

CNC Manufacturing of NACA 4412 Wing Sections for Wind Tunnel Test

by

Mohd Nuh Aizat B Mohd Daut

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

JANUARY 2008

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

CNC Manufacturing of NACA 4412 Wing Sections for Wind Tunnel Test

by

Mohd Nuh Aizat B Mohd Daut

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

(AP Dr Hussain H Al-Kayiem)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2008

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHD NUH AIZAT B MOHD DAUT

ABSTRACT

The manufacture of airfoil sections for experimental purposes for a specific profile is very expensive and time consuming. Due to the complexity of its contour and the need to have a good surface finish of the final model, airfoil model for wing tunnel test need to be manufactured precisely. This project is on manufacturing of NACA 4412 airfoil wing section for wind tunnel test. By using Computer Aided Manufacturing (CAD) and Computer Aided Manufacturing (CAM) procedure, a series of coordinates according to the NACA 4412 profile will need to be input to the machine.

This method is fast and also accurate thus, allowing the time and manufacturing cost to be substantially reduced, at the same time improving the accuracy and quality of the model.

The fabricated model was installed in the test section of low speed wind tunnel and connected to the 3 weight balance instruments. Series of test have been conducted and the characteristics of the airfoil based on the drag, lift and pitching moment coefficients are presented.

ACKNOWLEDGEMENT

First and foremost, Alhamdulillah and I would like to thank God Almighty, Allah S.W.T for His consent I have succeeded to complete this dissertation of Final year Project (FYP) in Universiti Teknologi Petronas (UTP) in order to complete my partial fulfilment of the requirement for the Bachelor Of Engineering (Hons) (Mechanical Engineering).

My special thanks go to my supervisor, Assoc. Prof. Dr Husain H Al-Kayiem for his supervision and his confidence in me through out this project. Also for his technical advices, information, and printed materials as well.

Also my great fullness to Lab Technicians, Mr. Hafiz and Mr. Jani for their comments, advices and technical assistance. Without their help, this project would not be success.

Last but not least, for those who are contributed directly and indirectly to the success of this project, thank you. Thank you again and may god bless all of you.

TABLE OF CONTENTS

Certification of Approval	i
Certification of Originality	ii
Abstract	iii
Acknowledgement	iv
1.0 Introduction	1
1.1 <i>Problem Statement</i>	1
1.2 <i>Significance of the Study</i>	1
1.3 <i>Objectives</i>	2
1.4 <i>Scope of Study</i>	2
2.0 Literature Review	4
2.1 <i>Manufacturing of Experimental Model</i>	4
2.2 <i>Materials of the Model</i>	5
3.0 Theory of Airfoils	6
3.1 <i>General Equation of NACA Airfoil</i>	6
4.0 Methodology	8
4.1 <i>Airfoil Mechaning</i>	8
4.1.1 Blockage of the Model	8
4.1.2 Familiarization with CompuFoil code	9
4.1.3 Generating the Coordinates of NACA 4412 using CompuFoil code.	9
4.2 <i>Scheduling of Work</i>	10
4.3 <i>The Gantt Chart</i>	12

5.0 Manufacturing Procedure and Test Results	13
5.1 <i>Work Completed</i>	
5.1.1 Gather Background Information	14
5.1.1.1 Measurement of the Chord Length	14
5.1.1.2 The Blockage of the Model	14
5.1.2 Comparing the coordinates	15
5.1.3 Computer Aided Design (CAD)	15
5.1.4 Manufacturing of Sample	16
5.2 <i>Manufacturing of the Final Model</i>	21
5.3 <i>Accuracy Checking</i>	22
5.4 <i>Static Test</i>	23
5.5 <i>Wind Tunnel Test</i>	24
5.6 <i>Problems encountered</i>	27
5.6.1 Bit Depth	27
5.6.2 Wind Tunnel Test Section	27
6.0 Conclusion	29
7.0 Recommendations	30
8.0 List of References	31
9.0 List of Figures	
Figure 3.1: Cross Section of Airfoil	6
Figure 4.1: Methodology Flowchart	11
Figure 4.2: Gantt Chart	12
Figure 5.1: Computer Aided Design	16
Figure 5.2: Manufacturing Process	17
Figure 5.3: Surface Profile in Mastercam	18
Figure 5.4: Regen Tool Path	18
Figure 5.5: Regen Drill	19
Figure 5.6: Generate Tool Path	19
Figure 5.7: Job Setup	20
Figure 5.8: NACA 4412 Model in Sections	20
Figure 5.9: Final Assembly	21
Figure 5.10: Definition of Surface Roughness	22
Figure 5.11: Initial Sections Assembly	28
Figure 5.12: Final Sections Assembly	28

Figure A3.1: -4° Angle of Attack	39
Figure A3.2: 0° Angle of Attack	39
Figure A3.3: 4° Angle of Attack	40
Figure A3.4: 8° Angle of Attack	40
Figure A3.5: 12° Angle of Attack	41
Figure A3.6: 16° Angle of Attack	41
Figure A3.7: 20° Angle of Attack	42
Figure A3.8: 22.5° Angle of Attack	42
Figure A4.1: Section 1	43
Figure A4.2: Section 2	43
Figure A4.3: Section 3	44
Figure A4.4: Section 4	44
Figure A4.5: Section 5	45
Figure A4.6: Section 6	45
Figure A5.1: Section 1	46
Figure A5.2: Section 2	46
Figure A5.3: Section 3	47
Figure A5.4: Section 4	47
Figure A5.5: Section 5	48
Figure A5.6: Section 6	48

10.0 List of Charts

Chart 5.1: C_D vs. Angle of Attack	25
Chart 5.2: C_L vs. Angle of Attack	25
Chart 5.3: C_M vs. Angle of Attack	26
Chart 5.4: C_D, C_L, and C_M vs. Angle of Attack	26

11.0 List of Table

Table 5.1: Surface Roughness	23
Table 5.2: Values of F_D, F_L, M, C_D, C_L and C_M at Various Angle of Attack	24

12.0 Appendices

<i>Appendix 1</i>	33
<i>Appendix 2</i>	36
<i>Appendix 3</i>	39
<i>Appendix 4</i>	43
<i>Appendix 5</i>	46

CHAPTER 1: INTRODUCTION

The main focus of this project is to manufacture a NACA 4412 airfoil model using CNC machine. During the initial stage, the airfoil surface is required by generating the required profile either by using a computer program or software. As for the manufacturing process, CNC machine is recognized as the basis on which modern computer aided manufacturing technology has been built (7), and it is of our interest to use CNC machining to manufacture this wing section.

1.1 Problem Statement

Universiti Teknologi Petronas (UTP) has its own small scale of wind tunnel. The test section size of the wind tunnel is 300mm x 300mm (90,000mm²) in area. Currently, the wind tunnel has a symmetrical airfoil model made of steel for demonstrations purposes. But it has yet to have a proper airfoil model for any research work.

For supporting the previous numerical analysis, there is a need to manufacture a suitable airfoil model to be used for experimental validation test of NACA 4412.

The design must take into consideration many manufacturing aspect such as suitability of the design with machining technique, type of material, cost and time.

1.2 Significance of the Study

Design and fabrication of experimental models for aerodynamic wind tunnel test is a field of interest by the researchers. The accuracy of the shape is of high importance in experimentations. In the present work, a procedure is established to use the CNC to design the NACA 4412 model. This procedure can be adopted by other researchers to fabricate their aerodynamic models.

1.3 Objectives

The primary objective of this project is to manufacture a high lift wing in this case NACA 4412 for a wind tunnel test using the available CNC machines in UTP. With the manufacturing of this airfoil model:

- a. It is hope that a procedure can be adopted to manufacture the experimental models using the CNC machine and the other facilities in the manufacturing lab in the university for further research.
- b. Preliminary wind tunnel test of the produced model to evaluate the aerodynamic characteristics of the 2-D airfoil section.

1.4 Scope of Study

a. Literature research

The scope includes thorough literature research for information gathering to understand on:

- a. how to configure the required ordinates for the airfoil profile, and
- b. how to select the suitable materials to be used for the CNC machining of the final product, and
- c. how to select the suitable dimension to meet wind tunnel experimental investigation.

b. CNC manufacturing processes

The study of these processes is extremely important to reduce the possibilities of modification of the designs due to operational constraints. The understanding of the

fundamental CNC manufacturing processes is essential to produce the wing section as per design and prevent any defects formation during the fabrication.

c. Aerodynamic characteristics

It is hope that investigation on the aerodynamic characteristics of a high lift wing can be done in UTP. These characteristics include lift coefficient (C_L), drag coefficient (C_D) and also the pitching coefficient. Besides that, attempt to measure the pressure distributions on the airfoil surface could also be carried out.

CHAPTER 2: LITERATURE REVIEW

In spite of the advances in manufacturing processes, the manufacture of experimental wing models of a specialized airfoil section is still a major obstacle in the path of aeronautical research. Even with the wide range of Computer Numerical Control (CNC) machines, getting the end result of a NACA airfoil is still a challenging job.

2.1 Manufacturing of Experimental Model

The conventional method of obtaining the profile of an airfoil section is by graphing the surface points or ordinates. This procedure consists of locating the ordinates on graph paper and then connecting these points by a smooth curve to obtain the airfoil profile. The ordinates are generally available in tabulated form, along the chord length for several sections of the chord. The ordinates of most common airfoil sections are given in several references **(1, 3-5)** as a standard tabulation consisting of 18 points for each surface (that is 18 stations). Recently, computer plotting facilities have enabled the profile to be drawn with better accuracy than that achieved by the manual plotting procedure.

A typical manufacturing procedure for experimental wing sections using unsophisticated machine tools describes how airfoil section ribs would be produced by hand using a template cut from the plotted profile, connected by spars and finally covered with metal sheets. The result is rigid structure of complex construction and limited surface accuracy. Previous research has **(4, 5)** shown that the surface contour is vitally important to the airflow characteristics of the airfoil, and effects the measurable aerodynamic characteristics of the standard airfoil section.

Recently, computer plotting facilities have enabled the profile to be drawn with better accuracy than that achieved manual plotting procedure **(1, 6)**.

An airfoil profile can also be generated using a computer program by just inputting type of NACA (4 digits, 5 digits or 6 digits), percentage of the camber, percentage of camber

position and its thickness. Example of this soft ware is CompuFoil **(10)** which can be used to generate the contour of the airfoil.

The advantages of using CNC machines are:

- a. Good and precise surface finish that requires little or no secondary finishing.
- b. CNC machines are programmed with a design which can then be manufactured hundreds or even thousands of times. Each manufactured product will be exactly the same.
- c. Less skilled/trained people can operate CNCs unlike manual lathes / milling machines etc. which need skilled engineers.
- d. Handle a wider variety of materials than other rapid prototyping systems.

