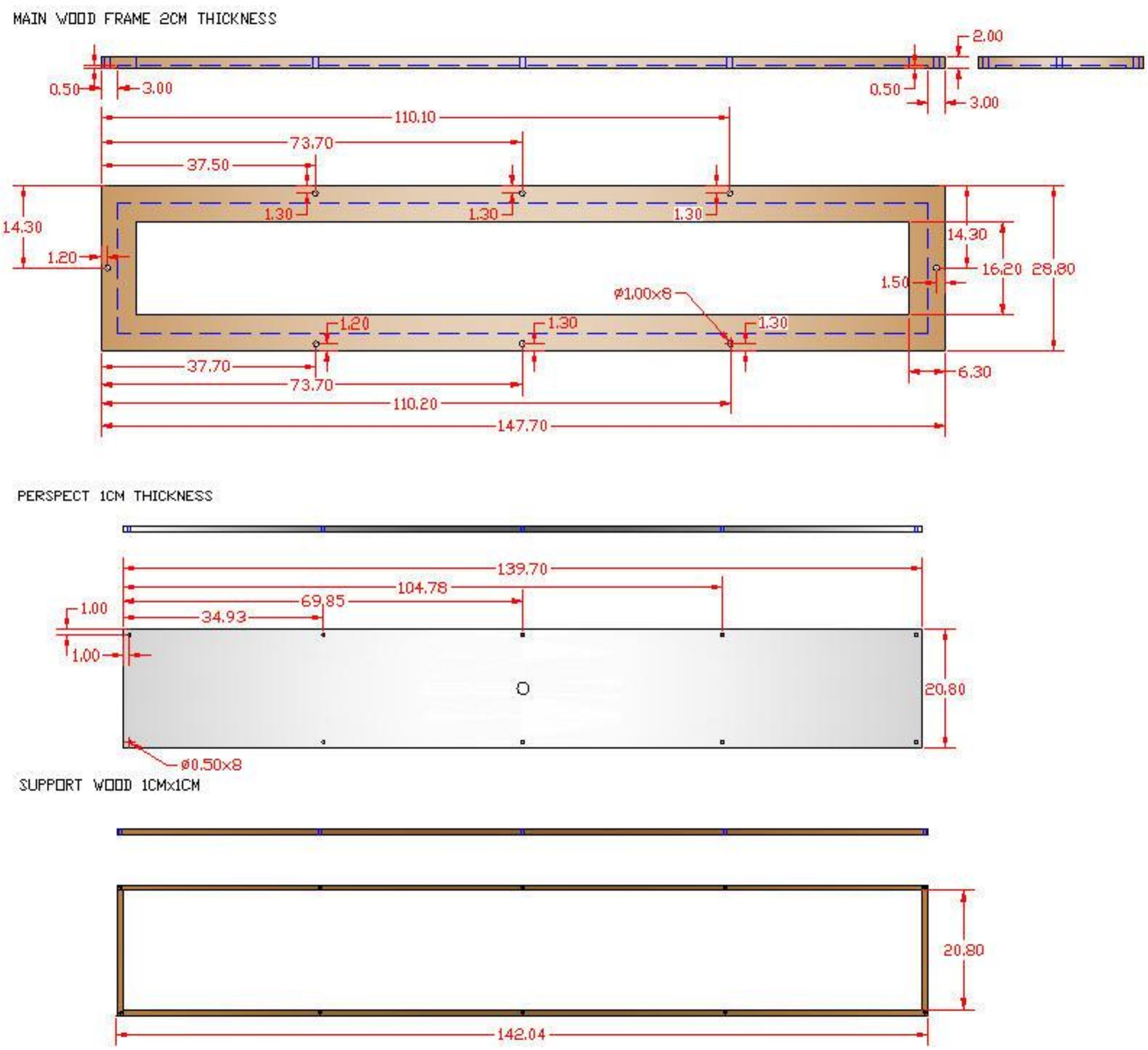
Figure 20: New fabricated aerofoil model.

Figure 21: New fabricated aerofoil model

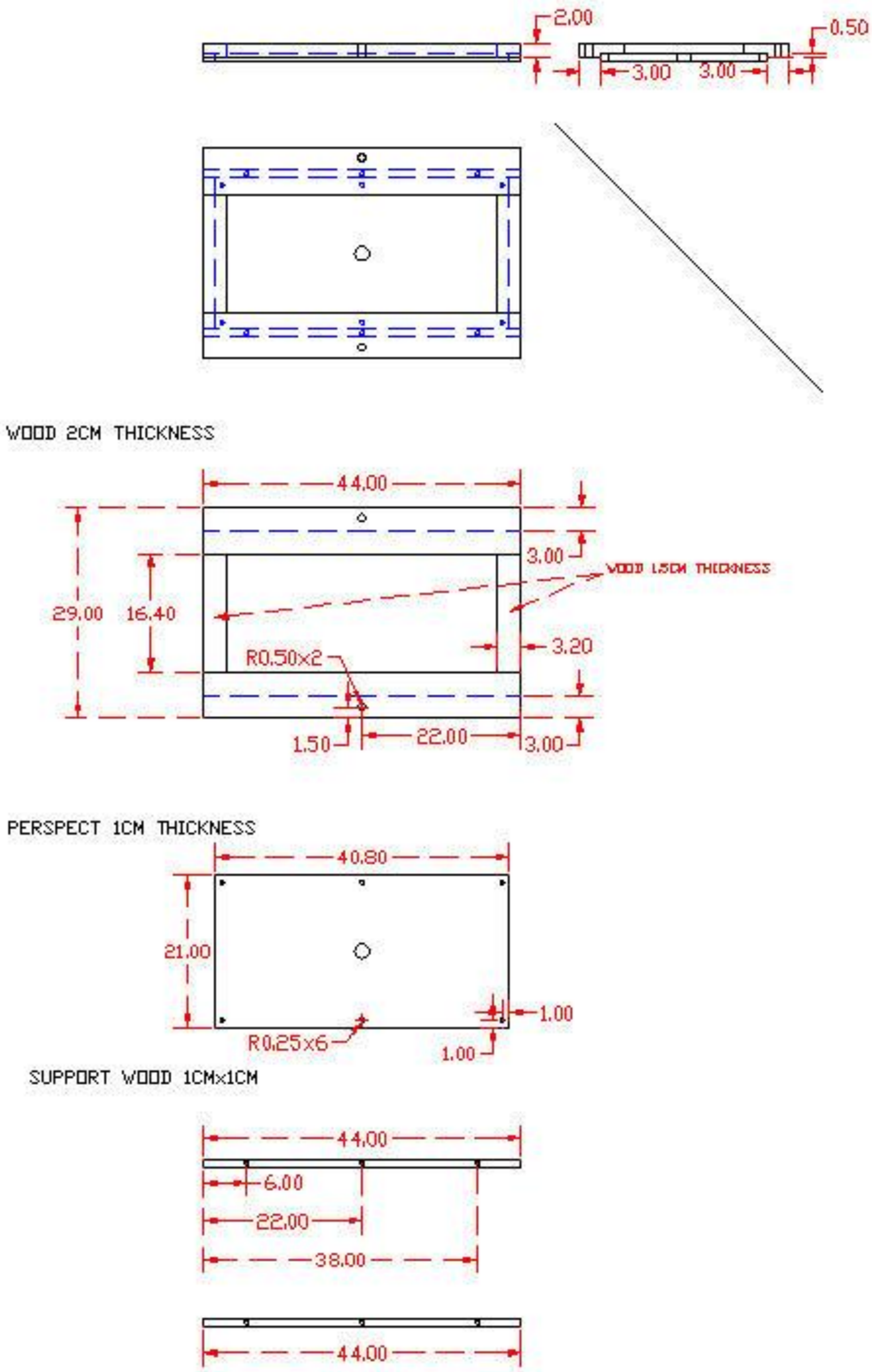
6.6 DESIGN OF NEW TEST SECTION OF WIND TUNNEL

In order to conduct study and experiment using the WT04 Sub-sonic Wind Tunnel Unit, it requires a fabrication of a new test section. The new test section will be made from Perspex and wood (as support). The design and dimensions of the new test section are done using AUTOCAD software and as shown below.

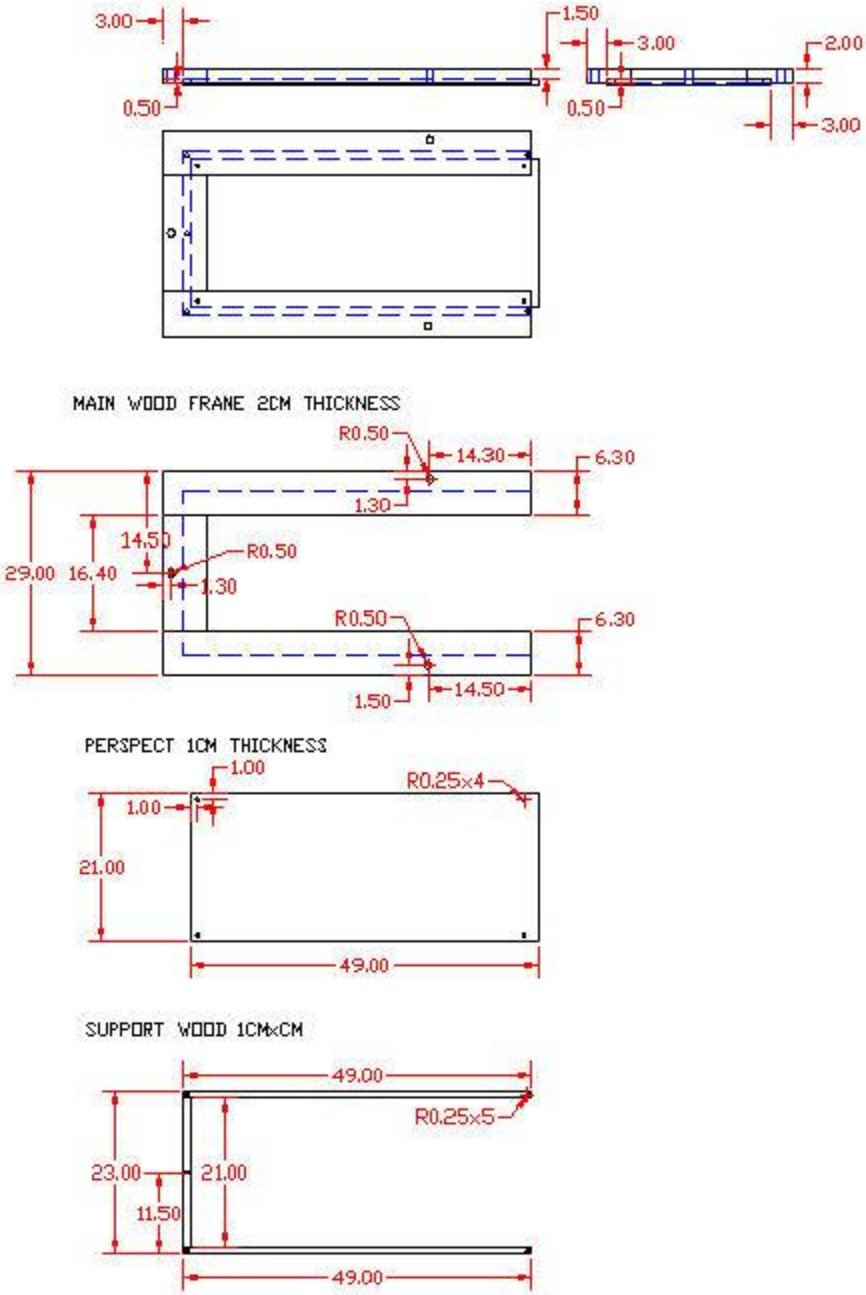
6.6.1 Design and dimensions for left side.