2.2 Materials of the Model

An important consideration when evaluating technologies for rapid prototyping is their ability to handle desired materials. Most of the newer rapid prototyping machines offer only a limited range of materials, and on a cost-per-pound basis, these materials cannot compare favorably to stock materials used on CNC machines **(8)**.

CNC machines come in all shapes and sizes, but even the smallest desktop machines can handle a wider variety of materials than other rapid prototyping systems. Machining centers **(9)** can be used to machine such materials as plastics, ceramics, woods, waxes and, of course, many different types of ferrous and nonferrous metals. In many cases, metal chips produced during machining may have value as recyclable scrap. With other rapid prototyping systems, secondary manufacturing processes are available that can be used to form prototypes in other materials. These additional steps, however, add time and cost to the project. Previous project **(1)**, the manufacturing process of an airfoil model was done using Perspex sheet. The process commenced by cutting rough blanks of Perspex sheet before the machining process begins. Further contacts will be attempted to track the best material for this applications.

CHAPTER 3: THEORY OF AIRFOILS

NACA four digit airfoil section families are designated by four digits:

1st is the maximum value of the camber line ordinate, expressed as a percentage of the chord length.

2nd is the distance from the leading edge to the location of the maximum camber in terms of one-tenth proportion of the chord.

3rd and 4th is the maximum section thickness as a percentage of the chord length.

Then, the NACA 4412 airfoil section is defined by

$$m = 0.04$$

$$p = 0.4$$

$$t_{\max} = 0.12$$

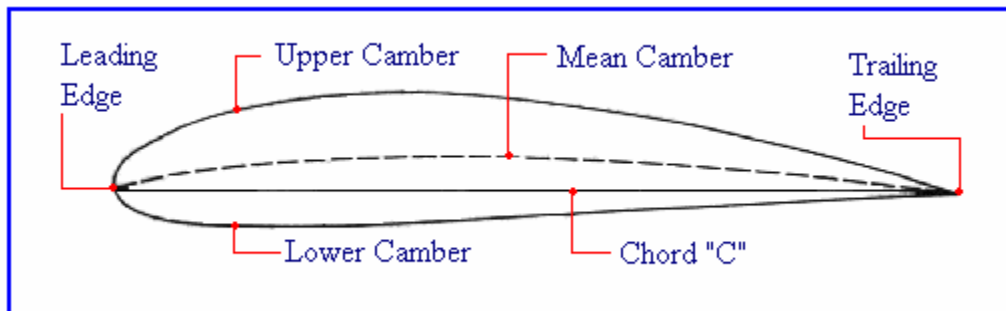


Figure 3.1: Cross Section of an Airfoil

3.1 General Equation of NACA Airfoil

The NACA airfoil section families are defined by a general equation in terms of ordinate (y) at the position x , where x is the proportional distance along the chord length c of the airfoil section:

$$\pm Y = a_0 \sqrt{x} + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4$$

It is then followed by modification to introduce a circular shape to the nose, where the leading edge radius is defined as the fraction of the cord length as:

$$R_n = \frac{1}{2} \{(t_{\max}/0.2)(a_0)\}^2$$

After gathering all the required equations, the airfoil points will be generated using a computer program.

It will then be followed by the manufacturing process using CNC machine. Modification on the shape of the airfoil is expected due to the fabrication constraints and the modification will then be analyzed before it is being implemented.

The final stage involved the assembly of the wing sections on the wind tunnel.

CHAPTER 4: METHODOLOGY

The method used in this project is fast and accurate. Thus, enabling the time and cost of manufacture to be reduced and at the same time, ensure the accuracy and quality of the model.

4.1 Airfoil Machining

The project will begin with the research on the suitable of the size of the wing section model accordance to the wind tunnel cross sectional area. The ratio between the wing section model to the wind tunnel area must be less than 20% in order to reduce the blockage affect.

$$\frac{A_{\text{airfoil model}}}{A_{\text{inlet}}} \times 100\%$$

4.1.1 Blockage of the Model

In a wind tunnel test, especially in determining the aerodynamic characteristics of a high lift wind, the test section area blockage must be less than 20%. Thus, for this project a set of calculation of the blockage percentage need to be done according to the different angle of attack. The higher the angle of attack, the higher the blockage area will be.

Blockage percentage will be calculated in two situations:

- i. Angle of attack, $\alpha=0$
- ii. Maximum angle of attack, $\alpha_{\text{max}}=30^{\circ}$

Applying the formula,

% Blockage = (A model/A section) * 100%
--

4.1.2 Familiarization with CompuFoil code

The conventional procedure to obtain the profile of an airfoil section was by drawing graphically the (x,y) surface points (ordinates) and connecting them by a smooth curve. A detailed description of this procedure is given by Malkin (1971). Nowadays, computer plotting facilities have enabled the profile to be drawn with better accuracy using the tabulated (x,y) values.

The software that I am using to generate the NACA 4412 airfoil is CompuFoil. It is a complete airfoil and modification system. CompuFoil is currently in use by over 1000 demanding modelers, several major model manufacturers, N.A.S.A., and universities.

CompuFoil Professional is a powerful airfoil plotting and editing software available. It can produce full sets of ribs in straight taper, elliptical, or modified elliptical planforms for built up wings, or templates for foam wings. This includes sheeting compensation, wire kerf compensation, leading edges, v-notches, building jig holes, spar slots, etc. CompuFoil consist of many module, to name a few; Base CompuFoil program, Modification Module, Generate Module, NACA. Generator and etc. For this project, I will only require to use the NACA Generator. By using this module, airfoil generator can produce four, five or six digit NACA airfoils.

Since I have no experience using the software, time was needed for me to get familiar with its tool bars and functions that are available. In doing this, I have to read the tutorial that was included with the software and a lot of computer time in understanding its capabilities in generating the required airfoil profile.

4.1.3 Generating the Coordinates of NACA 4412 using CompuFoil code

From this program, I were able to generate the required profile and able to get the standard ordinates for the profile. The standard ordinates means, the ordinates (x,y) are

achieved without taking the cord length into considerations. Thus, I have to manually multiply the ordinates (x,y) with the cord dimension, 10.5cm.

The steps involve in generating the NACA 4412 profile and coordinates are as follow:

- a. Select Generate [NACA Airfoils]
- b. NACA Generators dialog window will pop out. Select the airfoil profile to be used (4 digit, 5 digit or 6 digit).
- c. Select the percentage camber, camber position and maximum thickness.
- d. Click 'Use'.
- e. The complete profile of the airfoil will be generated.
- f. Select [Airfoil / View Airfoil Coordinates].
- g. A set of raw coordinates will be shown.

4.2 Scheduling of the work.

This project involves 3 main phases which are, the designing phase, manufacturing phase and testing phase. In the design phase, the processes include information gathering, definition of airfoil equation and also highlighting the design constraints. This will be followed by generating the upper and lower surface of the airfoil profile. As for the manufacturing phase, steps include, programming the CNC machine using Mastercam as well as preparing the raw material. Testing phase will be inclusive of static test on the final product and mounting it on the wind tunnel. The scheduling of this project can be further illustrated by the flowchart below.

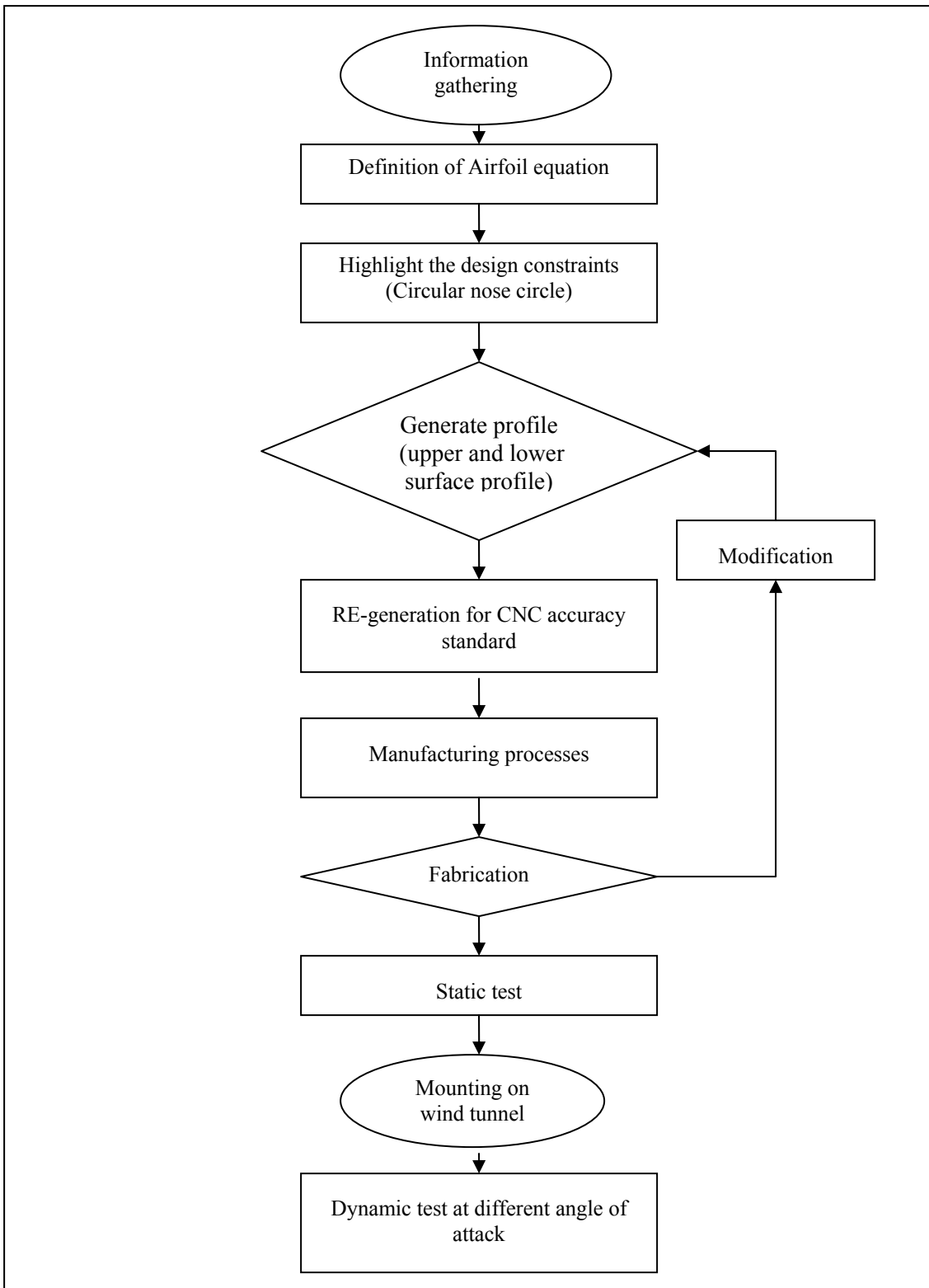


Figure 4.1: Methodology Flowchart

4.3 The Gantt Chart

The progress of my project can be illustrated by the Gantt chart below. Currently, I have completed the first phase of my project work for the manufacturing of the final product, which includes the programming of the airfoil surface into Mastercam for the CNC machine and also preparation of the raw material. After the submission of this progress report, I will continue to work on the CNC machine to produce the final product.