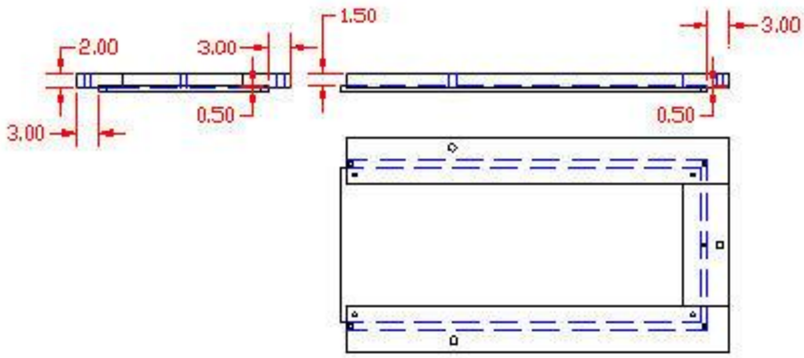
6.6.2 Design and dimensions for right side.



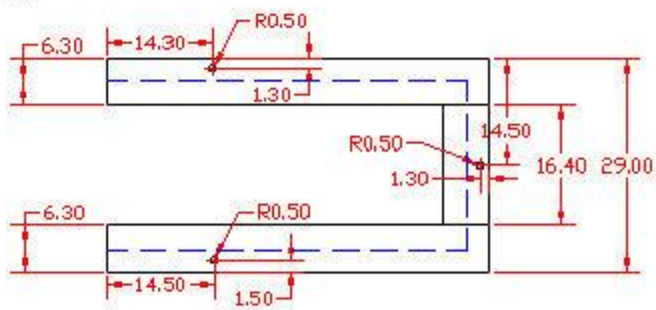
6.6.3 Design and dimensions for right side left section.



6.6.4 Design and dimensions for right side right section.

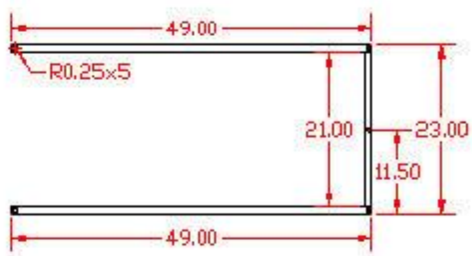


MAIN WOOD FRAME 2CM THICKNESS



PERSPECT 1CM THICKNESS

SUPPORT WOOD 1CM×CM



6.7 PERSPEX FOR WIND TUNNEL TEST SECTION.

Details of purchasing the Perspex are as table below:

Table 10: Details of purchasing item

Supplier	Venus Distributor Globe Plastic Industries (Ipoh) Sdn.Bhd
Dimensions	4 Inch x 6 Inch, thickness: ½ Inch
Price	RM 480.00

6.8 FABRICATION OF THE WIND TUNNEL TEST SECTION.

The fabrication processes of the wind tunnel test section are done during the mid semester holiday. The purposes of choosing mid semester holiday for fabrication because of the availability of technicians, tools and transportations. A few steps or methodology involved during the fabrications as listed below.

6.8.1 Marking points on the work piece (Perspex).

The purpose of marking a few points on the work piece (Perspex) is to prevent error during the fabrication processes. The points marked include positions to make holes and cutting purpose.

Figure 22: A few points marked on the work piece (Perspex).

6.8.2 Drilling holes on work piece (Perspex).

16 holes must be drilled on the work piece (Perspex) to fix with screws that available at the wind tunnel. All of them are 10 mm of diameter. To prevent the work piece from cracks or damages and to get driven track, holes are drilled using smaller size of drill bits. For this fabrication process, drill bits size of 6 mm, 7 mm, 8 mm, 9 mm are used. So for a single hole must be drilled 5 times using different sizes of drill bit to get the actual size of the hole (10 mm). Some safety precautions must be applied when conducting the drilling tools to prevent any injuries that might be occurred. Besides that, drilling processes must be done carefully to prevent any possible damages on work piece.

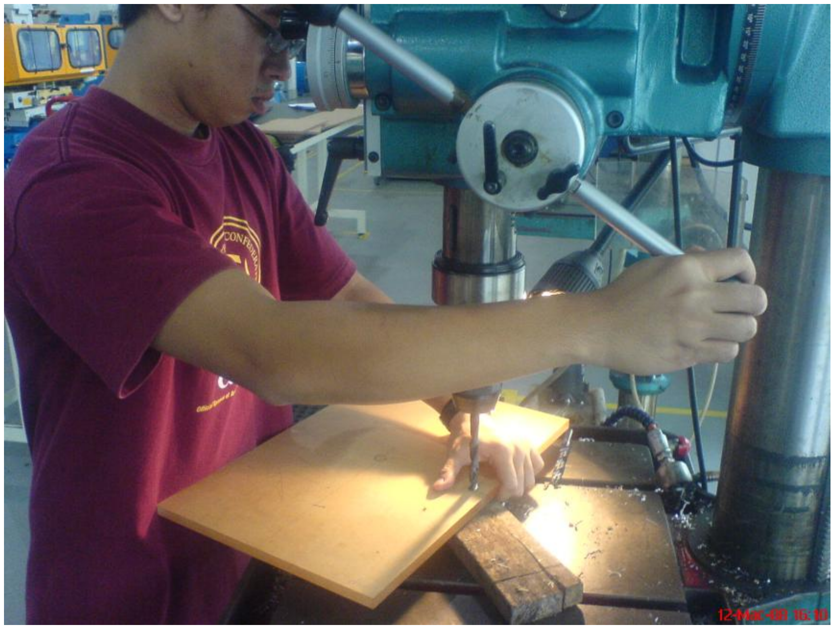


Figure 23: Drilling holes processes.

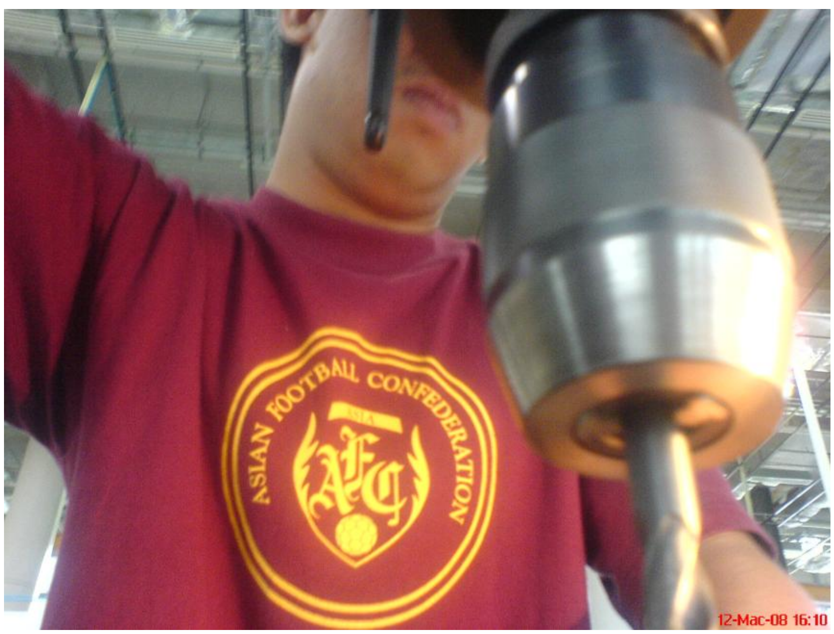


Figure 24: Drilling holes processes.

Figure 25: Drilling holes processes.

6.8.3 Testing the new test section.

The new test section must be tested to make sure that all the dimensions and holes drilled fix with the wind tunnel. Safety precautions must be practiced accurately when removing the existing test section and replacing the new test section. This is very important to prevent damages for both new test section and the existing test section.

Figure 26: Testing the new test section.

Figure 27: The new test section.

6.9 FABRICATION OF THE SUPPORTS AND POINTER.

The supports for aerofoil models are made from thin plate bar metal. The dimension for the metal bar is 1/8 inch X 6/8 Inch X 60 Inch. The material must be cut and customized to be the supports for models. One side of the support is drilled and permanently screwed to the model while the other side drilled and screwed to the wall of the new test section of the wind tunnel. For the main aerofoil model (the one with 3-component balance), no need supports for the both sides (if got supports then there is no used of 3-component balance).

Figure 28: The customized supports for aerofoil model.

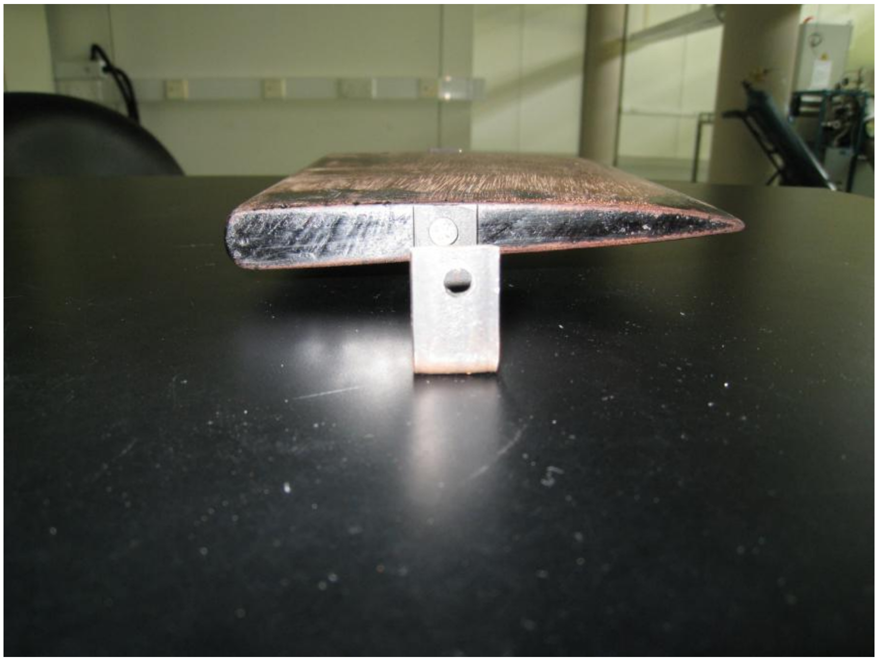


Figure 29: The supports screwed to the aerofoil model.

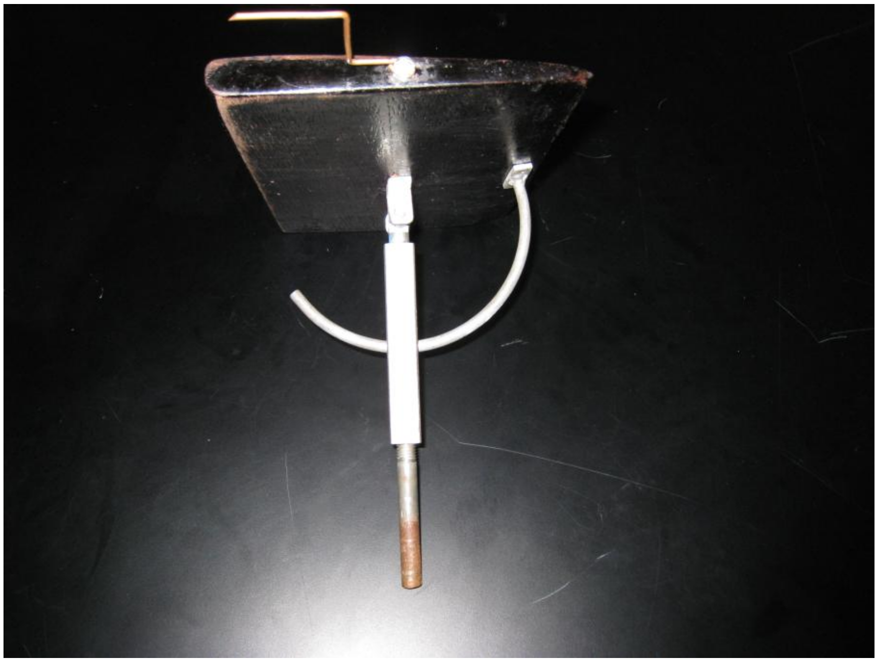


Figure 30: The 3 components balance support for the main aerofoil model.

The main model (with 3-component balance) must be allocated a pointer so that it can be used to point angle of attack. It is very important so that the desired angle of attack is accurately defined. The pointer is made from soft metal rod (cooper). This rod is bent at angle of 90 degree and sharpens at its end.

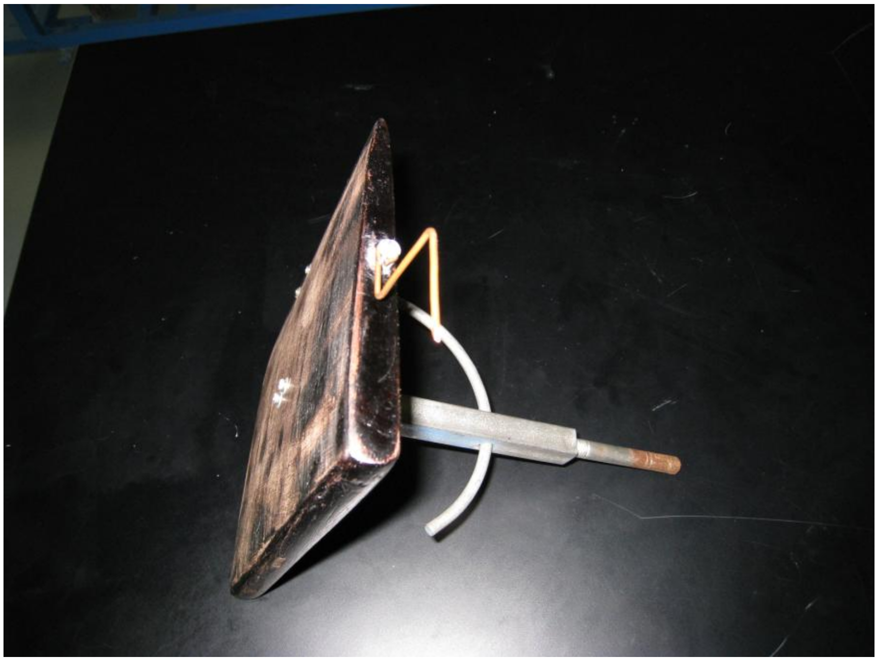


Figure 31: Pointer to point the angle required.

6.10 EXPERIMENTS ON THE EFFECT OF WAKE.

The experiments are performed using the fabricated aerofoil models and tested using the new fabricated wind tunnel test section. The experiments include testing a single aerofoil model and double aerofoil models. A single aerofoil is tested to define the drag and lift forces and it is functioning as references for comparison for the next experiment (double aerofoil models). The main objective of the experiments is to study the characteristic of drag and lift forces when two aerofoil models are placed in a specific distance of each other.

6.10.1 Effect of Free stream Velocity and various angles of attack on the Drag and Lift Forces of a single aerofoil model.

An aerofoil model is tested at various free stream velocity (10 m/s, 20 m/s, 30 m/s, 40 m/s and 45 m/s) and different angle of attack (0^o , 2^o, 4^o, 6^o, 8^o, 10^o, 12^o, 14^o, 16^o, 18^o, 20^o). The objective is to define the characteristic of drag and lift forces at all the conditions as stated above.

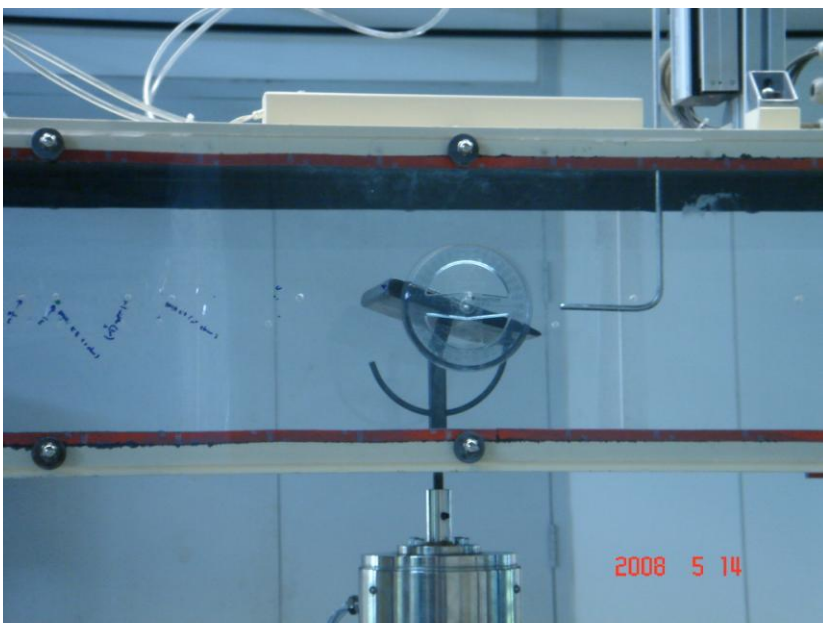


Figure 32: Testing a single aerofoil model.

Table 11: Experimental results for a single aerofoil model at 10 m/s

Angle of Attack (Degree)	Free Stream Velocity (m/s)	Drag Forces (N)	Lift Forces (N)
0	10	0.2	0.66
2	10	5.25	5.93
4	10	1.54	1.92
6	10	1.17	0.72
8	10	13.21	13.65
10	10	1.08	1.59
12	10	2.49	3.2
14	10	1.51	2.45
16	10	0.73	7.17
18	10	1.65	2.73
20	10	1.45	2.77

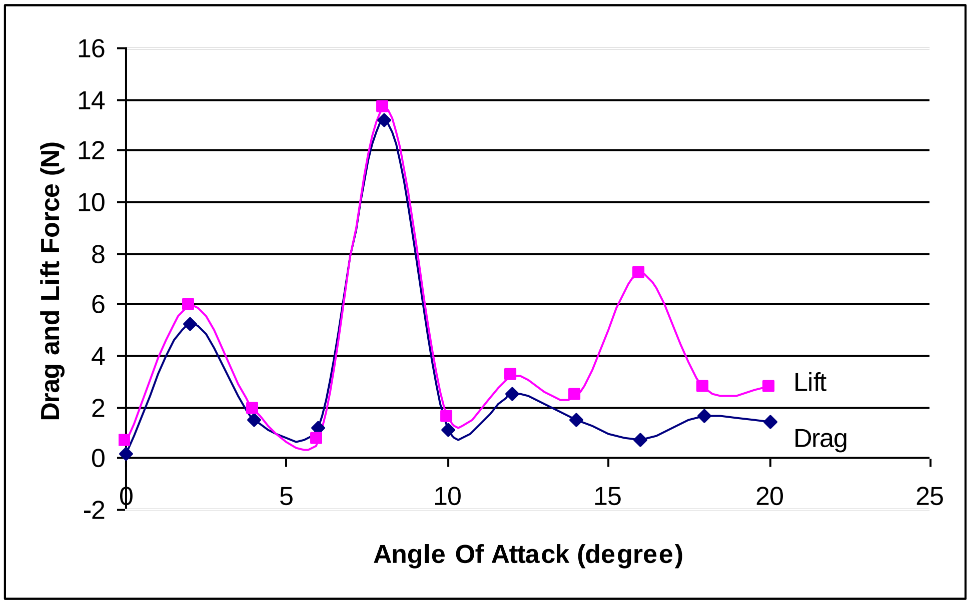


Figure 33: Angle of attack (degree) vs. Drag and Lift Force (N) for a single model at 10 m/s

Table 12: Experimental results for a single aerofoil model at 20 m/s

Angle of Attack (Degree)	Free Stream Velocity (m/s)	Drag Forces (N)	Lift Forces (N)
0	20	0.55	0.39
2	20	9.57	10.15
4	20	2.12	3.77
6	20	2.04	1.28
8	20	17.32	17.66
10	20	2.12	2.2
12	20	4.52	7.28
14	20	3.31	5.08
16	20	1.11	5.93
18	20	2.32	4.06
20	20	2.66	3.95

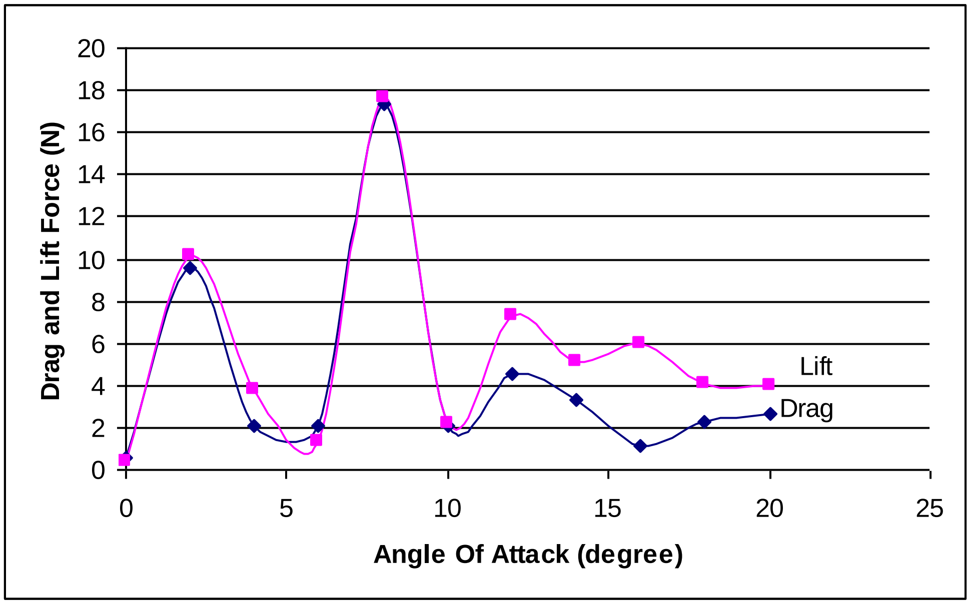


Figure 34: Angle of attack (degree) vs. Drag and Lift Force (N) for a single model at 20 m/s

Table 13: Experimental results for a single aerofoil model at 30 m/s

Angle of Attack (Degree)	Free Stream Velocity (m/s)	Drag Forces (N)	Lift Forces (N)
0	30	1.26	1.62
2	30	13.51	14.94
4	30	3.14	4.95
6	30	3.95	5.5
8	30	22.34	24.02
10	30	4.24	6.1
12	30	8.67	13.45
14	30	7.26	13.65
16	30	3.41	8.19
18	30	4.19	6.48
20	30	3.56	8.51

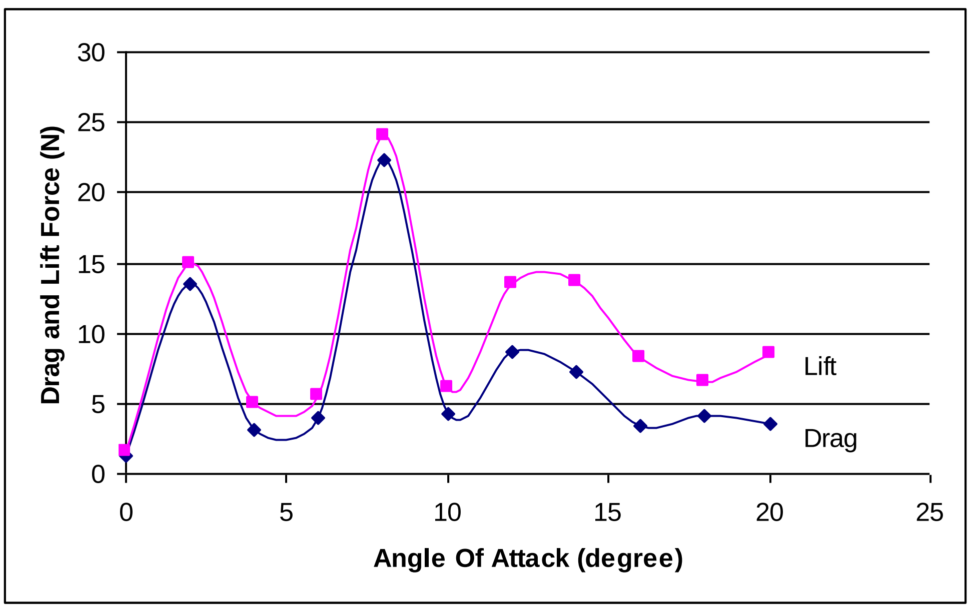


Figure 35: Angle of attack (degree) vs. Drag and Lift Force (N) for a single model at 30 m/s