No	Tasks	Plan Start	Plan Finish	Days	Weeks																
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		
1	Improvising CAD drawing and CNC programming	22/1/08	5/2/08	15	█	█															
2	Preparing aluminum blanks	6/2/08	13/2/08	7			█														
2	Submission of Progress Report 1	15/2/02	15/2/08	1				█													
3	Fabrication of Model	18/2/08	17/3/08	30				█	█	█											
4	Submission of Progress Report 2 (with seminar)	17/3/08	21/3/08	3									█								
5	Mounting on wind tunnel, static & dynamic tests	21/3/08	31/3/08	10										█							
6	Poster Exhibition	31/3/08	31/3/08	1											█						
7	Submission of dissertation	28/4/08	30/4/08	3												█					
8	Submission of Project Dissertation (Hard Bound Thesis)	1/5/08	7/5/08	7													█	█			

MID SEMESTER BREAK

Figure 4.2: Gantt Chart

CHAPTER 5: MANUFACTURING PROCEDURE AND TEST RESULTS

This chapter will talk about the results that I managed to get through the duration of the progress of my project. It is divided into the initial stage of work and the manufacturing of the final model. Below are the topics in completing this project for this semester:

5.1 Initial Stage

5.1.1 Gather Background Information

5.1.1.1 Measurement of the chord length

5.1.1.2 The Blockage of the Model

5.1.2 Comparing the coordinates from CompuFoil to the coordinates from previous project **(1)**.

5.1.3 Computer Aided Design (CAD).

5.1.4 Manufacturing of Sample

5.2 Manufacturing of the Final Model

5.3 Static Test

5.4 Wind Tunnel Test

5.5 Problems Encountered

I have now completed my project which includes the manufacturing of the final model of NACA 4412 and also its wind tunnel test. My observation so far is that this project will give meaningful insights on the process of generating airfoil profile for the manufacturing process and once completed, the model can be used for further analysis in getting the properties of a high lift wing.

5.1.1 Gather Background Information

Background information such as the chord length and the blockage of the model was to carry out before any work can be done in designing the airfoil. This is essential to get the correct dimension so that the model is suitable to be used in the wind tunnel test.

5.1.1.1 Measurement of the Chord Length

The measurement of the chord length for this airfoil model is done with reference to the current symmetrical airfoil available at the wind tunnel lab in block 18. From the measurement, it is found that the chord length is 10.5 cm.

5.1.1.2 The Blockage of the Model

The test section area of the wind tunnel is 900cm^2 ($30\text{cm} \times 30\text{cm}$).

Angle of attack, $\alpha=0$,

$$\begin{aligned} \text{A model} &= (29.6\text{cm}) * (1.3\text{cm}) = 38.48 \text{ cm}^2 \\ \% \text{ Blockage} &= (38.48\text{cm}^2 / 900\text{cm}^2) * 100\% = \mathbf{4.27\%} \end{aligned}$$

Angle of attack, $\alpha=30^\circ$,

$$\begin{aligned} \text{A model} &= (29.6\text{cm}) * (5.25\text{cm}) = 155.4\text{cm}^2 \\ \% \text{ Blockage} &= (155.4\text{cm}^2 / 900\text{cm}^2) * 100\% = \mathbf{17.267\%} \end{aligned}$$

From the above calculations, with the airfoil dimension, the required blockage percentage is met.

5.1.2 Comparing the coordinates from CompuFoil to the coordinates from previous project.

The coordinates obtained from CompuFoil is then compared with the coordinates obtained from ref (1). This is required to make sure that the coordinates are the same. From the comparison, it is found that the coordinates are closely the same. The difference occurs because the CompuFoil generates more points compare to the previous project (1). But the difference is acceptable because it will give more and accurate surface points for the machining process.

5.1.3 Computer Aided Design (CAD)

Coordinates obtained from CompuFoil are then transferred to CAD. The preferred software to be used is AutoCAD. All the coordinates is being input in term of x-coordinates and y-coordinates which represents both the upper surface (US) and lower surface (LS).

Both the upper and lower surface of the airfoil will have 120 x and y coordinates each. Each surface will then be divided into 4 sections, where in each sections, the number of required coordinates are determined. For example, the leading edge of the airfoil (both upper and lower surface) will have a higher number of coordinates points (30 points) compare to the trailing edge (10 points).

This is done due to the fact that, the crucial part of the model will be the leading edge because of the consideration of the nose circle. Although this problem has been calculated by the CompuFoil, still a higher number of points at the leading edge will ensure a higher accuracy of the final model. Miley (5) reported that one of the most important considerations in aerodynamic research and boundry later studies was the quality of the manufactured wing or blade surface, including the accuracy of the airfoil profile and the smoothness of the surface.

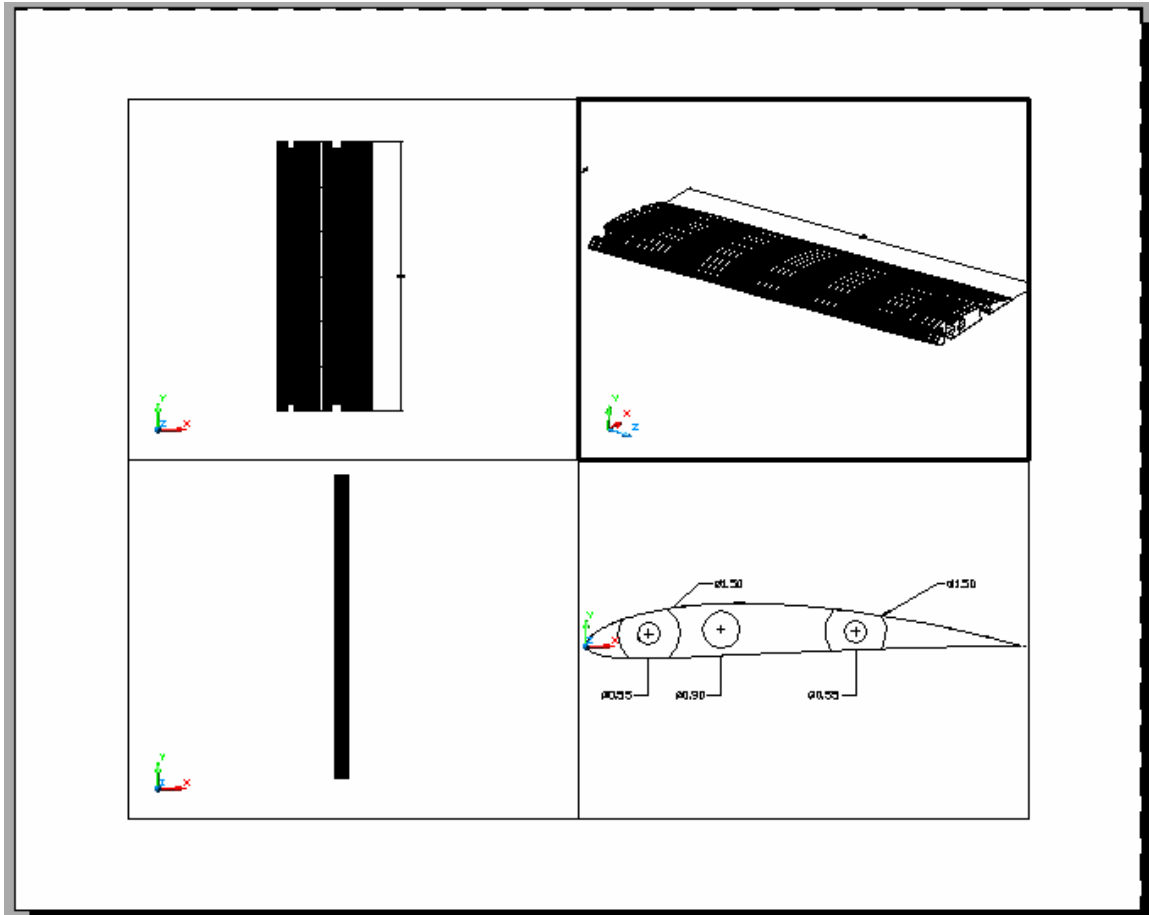


Figure 5.1: Computer Aided Design

5.1.4 Manufacturing of Sample

A series of manufacturing process has to be followed to manufacture the surface profile (**Figure 5: Manufacturing Process**). Surface profile of the NACA 4412 airfoil model will be transferred to Mastercam in order to develop the Computer Aided Manufacturing (CAM), application (**Figure 6: Surface Profile In Mastercam**). CAM procedure will start from verifying the tool path according to the surface profile (**Figure 7: Regen Tool Path**). This process is called regening of the tool path. It is the followed by regening the holes (**Figure 8: Regen Drill**). Once the process is completed, the program will generate the Numerical Control (NC) path program. Here, a simulation (**Figure 9: Generate Tool Path**) of the tool cutting through the material will be done, and at the same time, the

computer will record all the required command for the NC program. Once the tool path has been acquired, job setup (**Figure 10: Job Setup**) is needed before the program can be transferred to the CNC machine as an input for the command of the tool.