Table 14: Experimental results for a single aerofoil model at 40 m/s

Angle of Attack (Degree)	Free Stream Velocity (m/s)	Drag Forces (N)	Lift Forces (N)
0	40	2.13	0.66
2	40	17.85	18.25
4	40	5.06	7.61
6	40	4.69	8.24
8	40	23.55	30.56
10	40	5.73	8.93
12	40	12.5	17.71
14	40	10.28	18
16	40	5.55	13.55
18	40	5.69	8.77
20	40	7.06	12.32

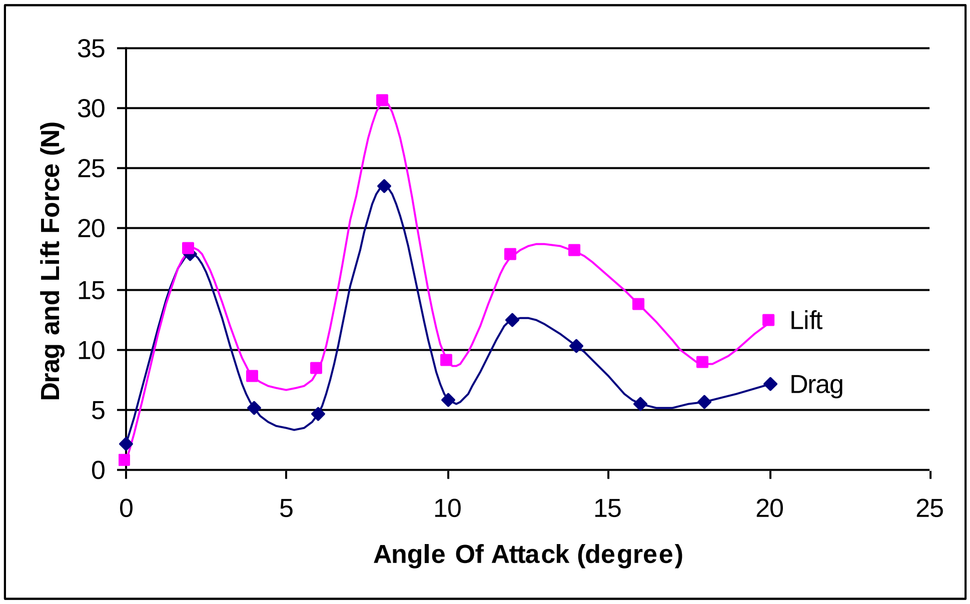


Figure 36: Angle of attack (degree) vs. Drag and Lift Force (N) for a single model at 40 m/s

Table 15: Experimental results for a single aerofoil model at 45 m/s

Angle of Attack (Degree)	Free Stream Velocity (m/s)	Drag Forces (N)	Lift Forces (N)
0	45	3.11	1.46
2	45	19.39	20.61
4	45	7.55	10.89
6	45	7.58	12.49
8	45	26.79	35.12
10	45	6.62	12.15
12	45	13.61	23.27
14	45	13.61	23.32
16	45	9.03	18.27
18	45	9.65	12.58
20	45	10.66	20.86

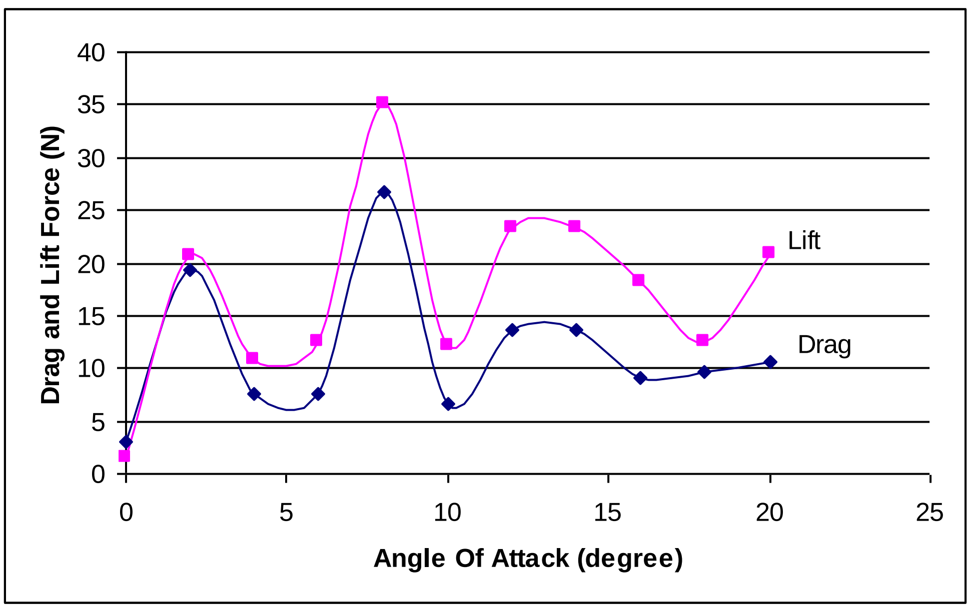


Figure 37: Angle of attack (degree) vs. Drag and Lift Force (N) for a single model at 45 m/s

From the experiments, it can be observed that the stall angle for this aerofoil model is in between 2^o and 3^o and it is lower than expected. For this aerofoil type (NACA0012) the expected stall angle is at 16^o. Stall angle is depends on Reynold's Number. The result on this lower stall angle is because the experiments are carried out at very low Reynold's Number (zone where drag and lift coefficient change with Reynold's Number). However the experiments also show that the drag and lift forces are increase as the free stream velocity increases. Thus, the results are applicable as the trends are similar to the real condition except for the numeric values.

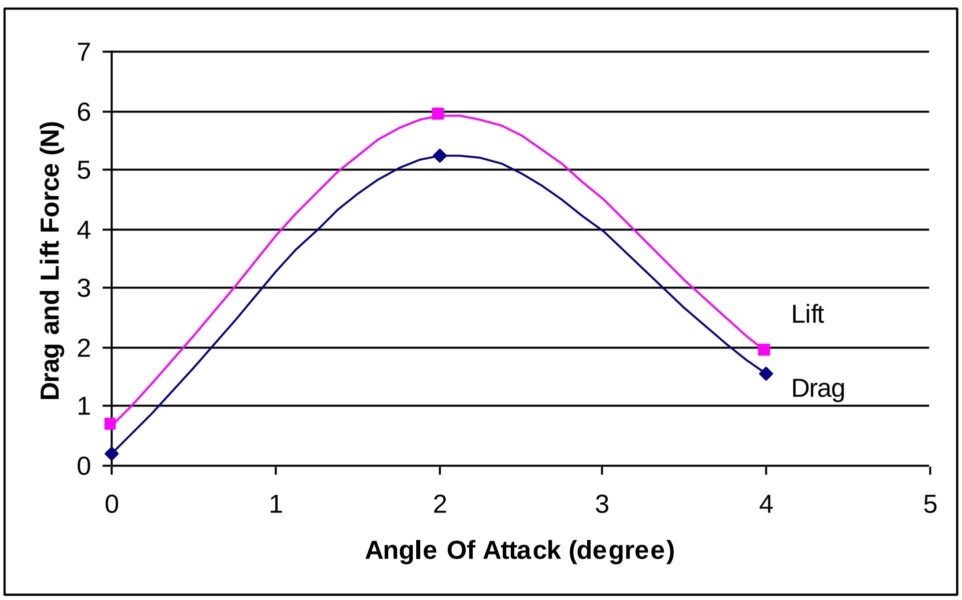


Figure 38: Stall angle for a single model at 10 m/s

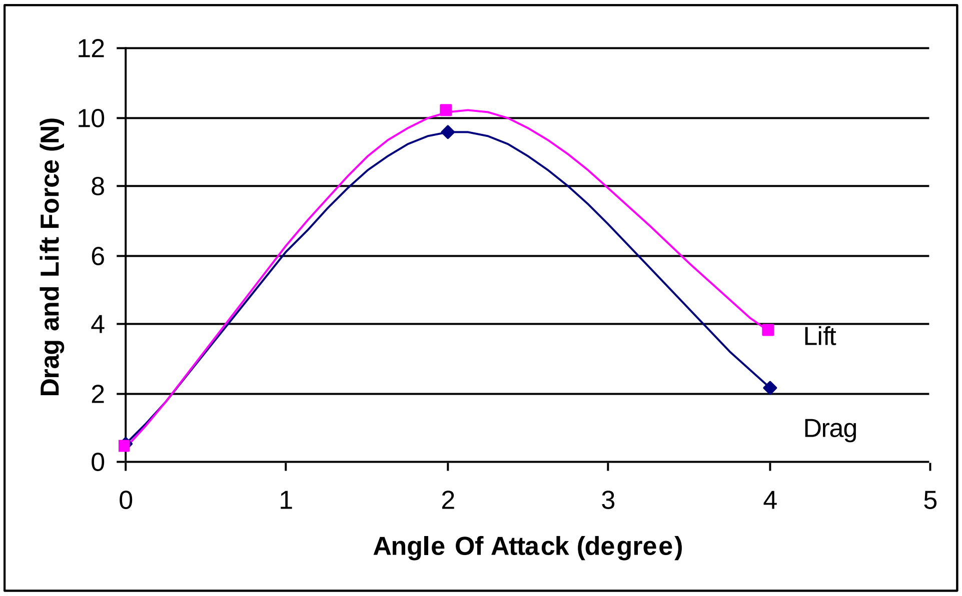


Figure 39: Stall angle for a single model at 20 m/s

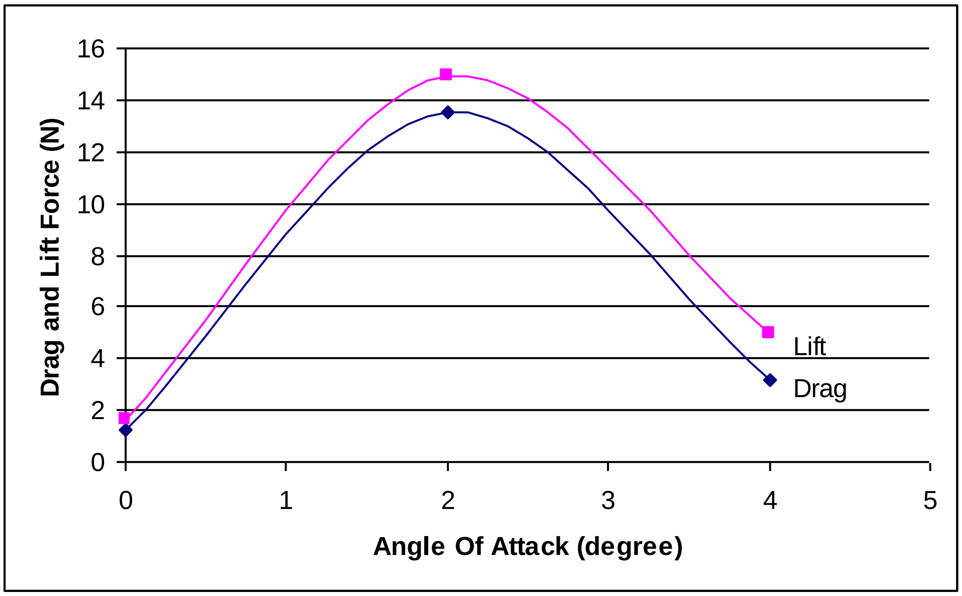


Figure 40: Stall angle for a single model at 30 m/s

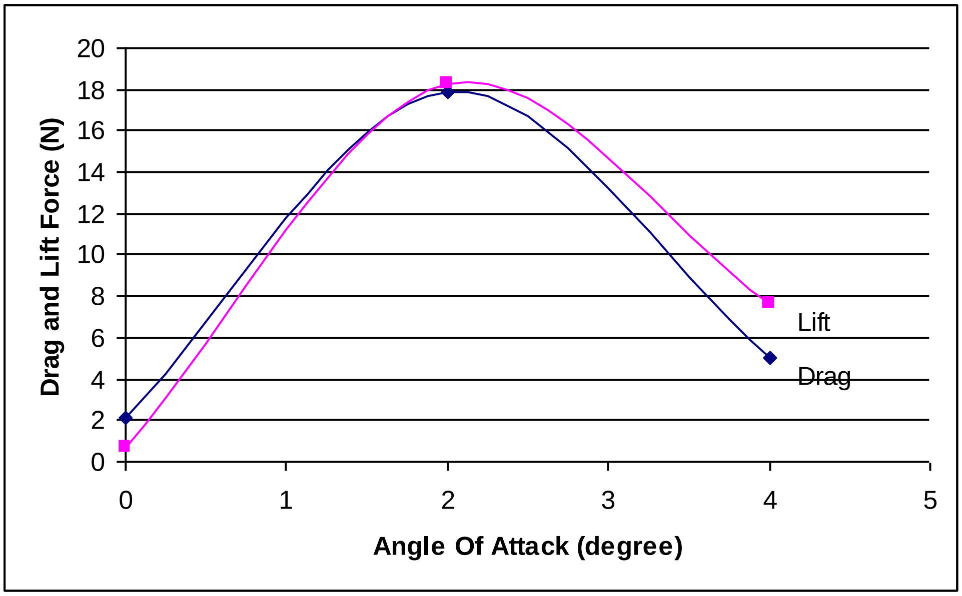


Figure 41: Stall angle for a single model at 40 m/s

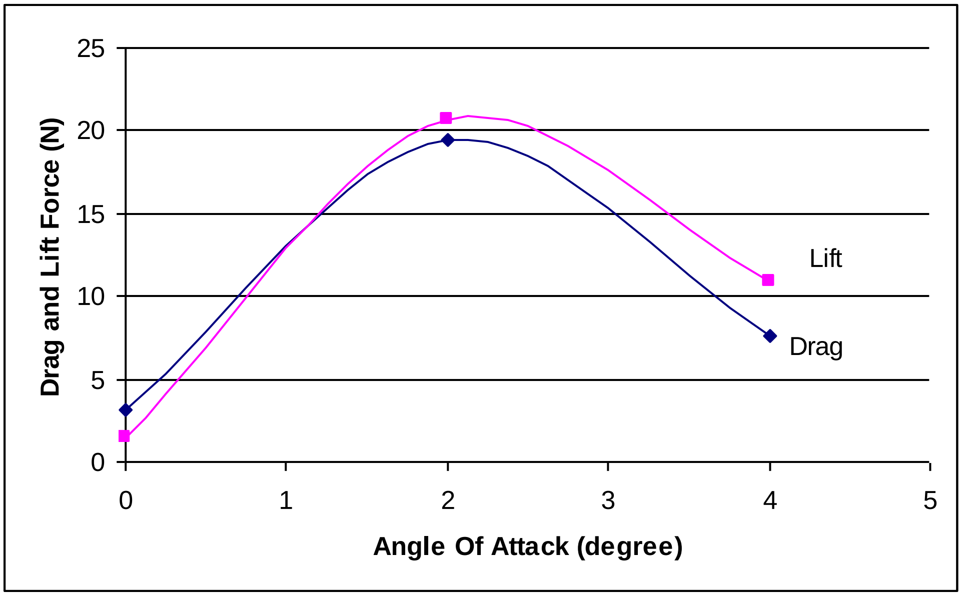


Figure 42: Stall angle for a single model at 45 m/s

6.10.2 Effect of Free stream Velocity and various angles of attack on the Drag and Lift Forces of two aerofoil models.

Two aerofoil models are tested at various free stream velocity (10 m/s, 20 m/s, 30 m/s, 40 m/s and 45 m/s) and different angle of attack (0^o , 2^o, 4^o, 6^o, 8^o, 10^o, 12^o, 14^o, 16^o, 18^o, 20^o). The distance between models is 20 cm (1 span).The objective is to define the characteristic of drag and lift forces at all the conditions as stated above.

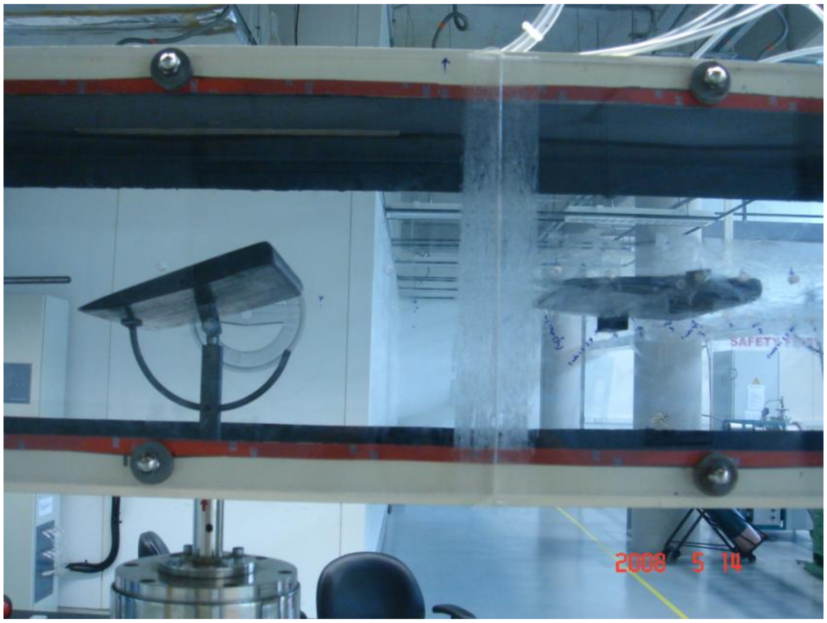


Figure 43: Testing 2 aerofoil models at 20 cm (1 span) in distance.

Table 16: Experimental results for 2 aerofoil models at 10 m/s

Angle of Attack (Degree)	Free Stream Velocity (m/s)	Drag Forces (N)	Lift Forces (N)
0	10	0.93	-2.67
2	10	1.22	-1.79
4	10	1.53	-0.33
6	10	4.1	2.28
8	10	1.16	0.37
10	10	1.08	4.64
12	10	1.56	0.36
14	10	1.46	0.11
16	10	1.04	0.8
18	10	0.2	1.99
20	10	0.47	1.46

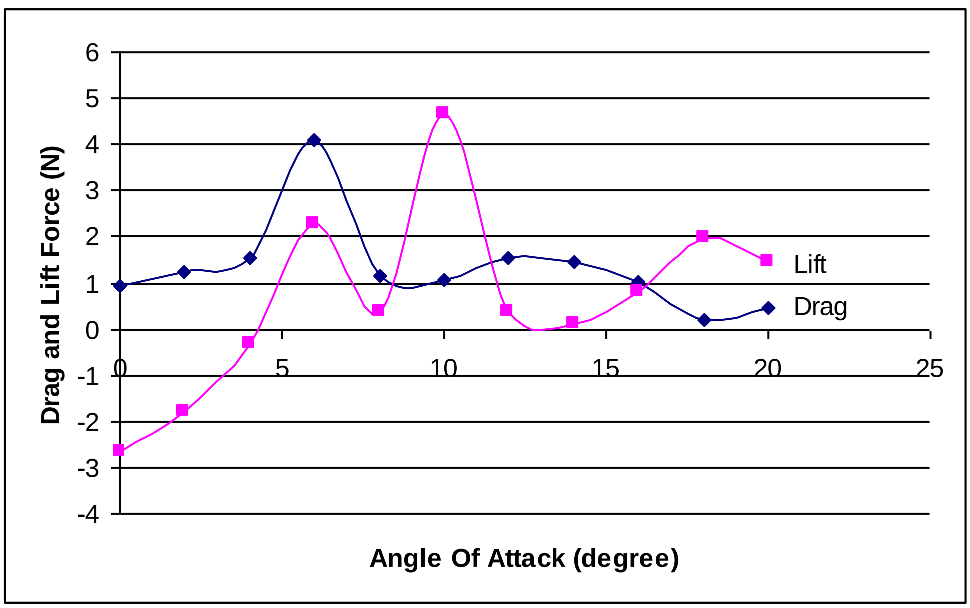


Figure 44: Angle of attack (degree) vs. Drag and Lift Force (N) for 2 aerofoil models at 10 m/s

Table 17: Experimental results for 2 aerofoil models at 20 m/s

Angle of Attack (Degree)	Free Stream Velocity (m/s)	Drag Forces (N)	Lift Forces (N)
0	20	2.39	-0.76
2	20	2.24	-1.36
4	20	2.14	0.93
6	20	8.95	8.55
8	20	3.11	2.62
10	20	2.13	5.75
12	20	2.25	1.38
14	20	2.84	0.93
16	20	0.22	4.83
18	20	1.32	4.88
20	20	1.92	4.02

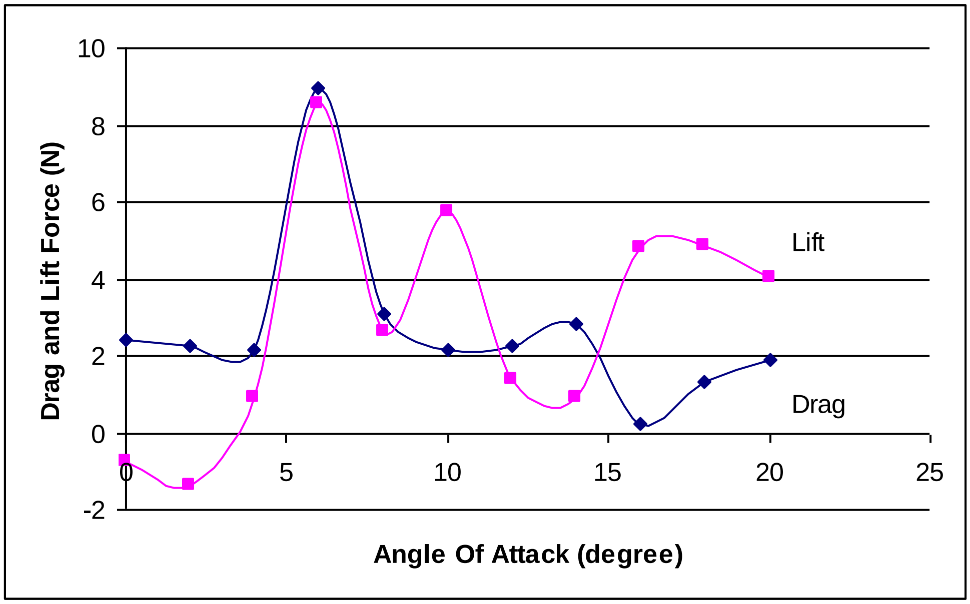


Figure 45: Angle of attack (degree) vs. Drag and Lift Force (N) for 2 aerofoil models at 20 m/s

Table 18: Experimental results for 2 aerofoil models at 30 m/s

Angle of Attack (Degree)	Free Stream Velocity (m/s)	Drag Forces (N)	Lift Forces (N)
0	30	3.12	0.12
2	30	3.83	0.6
4	30	1.33	5.57
6	30	13.5	13.41
8	30	7.98	6.81
10	30	5.27	4.99
12	30	2.73	2.22
14	30	4.52	1.55
16	30	0.82	7.77
18	30	3.3	7.54
20	30	2.91	8.4