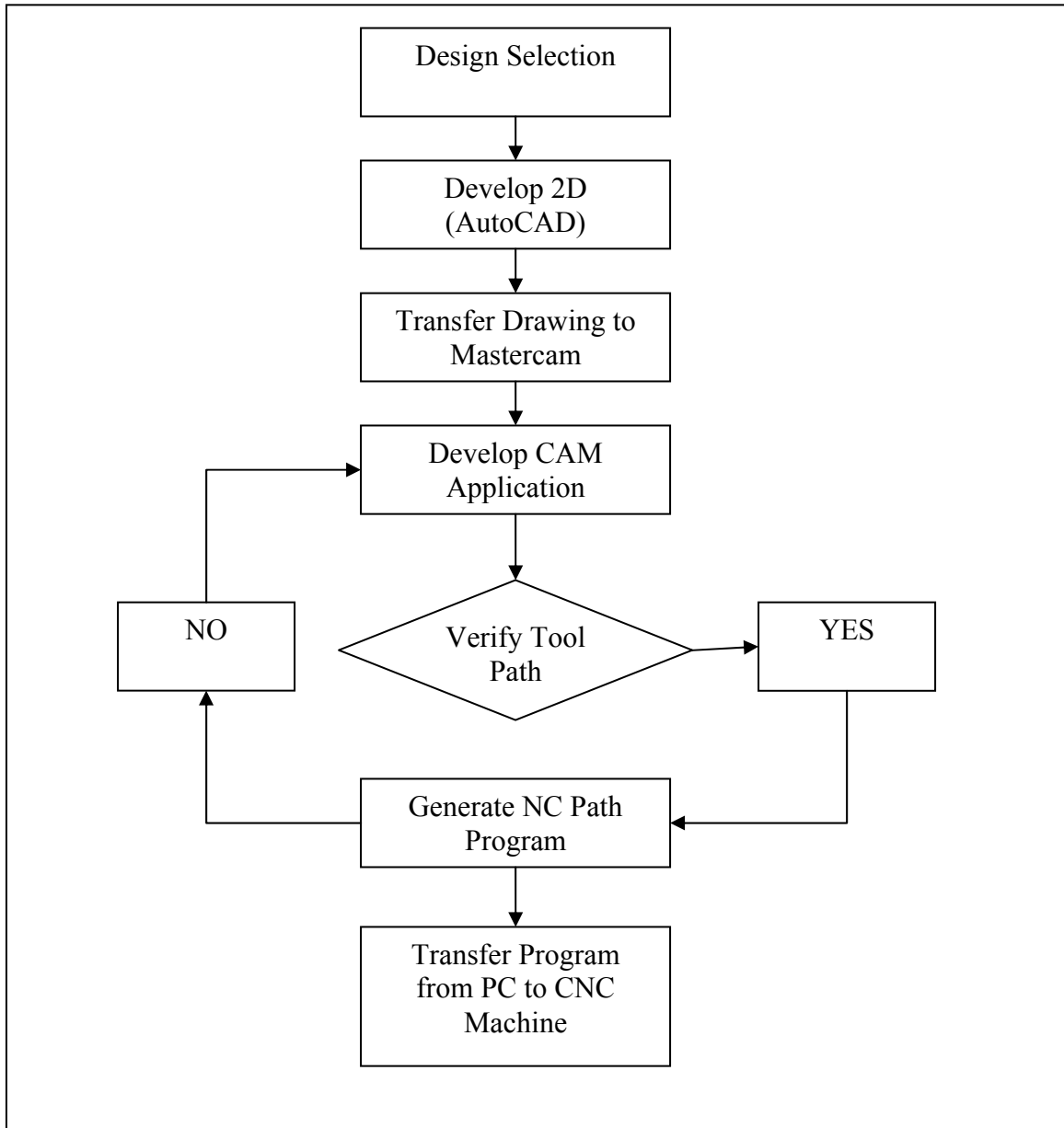


Figure 5.2: Manufacturing Process

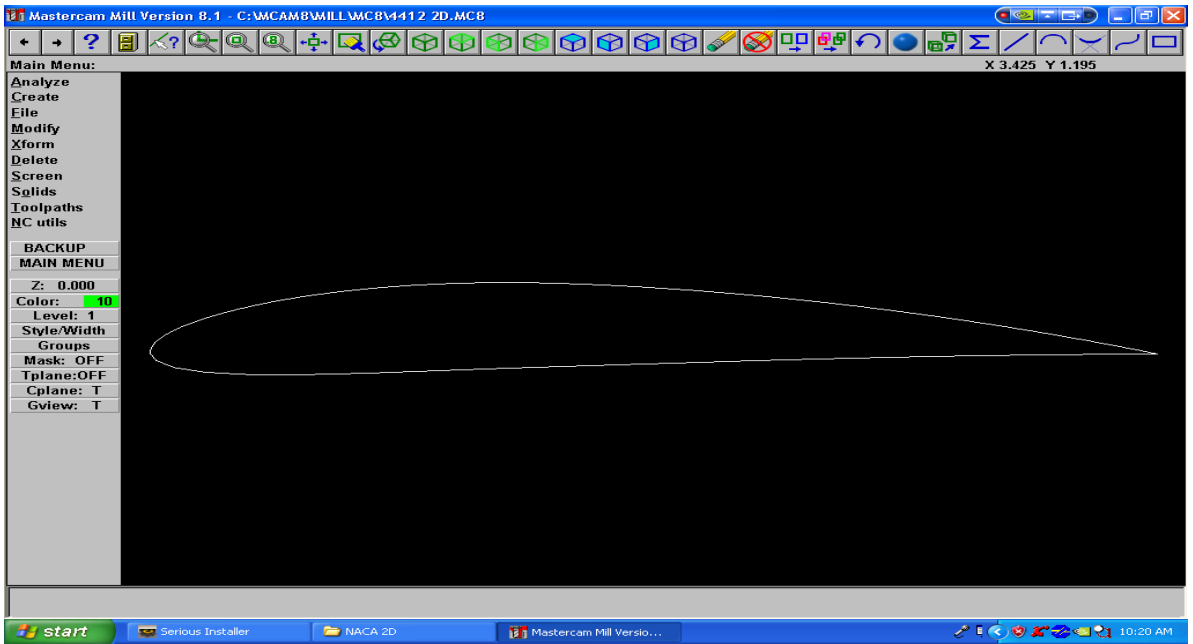


Figure 5.3: Surface Profile In Mastercam

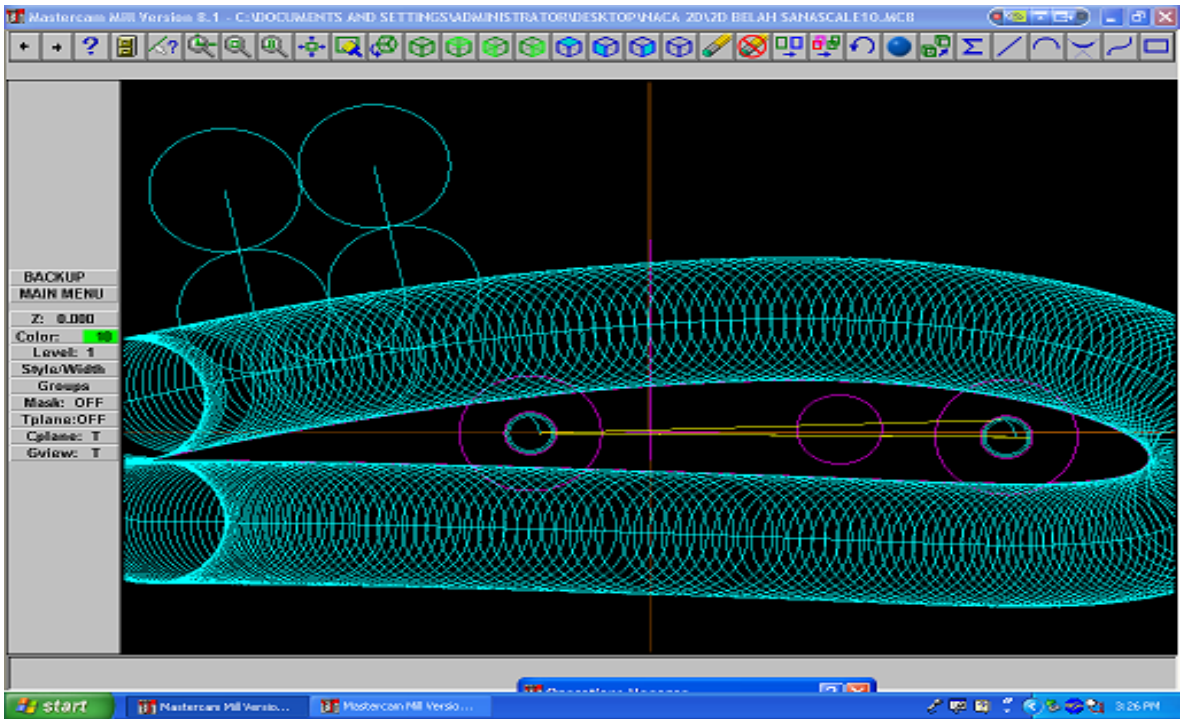


Figure 5.4: Regen Tool Path

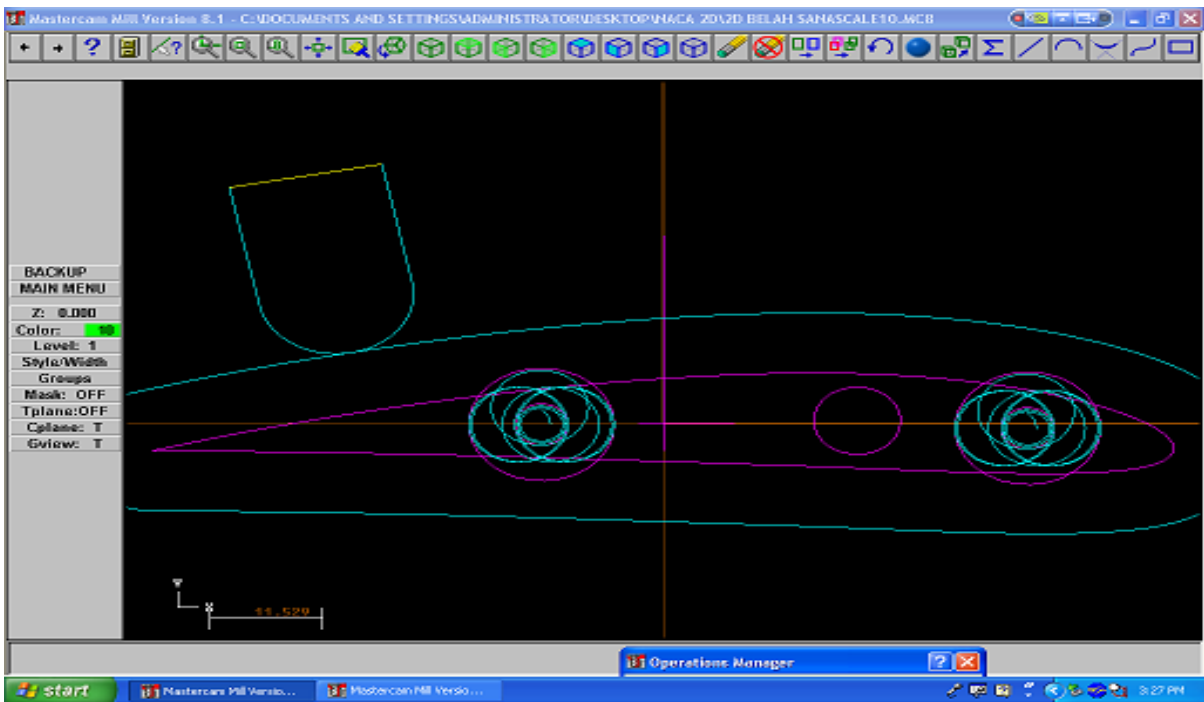


Figure 5.5: Regen Drill

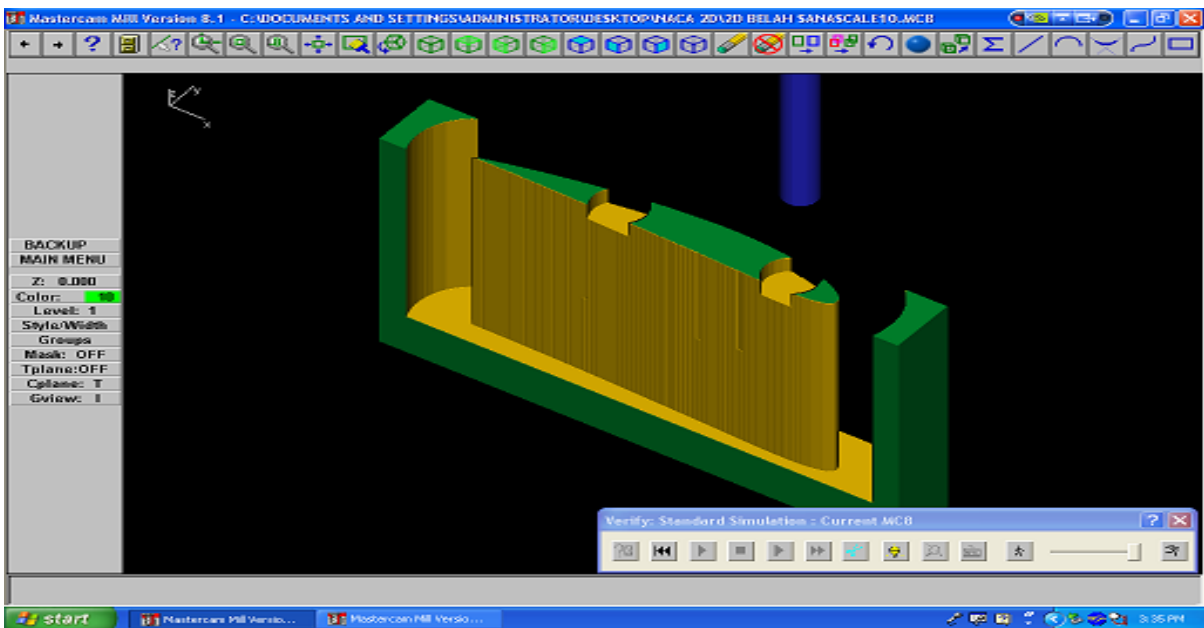


Figure 5.6: Generate Tool Path

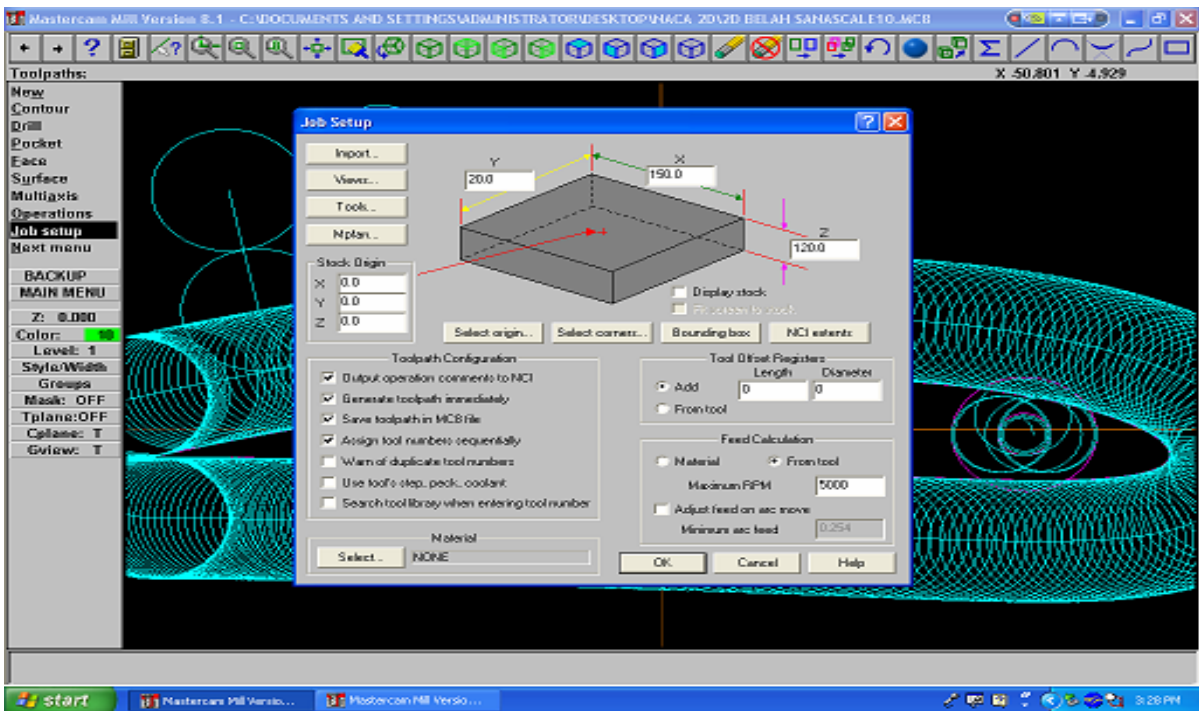


Figure 5.7: Job Setup



Figure 5.8: NACA 4412 Model in Sections

5.2 Manufacturing of the Final Model

The sample of the airfoil 4412 model with the cord length of 10.5 cm and a span of 4.5 cm was successfully manufactured. The surface finish of the sample model was above expectations with the CNC machine having a very high accuracy.

The manufacturing process of the final model has been completed. It has a dimension of 10.5 cm for its cord length and 29.7 cm for its span. Due to its long span and the limitation of the CNC machine, the model was manufactured in sections. The airfoils sections were then clamped together to form the wing model by screwing two rods through the precision machined holes on each blanked. These holes were machined near the leading and trailing edge. There is also a hole with a diameter of 0.9 cm in the middle for the pressure tubes. This is for further manufacturing of the pressure holes on top of the airfoil surface.



Figure 5.9: Final Assembly

5.3 Accuracy Checking

Roughness is a measure of the texture of a surface. It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small the surface is smooth.

These are the result of the manufacturing process employed to create the surface. Surface roughness Ra is rated as the arithmetic average deviations of the surface valleys and peaks expressed in micrometers or microinches.

The ability of a manufacturing operation to produce a specific surface roughness depends on many factors. For example, in mill cutting, the final surface depends on the rotational speed of the mill cutter, the rate of feed, the amount and type of lubrication at the point of cutting, and the mechanical properties of the piece being machined. Any small change of the above factors can have a significant effect on the surface being machined (11).

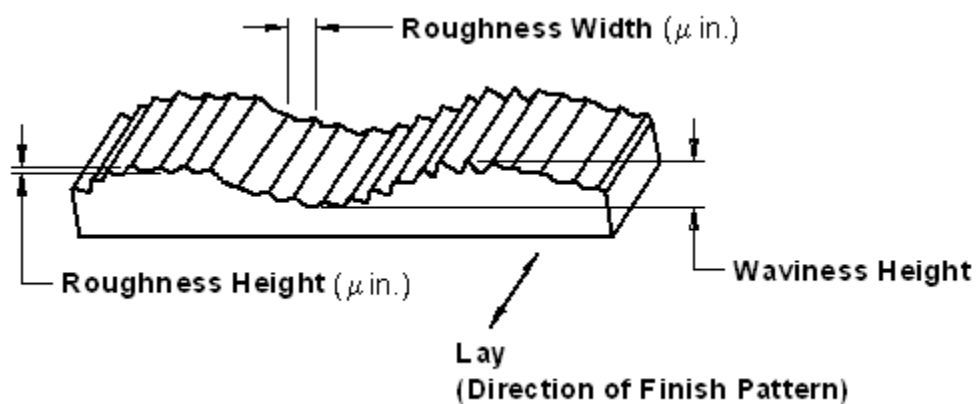


Figure 5.10: Definition of Surface Roughness

For this model, its surface roughness is measured using the Surface Roughness Tester that is available in Material Lab Building 17. The measurements gathered, were those of the upper surface and lower surface of the airfoil sections (**Appendix 3 and Appendix 4**).

Sections	Lower Surface Roughness, Ra (µm)	Upper Surface Roughness, Ra (µm)
1	1.026	2.838
2	3.407	3.82
3	2.316	2.846
4	2.152	2.159
5	0.714	1.632
6	0.854	2.914
Average	1.745	2.7015

Table 5.1: Surface Roughness

For milling process, the normal surface roughness values, Ra is in the range between 1.6µm to 6.35µm. Thus, the values of the surface roughness for this airfoil sections is within range.