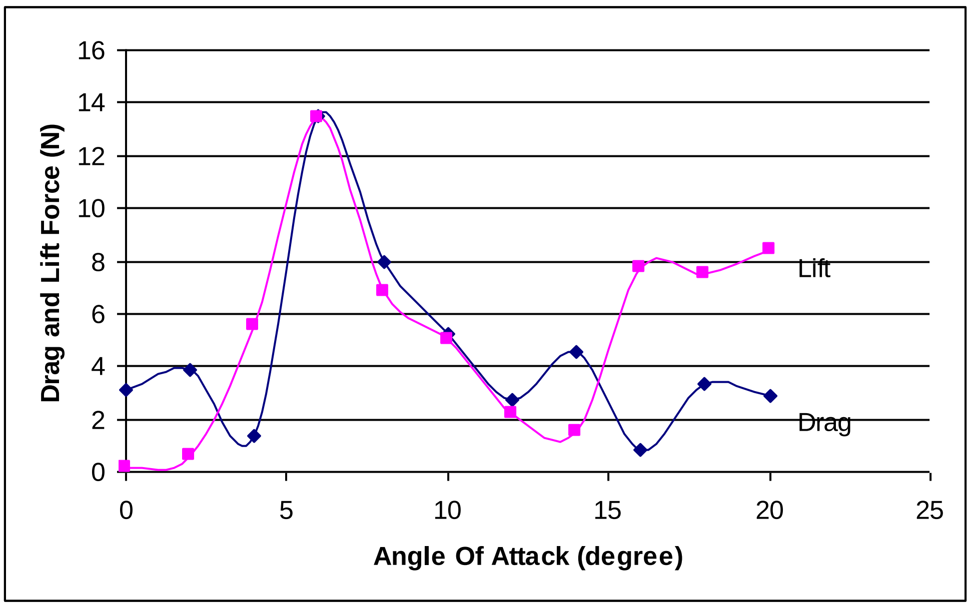


Figure 46: Angle of attack (degree) vs. Drag and Lift Force (N) for 2 aerofoil models at 30 m/s

Table 19: Experimental results for 2 aerofoil models at 40 m/s

Angle of Attack (Degree)	Free Stream Velocity (m/s)	Drag Forces (N)	Lift Forces (N)
0	40	2.13	0.66
2	40	17.85	18.25
4	40	5.06	7.61
6	40	4.69	8.24
8	40	23.55	30.56
10	40	5.73	8.93
12	40	12.5	17.71
14	40	10.28	18
16	40	5.55	13.55
18	40	5.69	8.77
20	40	7.06	12.32

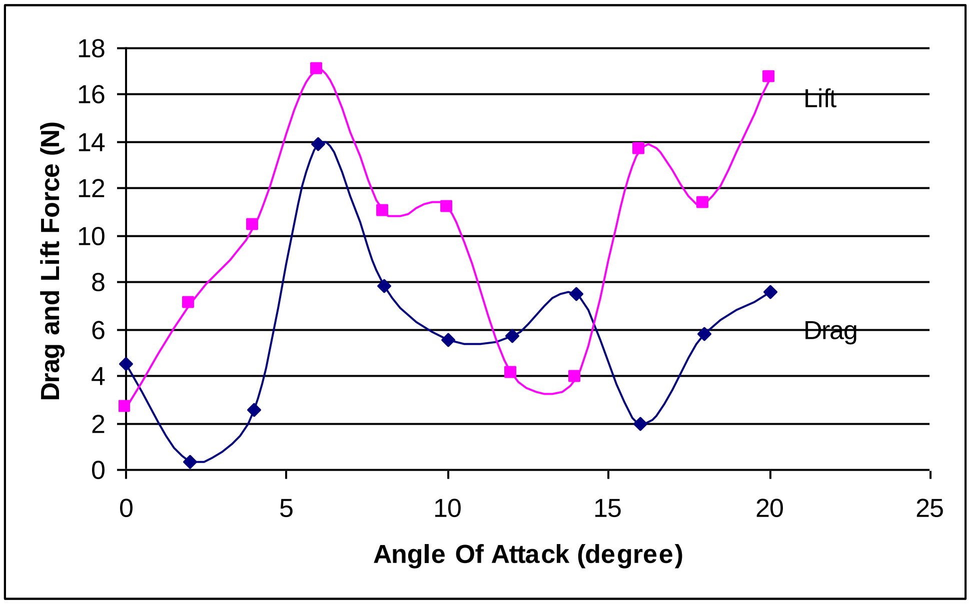


Figure 47: Angle of attack (degree) vs. Drag and Lift Force (N) for 2 aerofoil models at 40 m/s

Table 20: Experimental results for 2 aerofoil models at 45 m/s

Angle of Attack (Degree)	Free Stream Velocity (m/s)	Drag Forces (N)	Lift Forces (N)
0	45	5.47	3.07
2	45	3.16	7.42
4	45	5.51	14.72
6	45	16.25	19.25
8	45	9.8	14.27
10	45	7.41	18.59
12	45	8.12	6.08
14	45	11.8	9.75
16	45	5.6	19.88
18	45	10.13	17.6
20	45	10.72	22.77

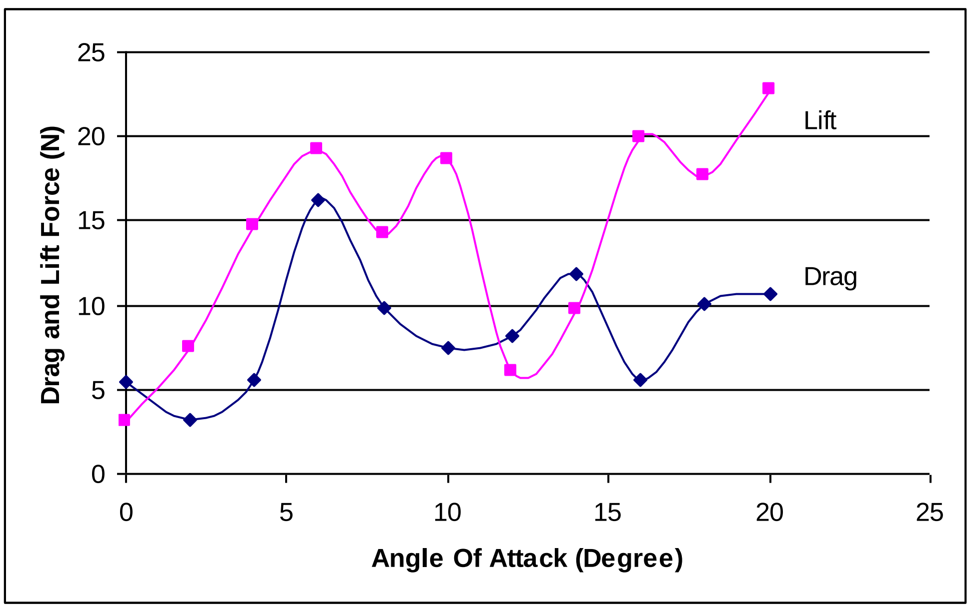


Figure 48: Angle of attack (degree) vs. Drag and Lift Force (N) for 2 aerofoil models at 45 m/s

From the experiments conducted, it shows that as an aerofoil model is located 20 cm (1 span) in front of the existing model, the stall angle of the existing model increases to 6^o. Based on these findings, the expectation is the stall angle will be also increasing in the real condition. During the experiments, it can be observed that the model that located at the back are oscillating and vibrating. This is one of the effects of the wake turbulence produced by the front aerofoil model.

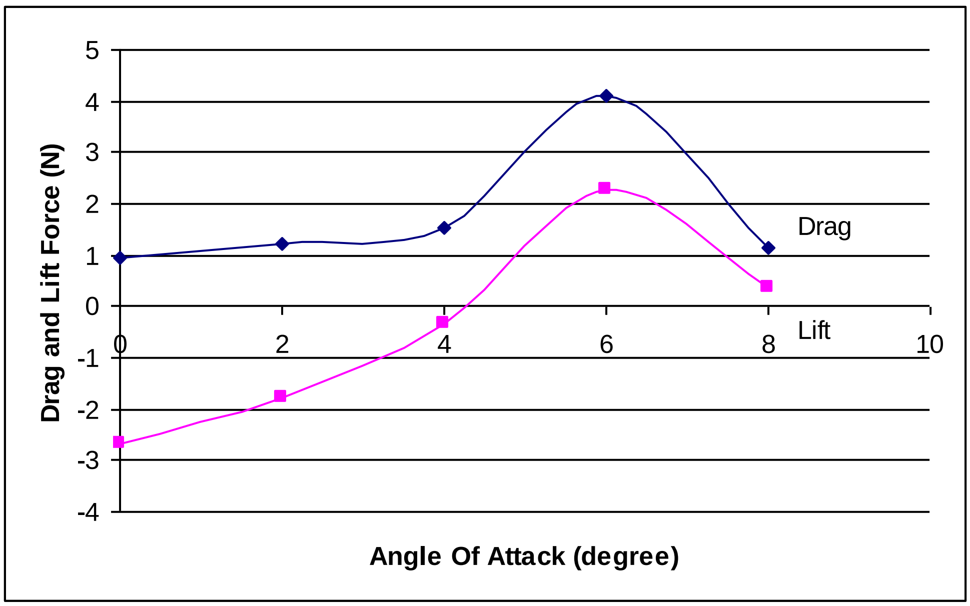


Figure 49: Stall angle for 2 aerofoil models at 10 m/s

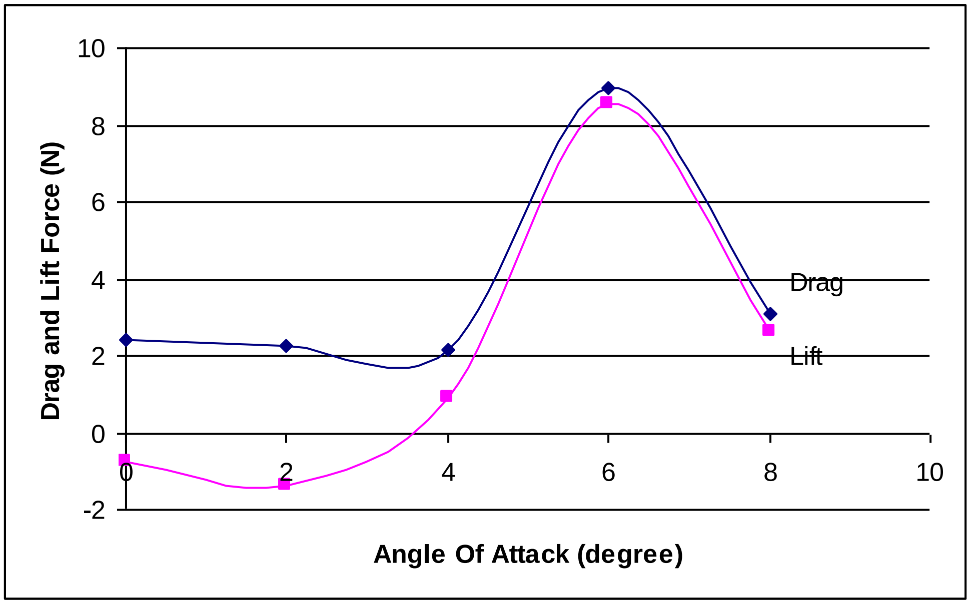


Figure 50: Stall angle for 2 aerofoil models at 20 m/s

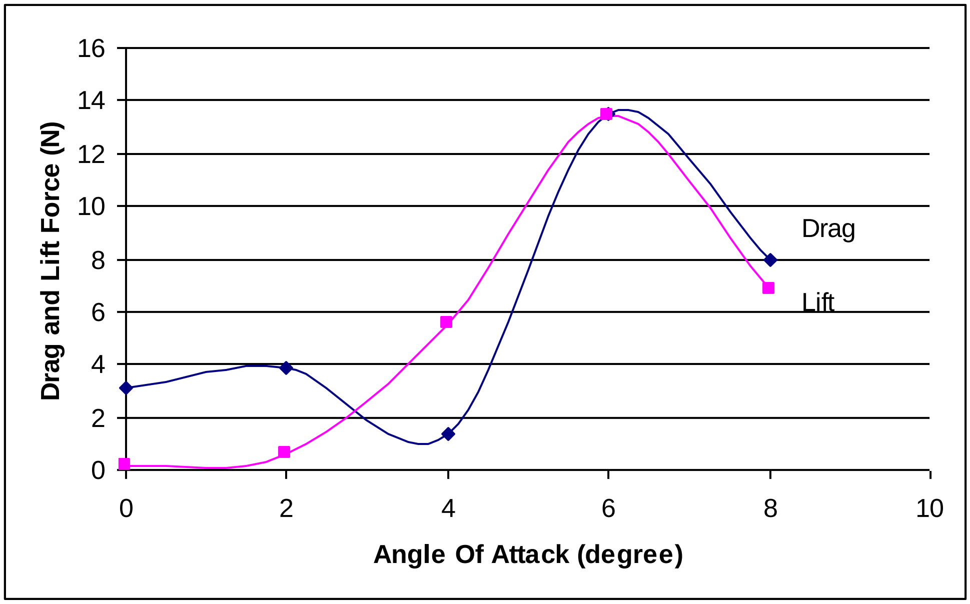


Figure 51: Stall angle for 2 aerofoil models at 30 m/s

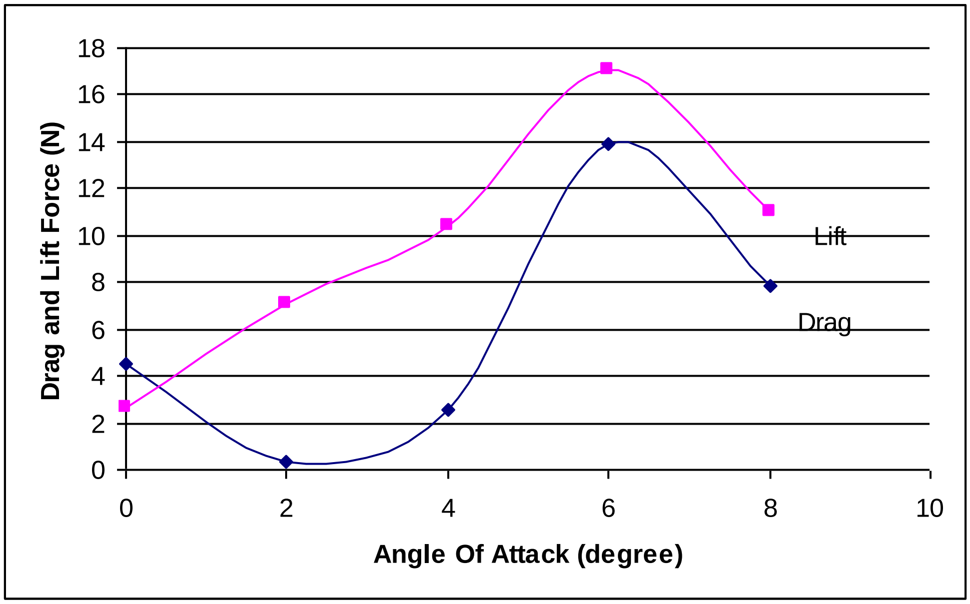


Figure 52: Stall angle for 2 aerofoil models at 40 m/s

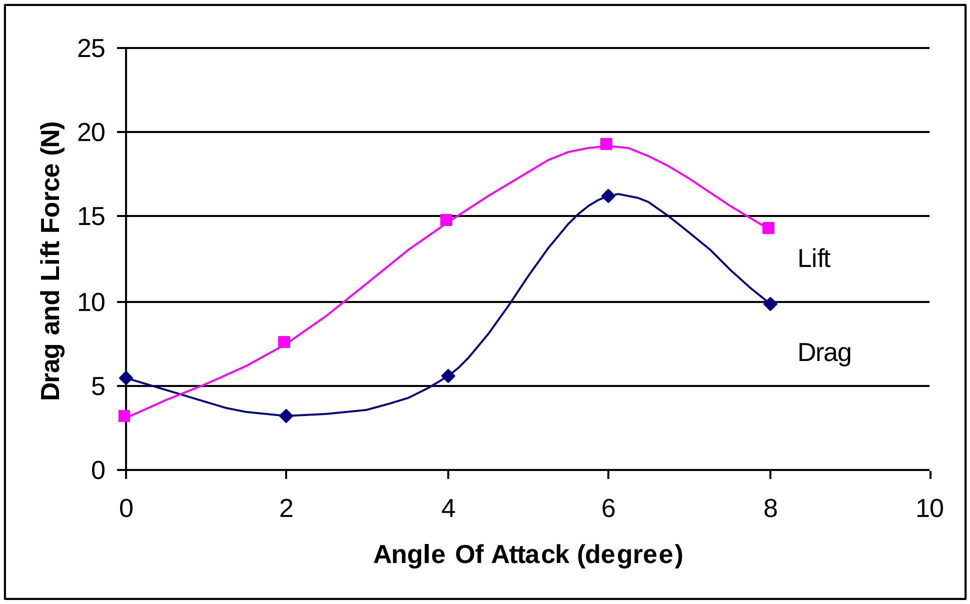


Figure 53: Stall angle for 2 aerofoil models at 45 m/s

CHAPTER 7
CONCLUSION

Through out completing this precious project, a few findings are carried out and meet the objective of the project. A single aerofoil model is tested in the wind tunnel to study the characteristics of the drag and lift forces produced and it is functioning as a reference to figure out the effects and changes that will be experienced when another aerofoil model is located in front of it at a certain distance. As a result, the stall angle of the model is increased from 2^o to 6^o. During the experiments, it can be noticed that the aerofoil model at the back is vibrating and oscillating due to the wake turbulence produced by front aerofoil model. The findings of this project are significance with the case studies of real life situation or condition where many fatal aircraft accident occurred due to the effect of the wake turbulence. The results from the project are very applicable in future especially to prevent or al least reduced the aircraft accident due to wake turbulence.

CHAPTER 8
RECOMMENDATION

A few recommendations are suggested for improvement of this project on study the effect of wake of an aircraft on a following aircraft. To achieve the desire results it would be better if the models are tested in the high speed or supersonic wind tunnel so that the models can be tested at real condition. To get more accurate and precise results, the models are recommended to be tested at variable distances such as 1 span, 2 spans and more.

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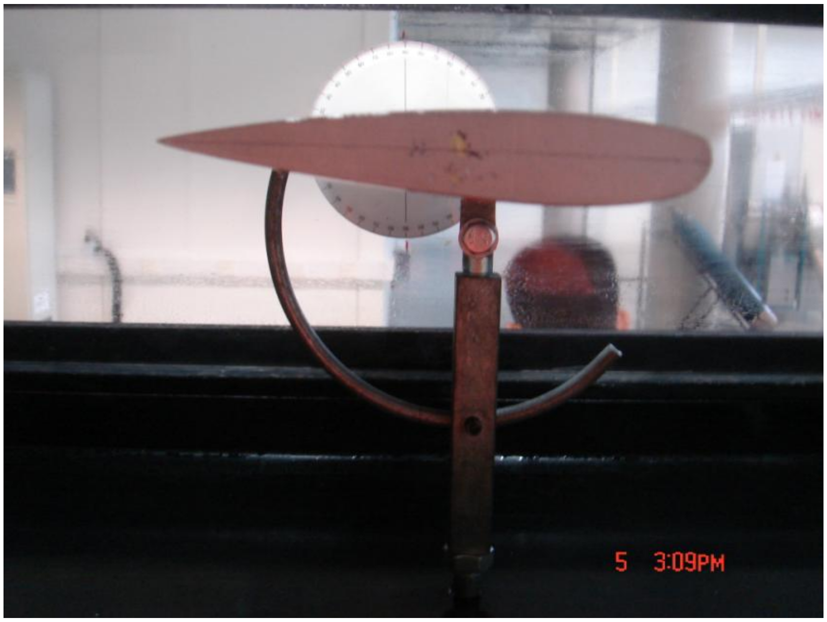
APPENDIX I