5.4 Static Test

Static test is done to the fully assemble NACA 4412 airfoil model to replicated the load anticipated during a high lift force, F_L . This is done by equally distributing the loads along the lower surface of the wing section. The anticipated load is to be 80 N with a safety factor of 1.3. This value is calculated using the equation below:

$$F_L = C_L \left\{ \frac{1}{2} \rho V^2 A \right\} S.F$$

With:

$$C_L = 1.6$$

$$V^2 = 46 \text{ m/s}$$

$$A = \text{chord} * \text{span} = (10.5\text{cm}) * (29.7\text{cm})$$

$$S.F = 1.3$$

$$P = 1.24 \text{ kg/m}^3$$

5.5 Wind Tunnel Test

Wind tunnel test was done on the NACA 4412 airfoil wing section for validation purposes. It is done by using the available wind tunnel facilities in Universiti Teknologi Petronas (UTP). The measurements that are required are the lift force, drag force and pitch moment. After gathering all these three measurements at specific angle of attack (-4° , 0° , 4° , 8° , 12° , 16° , 20° and 22.5°), the values of the coefficient of moment (C_L), coefficient of drag (C_D) and coefficient of moment (C_M) can be determined by using the following equations:

$$F_L = C_L \{ \frac{1}{2} \rho V^2 A \}$$

$$F_D = C_D \{ \frac{1}{2} \rho V^2 A \}$$

$$M = C_M \{ \frac{1}{2} \rho V^2 A \} S c$$

Where:

F_L = Lift force C_L = Coefficient of lift ρ = air density (1.24kg/m^3)

F_D = Drag force C_D = Coefficient of drag A = Area (Chord*Span)

M = Pitch moment C_M = Coefficient of moment $S = A$ (Area) c = chord

Angle of attack	F_D (N)	F_L (N)	M (N.m)	C_D	C_L	C_M
-4	0	5.31	-0.24	0	0.12979	0.055869
0	1.12	10.35	-0.03	0.027376	0.252981	0.006984
4	2.8	21.2	-0.21	0.068439	0.518183	0.048885
8	2.17	25.96	-0.03	0.05304	0.634529	0.006984
12	3.24	34.15	-0.06	0.079194	0.834714	0.013967
16	5.51	44.26	0.08	0.134679	1.081828	-0.01862
20	6.43	40.52	-0.02	0.157166	0.990413	0.004656
22.5	7.03	38.6	-0.08	0.171831	0.943483	0.018623

Table 5.2: Values of F_D , F_L , M , C_D , C_L and C_M at Various Angle of Attack

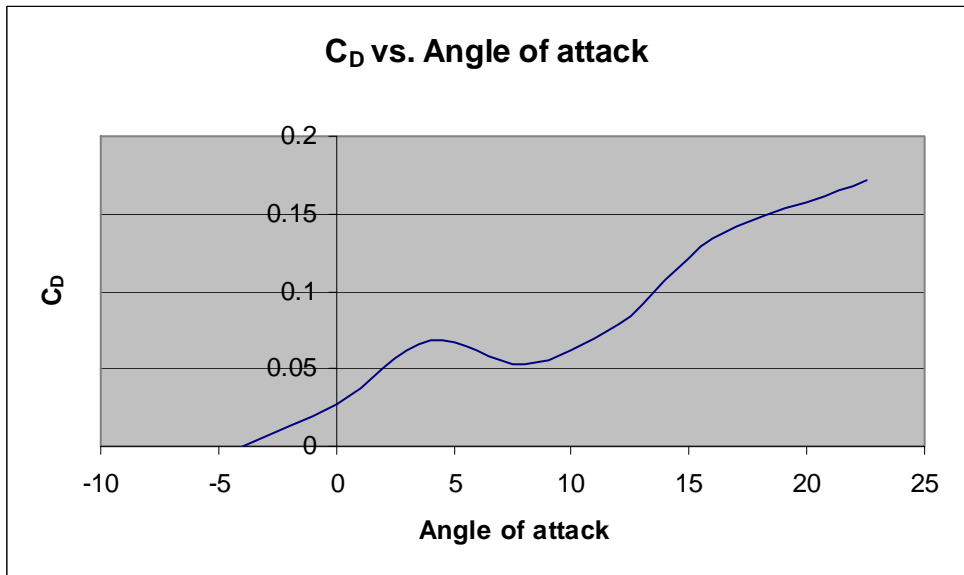


Chart 5.1: C_D vs. Angle of attack

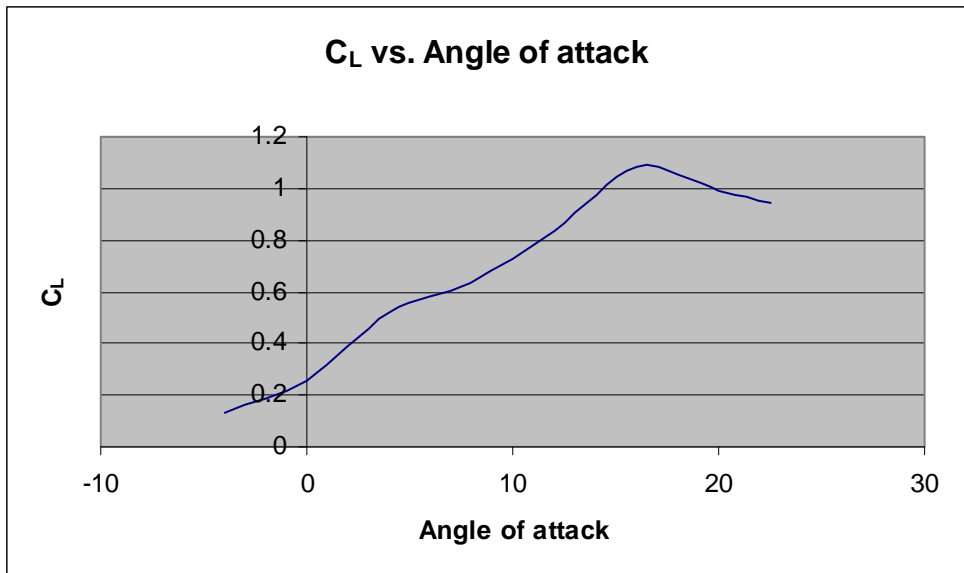


Chart 5.2: C_L vs. Angle of attack

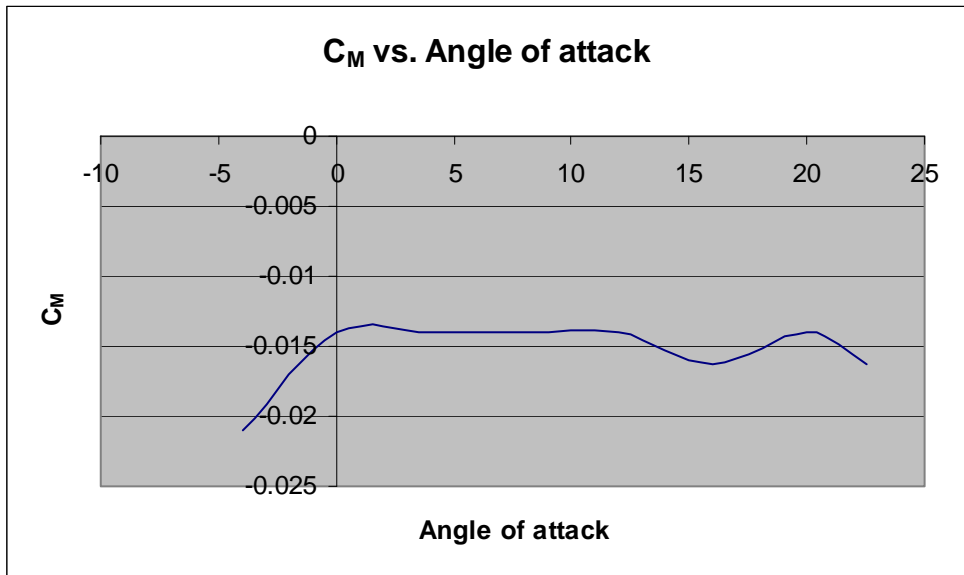


Chart 5.3: C_M vs. Angle of attack

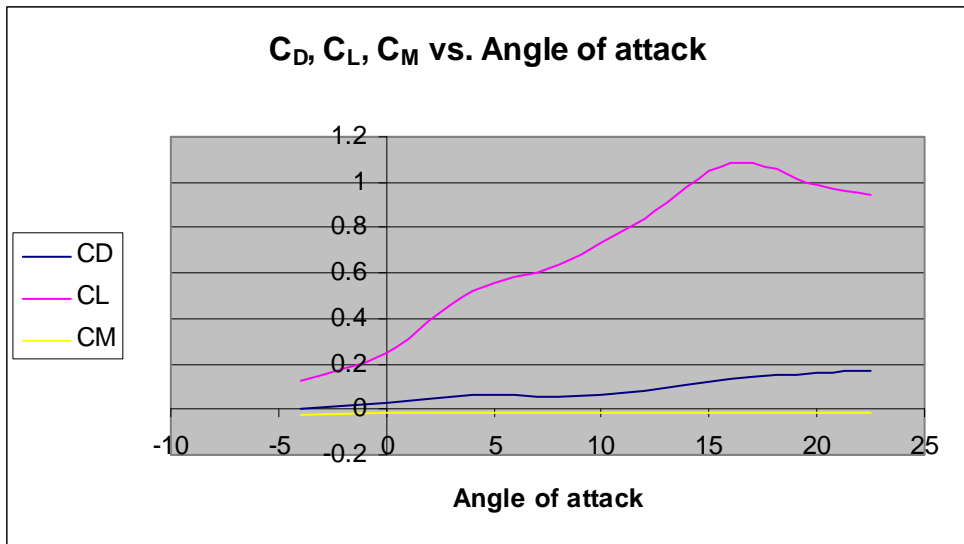


Chart 5.4: $C_D, C_L,$ and C_M vs. Angle of attack

5.6 Problems Encountered

Initial recommendations was to build the airfoil into sections each having a span of 9.9cm, which required only three sections to make up the 29.7cm wing span. Due to the limitation of the CNC machine, the initial sections of the 9.9cm span has to be reconsidered (**Figure 13: Initial Sections Assembly**).

5.6.1 Bit Depth

As mentioned earlier, to make up the 29.7cm wing span, the wing model has to be machined section by section. Thus, to make the end product, these sections has to be clamped together using rods and bolts. The CNC machined has a limitation of drilling a through hole with a maximum depth of 5.5cm. So, the initial depth of 9.9cm for the holes cannot be met. Modifications on the drawing and also the programming of the Mastercam were carried out and a final sections depth of 4.95cm each will be machined. This will results in 6 sections which will be clamped together for the final assembly (**Figure 15: Final Sections Assembly**).

5.6.2 Wind Tunnel Test Section

During the wind tunnel experiments on the NACA 4412 wing section, the mechanism for adjusting the angle of attack of the model is not accurate as anticipated. This is because, the wind model has to be tilted manually and the values for the angle are only indicated by a simple protector. Thus the values its measure will be affected slightly.

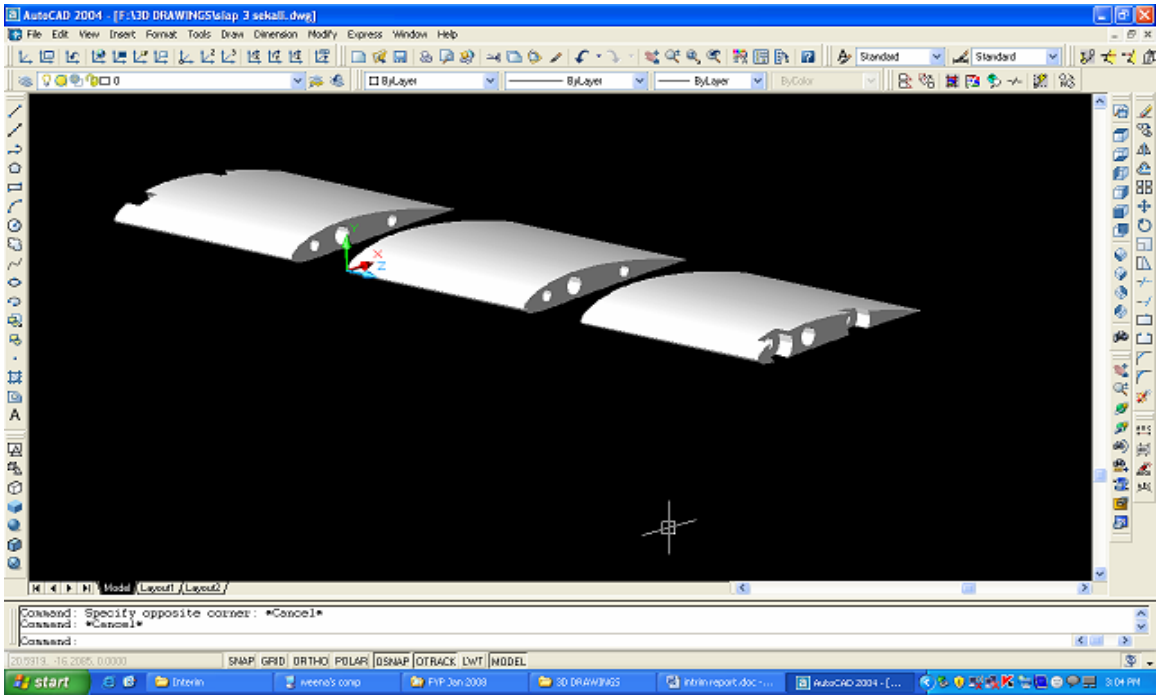


Figure 5.11: Initial Sections Assembly

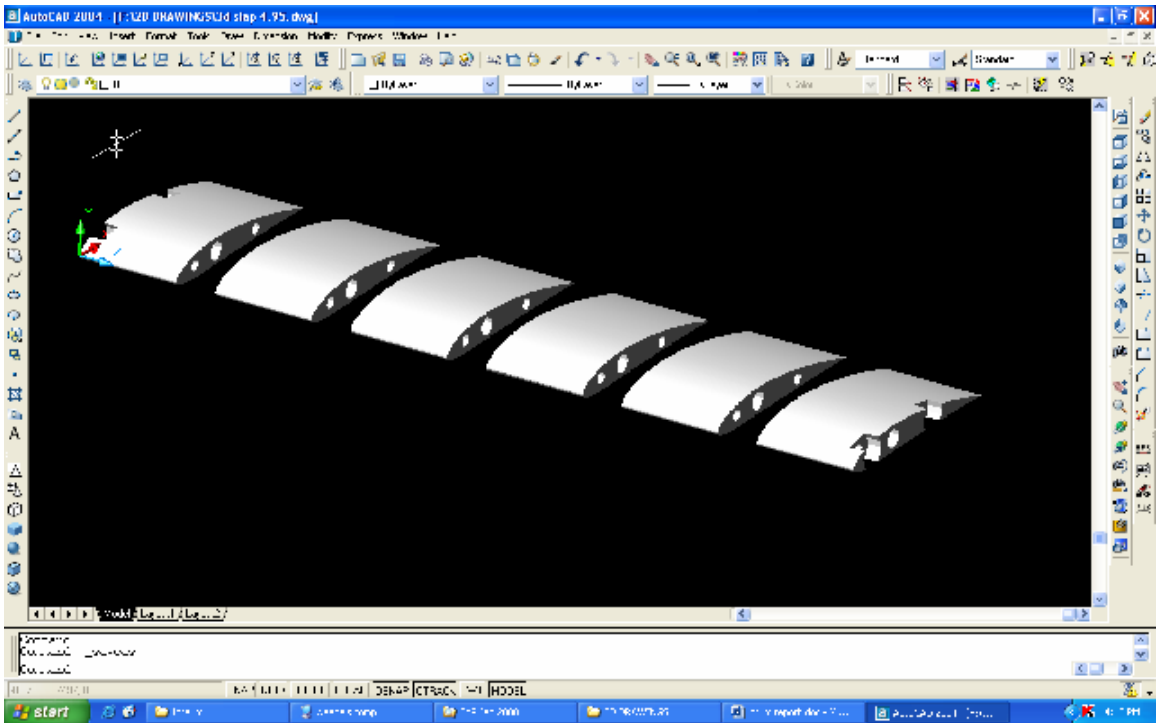


Figure 5.12: Final Sections Assembly

CHAPTER 6: CONCLUSION

Time spent familiarizing with the CompuFoil software has provided valuable information on generating the profile of the airfoil. A computer aided manufacturing procedure for accurate model wing cross sections has been established. The procedure of generating the coordinates from CompuFoil to generate the surface points in AutoCAD is straightforward and with this, complex geometrical wing cross sections can be machined at the workshop using a 5 1/2 axis CNC machine.

As for the manufacturing process, it is also straightforward. The surface profile from the AutoCAD was transferred to the Mastercam program so that a set of code can be generated. Once the code is established, it is then being fed to the CNC machine for the machining of the final product.

The total time taken for the manufacture of a model wing section from 20 mm X 190 mm X 120 mm of aluminum was about 2 1/2 days, made up as follows:

- | | |
|---|-------------------|
| a) Entry of NACA profile data to Mastercam and running the program to generate CNC program points | 30 minutes |
| b) Production of 6 airfoils sections | 1 day |
| c) Assembly | 30 minutes |
| d) Hand finishing and polishing | 1 day |

Surface finishing was achieved by scraping and then hand rubbing with very fine grade sand paper together with ordinary engine oil. This is to get a polished finished of the final product.

The method is thus very efficient, being much more time and cost effective than the previous method (1). Other materials, e.g. mild steel and Perspex might alter the machining time. But aluminum is found to be the easiest way to machine compare to mild steel and Perspex.

CHAPTER 7: RECOMMENDATIONS

Although the standard procedure for generating the coordinates of airfoil model profile and its manufacturing procedure has been established, there are still improvements that can be done in the production of the final product.

For the final product, the number of surface points for upper and lower surface of the profile will be increased especially at the leading edge so that the surface finish of the final model will be smooth and no surface flaws. This accuracy was crucial to the finished quality but was easily achieved with the relatively low cost modern CNC machined tool used **(1)**.

The final model of airfoil will be constructed with six different airfoil sections, each having a span of 4.95 cm. This is because of the limitation of the machining tool which only has a drill depth of 5.5cm (55 mm). Each sections of the airfoil will be having two holes each near the leading edge and tailing edge. These holes will be precision machined so that all four sections will aligned accurately once being assembled. The final assembly of the wing section will be done by inserting tubular rods threaded at both ends and pushed through the precision holes **(1)**. The airfoil sections will then be clamped together to form the wing model by screwing up each rod until a rigid assembly was produced.

A static and dynamic test of the model airfoil can also be implemented to check its accuracy. These tests include the moment coefficient (C_M), lift coefficient (C_L) and drag coefficient (C_D).

LIST OF REFERENCES

1. **Al-Kayiem, H.H.** *Separated flow on a high lift wing*. PhD thesis, 1989, Department of Mechanical and Manufacturing Engineering, university of Bradford.
2. **Malkin, J.** *Airfoil sections (for model airplanes)*, 1971 (Upper Hutt, New Zealand).
3. **Abott, I. H. and Doenhoff, A. E.** *Theory of wings sections*, 1949 (Dover Publications, New York).
4. **Jacobs, E. N., Wark, K.E. and Pinkerton, R. M.** the characteristic of 78 relate airfoil sections from test in the variable-density wind tunnel. NASA report 60, 1975.
5. **Miley, S. J.** *Catalog of low- Reynolds-number airfoil data for wind turbine applications*, 1982, Rockwell International Corp., Golden, Colo., Rocky, Flat Plant.
6. **Presnell, M.** *Aerofoils for aeromodellers*, 1977 (Pitman Publishing, London)
7. **Groover, M. P. and Zimmers, E. W.** *CAD/CAM – computer aided design and manufacturing*, Part III, 1984 (Prentice Hall)
8. **Herbert Grünbacher, Reiner W. Hartenstein** *Field programmable gate arrays: Architecture and tools for rapid prototyping*, Second Edition, 1992 (Springer-Verlag)
9. <http://www.amrcc.com/pdtt/rp.asp>
10. <http://www.ctaz.com/~kelcomp/airfoils5.htm>
11. http://www.engineersedge.com/surface_finish.htm

APPENDICES

APPENDIX 1: Tabulations of Coordinates from the CompuFoil code.

APPENDIX 2: Tabulations of Coordinates from Previous Project (1).

APPENDIX 3: Wind Tunnel Data.

APPENDIX 4: Lower Sections Surface Roughness.

APPENDIX 5: Upper Sections Surface Roughness.