WT04 Sub-Sonic Wind Tunnel

Test Section

Test Section

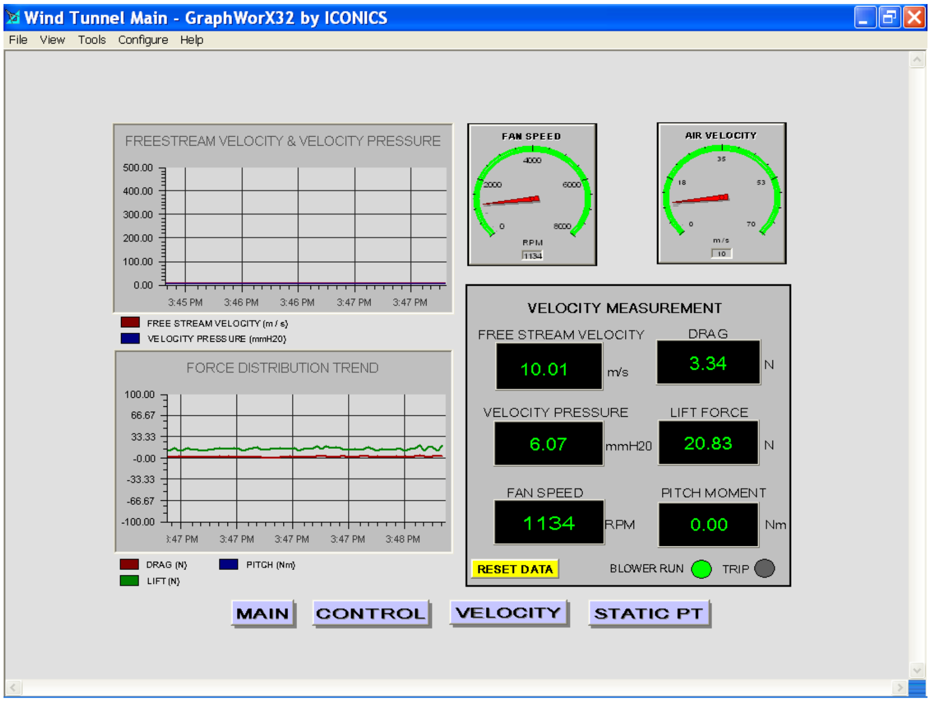
Top view of symmetrical aerofoil model



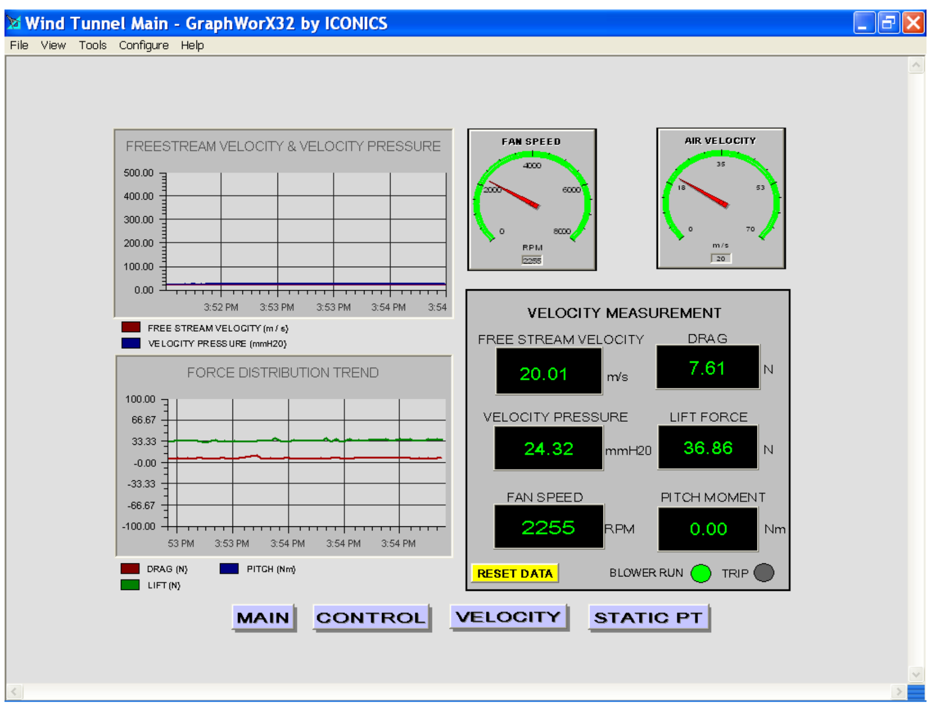
Side view of symmetrical aerofoil model

APPENDIX II

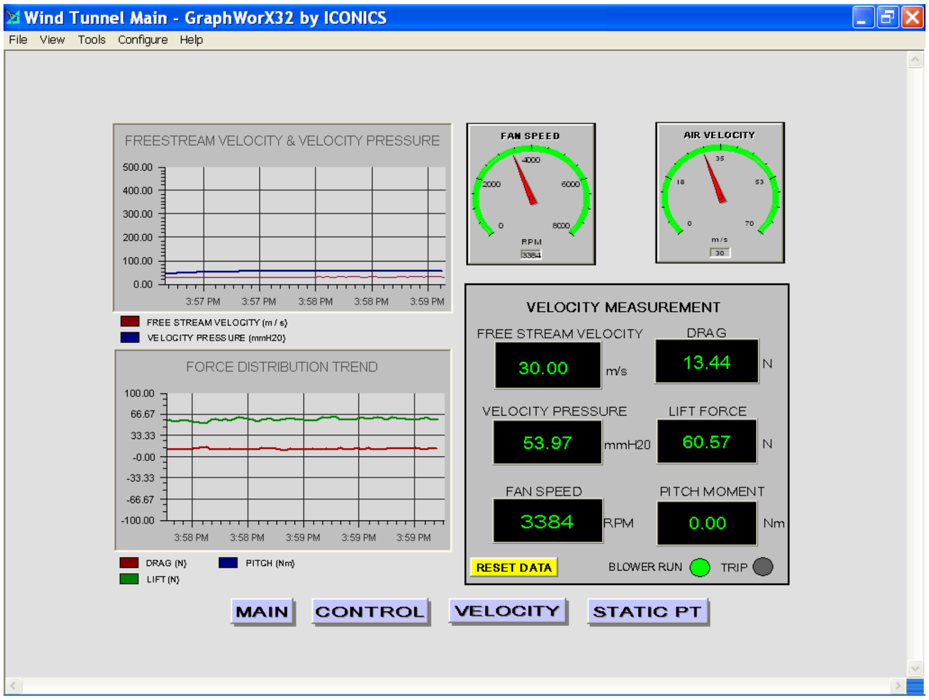
Experimental Results Sensitivity Results of Reynold's Number



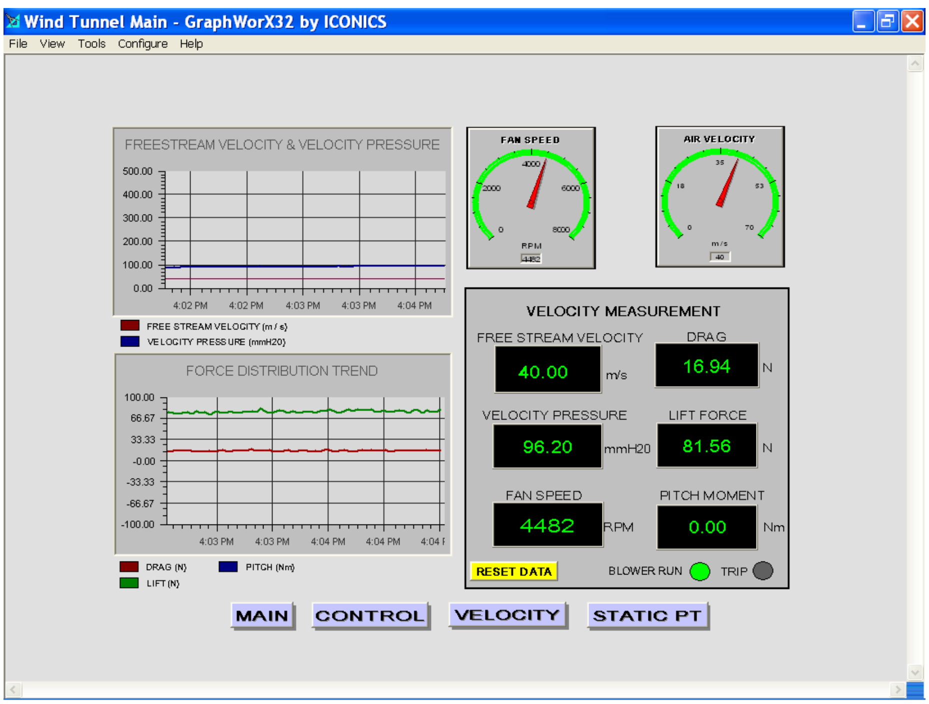
Free Stream Velocity at 10 m/s



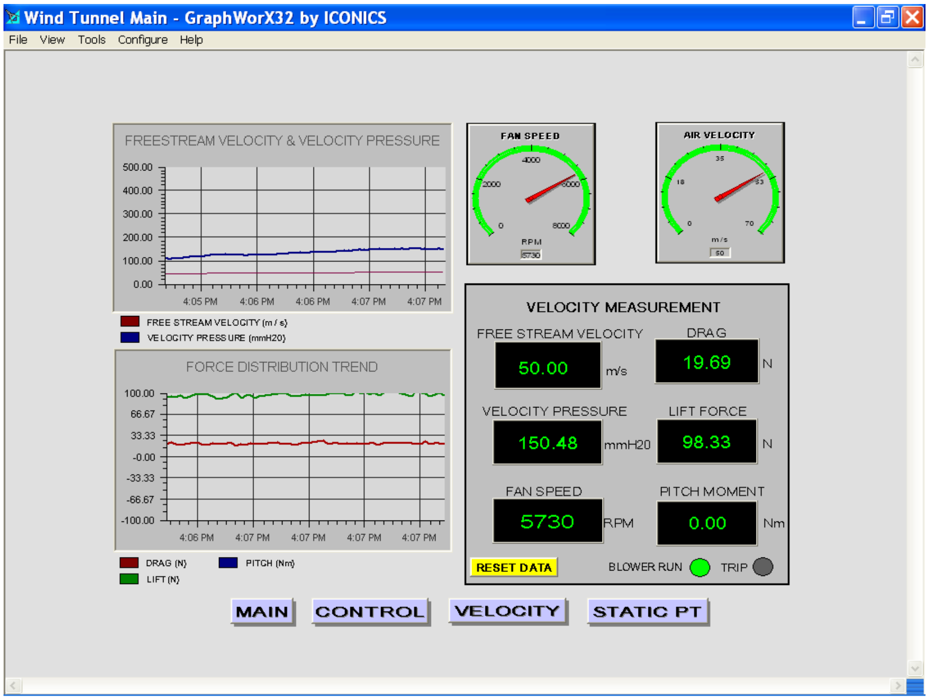
Free Stream Velocity at 20 m/s



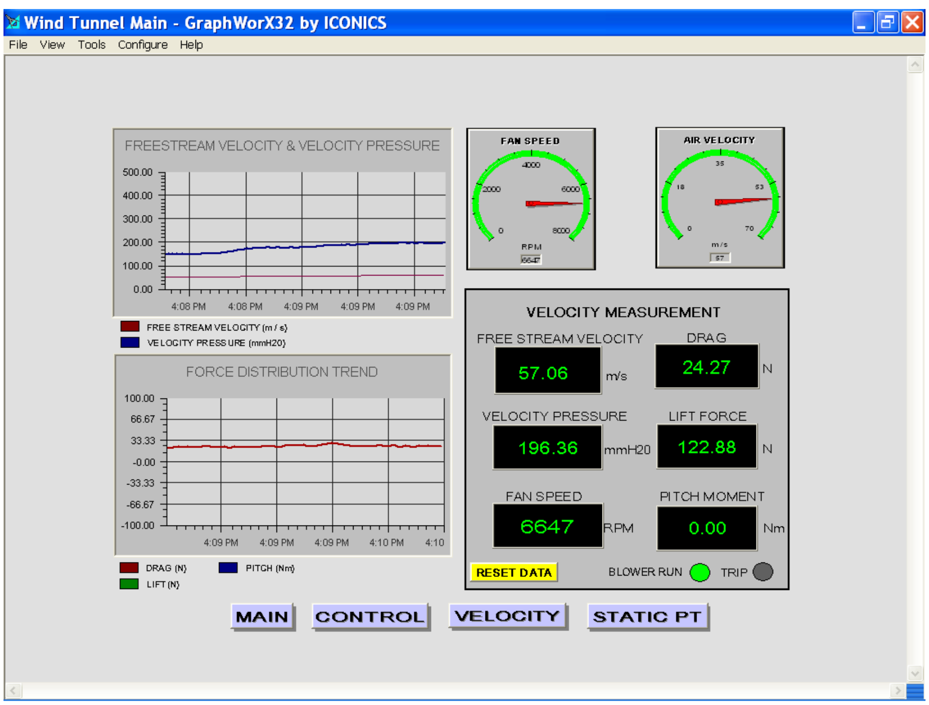
Free Stream Velocity at 30 m/s



Free Stream Velocity at 40 m/s



Free Stream Velocity at 50 m/s



Free Stream Velocity at 57 m/s (maximum)

APPENDIX III

Fabrication process

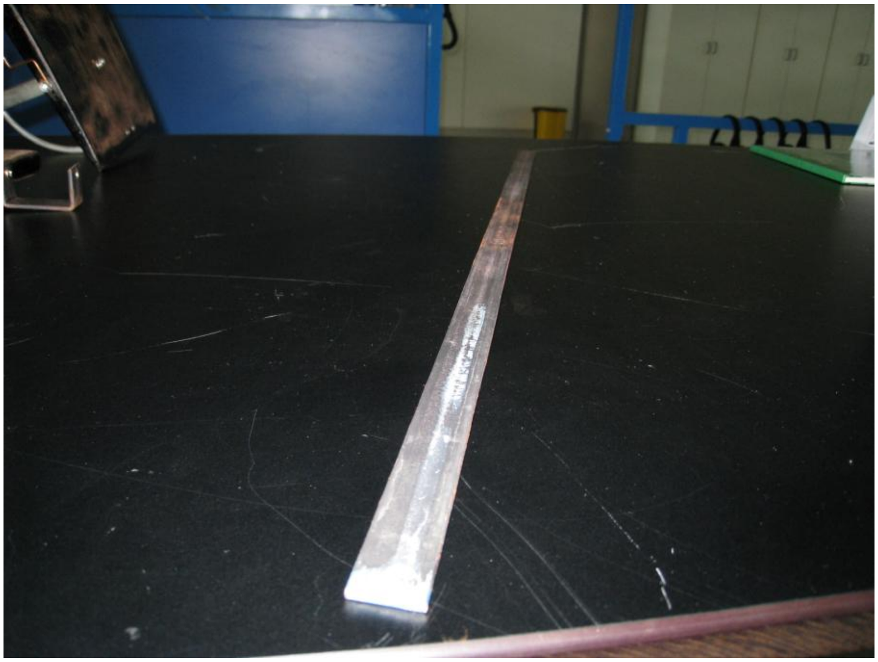


Plate bar used in the fabrication of aerofoil support.

Nuts used in fabrication process

Screws used in fabrication process.