Appendix 1

UPPER SURFACE					
X			y		
0	10.5	0	0.00231443	10.5	0.024301515
0.00006363	10.5	0.000668115	0.0046767	10.5	0.04910535
0.00047692	10.5	0.00500766	0.00707562	10.5	0.07429401
0.0012405	10.5	0.01302525	0.00951448	10.5	0.09990204
0.00235474	10.5	0.02472477	0.01199341	10.5	0.125930805
0.00381978	10.5	0.04010769	0.01450993	10.5	0.152354265
0.00563553	10.5	0.059173065	0.01706197	10.5	0.179150685
0.00780162	10.5	0.08191701	0.01964707	10.5	0.206294235
0.01031746	10.5	0.10833333	0.02226248	10.5	0.23375604
0.01318217	10.5	0.138412785	0.02490512	10.5	0.26150376
0.01639465	10.5	0.172143825	0.02757159	10.5	0.289501695
0.01995351	10.5	0.209511855	0.03025823	10.5	0.317711415
0.02385709	10.5	0.250499445	0.03296109	10.5	0.346091445
0.02810347	10.5	0.295086435	0.03567598	10.5	0.37459779
0.03269046	10.5	0.34324983	0.03839846	10.5	0.40318383
0.03761557	10.5	0.394963485	0.04112388	10.5	0.43180074
0.04287606	10.5	0.45019863	0.04384737	10.5	0.460397385
0.04846887	10.5	0.508923135	0.04656391	10.5	0.488921055
0.05439068	10.5	0.57110214	0.04926831	10.5	0.517317255
0.06063786	10.5	0.63669753	0.05195524	10.5	0.54553002
0.06720649	10.5	0.705668145	0.05461925	10.5	0.573502125
0.07409237	10.5	0.777969885	0.05725483	10.5	0.601175715
0.08129099	10.5	0.853555395	0.05985637	10.5	0.628491885
0.08879756	10.5	0.93237438	0.06241824	10.5	0.65539152
0.09660698	10.5	1.01437329	0.06493475	10.5	0.681814875
0.10471388	10.5	1.09949574	0.06740026	10.5	0.70770273
0.11311257	10.5	1.187681985	0.06980913	10.5	0.732995865
0.1217971	10.5	1.27886955	0.07215576	10.5	0.75763548
0.13076121	10.5	1.372992705	0.07443464	10.5	0.78156372
0.13999839	10.5	1.469983095	0.07664032	10.5	0.80472336
0.14950185	10.5	1.569769425	0.07876748	10.5	0.82705854
0.16927904	10.5	1.77742992	0.08276566	10.5	0.86903943
0.1900332	10.5	1.9953486	0.08638957	10.5	0.907090485
0.21170086	10.5	2.22285903	0.08960254	10.5	0.94082667
0.23421496	10.5	2.45925708	0.09237142	10.5	0.96989991
0.25750523	10.5	2.703804915	0.09466695	10.5	0.994002975
0.28149855	10.5	2.955734775	0.09646411	10.5	1.012873155
0.30611939	10.5	3.214253595	0.09774247	10.5	1.026295935
0.3312902	10.5	3.4785471	0.0984863	10.5	1.03410615
0.35693189	10.5	3.747784845	0.09868476	10.5	1.03618998
0.38296422	10.5	4.02112431	0.09833192	10.5	1.03248516
0.40916434	10.5	4.29622557	0.09743814	10.5	1.02310047
0.43533313	10.5	4.570997865	0.09614742	10.5	1.00954791
0.46166691	10.5	4.847502555	0.09451256	10.5	0.99238188

0.48809032	10.5	5.12494836	0.09254817	10.5	0.971755785
0.54090544	10.5	5.67950712	0.08769927	10.5	0.920842335
0.58019594	10.5	6.09205737	0.08333443	10.5	0.875011515
0.61893678	10.5	6.49883619	0.07842772	10.5	0.82349106
0.66932033	10.5	7.027863465	0.07118054	10.5	0.74739567
0.70585308	10.5	7.41145734	0.06532996	10.5	0.68596458
0.74106192	10.5	7.78115016	0.05922457	10.5	0.621857985
0.77473414	10.5	8.13470847	0.05295937	10.5	0.556073385
0.80666816	10.5	8.47001568	0.0466321	10.5	0.48963705
0.8366746	10.5	8.7850833	0.04034238	10.5	0.42359499
0.85552041	10.5	8.982964305	0.03621974	10.5	0.38030727
0.88192944	10.5	9.26025912	0.03021597	10.5	0.317267685
0.9059724	10.5	9.5127102	0.02451658	10.5	0.25742409
0.92751193	10.5	9.738875265	0.01921813	10.5	0.201790365
0.9464263	10.5	9.93747615	0.01441255	10.5	0.151331775
0.96260977	10.5	10.10740259	0.01018522	10.5	0.10694481
0.97597278	10.5	10.24771419	0.00661291	10.5	0.069435555
0.98644207	10.5	10.35764174	0.00376175	10.5	0.039498375
0.99396073	10.5	10.43658767	0.00168539	10.5	0.017696595
0.99848816	10.5	10.48412568	0.00042339	10.5	0.004445595
1	10.5	10.5	0	10.5	0

LOWER SURFACE					
X			y		
1	10.5	10.5	0	10.5	0
0.9993279	10.5	10.49294295	-0.0000055	10.5	-0.00005775
0.99580377	10.5	10.45593959	-0.00003472	10.5	-0.00036456
0.98927848	10.5	10.38742404	-0.00009055	10.5	-0.000950775
0.97978721	10.5	10.28776571	-0.00017592	10.5	-0.00184716
0.96738144	10.5	10.15750512	-0.00029537	10.5	-0.003101385
0.95212898	10.5	9.99735429	-0.00045527	10.5	-0.004780335
0.93411396	10.5	9.80819658	-0.00066398	10.5	-0.00697179
0.91343674	10.5	9.59108577	-0.00093195	10.5	-0.009785475
0.89021376	10.5	9.34724448	-0.00127165	10.5	-0.013352325
0.86457721	10.5	9.078060705	-0.00169724	10.5	-0.01782102
0.8366746	10.5	8.7850833	-0.00222396	10.5	-0.02335158
0.8066816	10.5	8.4701568	-0.00224964	10.5	-0.02362122
0.77473414	10.5	8.13470847	-0.00286727	10.5	-0.030106335
0.74106192	10.5	7.78115016	-0.00312229	10.5	-0.032784045
0.70585308	10.5	7.41145734	-0.00364159	10.5	-0.038236695
0.66932033	10.5	7.027863465	-0.00455885	10.5	-0.047867925
0.63168637	10.5	6.632706885	-0.00522752	10.5	-0.05488896
0.59318267	10.5	6.228418035	-0.00562683	10.5	-0.059081715
0.55404821	10.5	5.817506205	-0.00684744	10.5	-0.07189812
0.5013121	10.5	5.26377705	-0.0072872	10.5	-0.0765156

0.47487212	10.5	4.98615726	-0.008215	10.5	-0.0862575
0.44848411	10.5	4.709083155	-0.00925412	10.5	-0.09716826
0.4222234	10.5	4.4333457	-0.0097148	10.5	-0.1020054
0.39610161	10.5	4.159066905	-0.01112679	10.5	-0.116831295
0.36990427	10.5	3.883994835	-0.01132199	10.5	-0.118880895
0.34405718	10.5	3.61260039	-0.01290452	10.5	-0.13549746
0.31864096	10.5	3.34573008	-0.0135689	10.5	-0.14247345
0.29373533	10.5	3.084220965	-0.01458693	10.5	-0.153162765
0.26941868	10.5	2.82889614	-0.01470551	10.5	-0.154407855
0.24576758	10.5	2.58055959	-0.01582866	10.5	-0.16620093
0.22285643	10.5	2.339992515	-0.01617385	10.5	-0.169825425
0.20075695	10.5	2.107947975	-0.01691954	10.5	-0.17765517
0.17953788	10.5	1.88514774	-0.01766526	10.5	-0.18548523
0.1592645	10.5	1.67227725	-0.01796541	10.5	-0.188636805
0.14950185	10.5	1.569769425	-0.01906126	10.5	-0.20014323
0.13999839	10.5	1.469983095	-0.01908755	10.5	-0.200419275
0.13076121	10.5	1.372992705	-0.02029602	10.5	-0.21310821
0.1217971	10.5	1.27886955	-0.0203621	10.5	-0.21380205
0.11311257	10.5	1.187681985	-0.02155603	10.5	-0.226338315
0.10471388	10.5	1.09949574	-0.02156814	10.5	-0.22646547
0.09660698	10.5	1.01437329	-0.02267987	10.5	-0.238138635
0.08879756	10.5	0.93237438	-0.02283076	10.5	-0.23972298
0.08129099	10.5	0.853555395	-0.02369792	10.5	-0.24882816
0.07409237	10.5	0.777969885	-0.02408209	10.5	-0.252861945
0.06720649	10.5	0.705668145	-0.02462307	10.5	-0.258542235
0.06063786	10.5	0.63669753	-0.02527133	10.5	-0.265348965
0.05439068	10.5	0.57110214	-0.02545622	10.5	-0.26729031
0.04846887	10.5	0.508923135	-0.02619845	10.5	-0.275083725
0.04287606	10.5	0.45019863	-0.02636002	10.5	-0.27678021
0.03761557	10.5	0.394963485	-0.026851	10.5	-0.2819355
0.03269046	10.5	0.34324983	-0.02731066	10.5	-0.28676193
0.02810347	10.5	0.295086435	-0.02741528	10.5	-0.28786044
0.02385709	10.5	0.250499445	-0.02789297	10.5	-0.292876185
0.01995351	10.5	0.209511855	-0.02808754	10.5	-0.29491917
0.01639465	10.5	0.172143825	-0.02828586	10.5	-0.29700153
0.01318217	10.5	0.138412785	-0.02859594	10.5	-0.30025737
0.01031746	10.5	0.10833333	-0.02865711	10.5	-0.300899655
0.00780162	10.5	0.08191701	-0.02882543	10.5	-0.302667015
0.00563553	10.5	0.059173065	-0.02885447	10.5	-0.302971935
0.00381978	10.5	0.04010769	-0.02897696	10.5	-0.30425808
0.00235474	10.5	0.02472477	-0.02898918	10.5	-0.30438639
0.0012405	10.5	0.01302525	-0.0290501	10.5	-0.30502605
0.00047692	10.5	0.00500766	-0.02905401	10.5	-0.305067105
0.00006363	10.5	0.000668115	0.00200193	10.5	0.021020265

Appendix 2

UPPER INTERSECT POINT					
X			y		
0.343	0.042	0.014406	2.564	0.042	0.107688
0.414	0.042	0.017388	2.732	0.042	0.114744
0.988	0.042	0.041496	3.57	0.042	0.14994
1.719	0.042	0.072198	4.775	0.042	0.20055
2.482	0.042	0.104244	5.497	0.042	0.230874
3.276	0.042	0.137592	6.248	0.042	0.262416
3.909	0.042	0.164178	6.79	0.042	0.28518
4.327	0.042	0.181734	7.123	0.042	0.299166
5.042	0.042	0.211764	7.653	0.042	0.321426
6.878	0.042	0.288876	8.834	0.042	0.371028
7.742	0.042	0.325164	9.33	0.042	0.39186
8.431	0.042	0.354102	9.713	0.042	0.407946
9.179	0.042	0.385518	10.125	0.042	0.42525
10.157	0.042	0.426594	10.672	0.042	0.448224
12.484	0.042	0.524328	11.847	0.042	0.497574
14.913	0.042	0.626346	12.838	0.042	0.539196
17.4	0.042	0.7308	13.8	0.042	0.5796
19.98	0.042	0.83916	14.742	0.042	0.619164
25.65	0.042	1.0773	16.622	0.042	0.698124
29.306	0.042	1.230852	17.701	0.042	0.743442
32.671	0.042	1.372182	18.608	0.042	0.781536
37.151	0.042	1.560342	19.691	0.042	0.827022
42.764	0.042	1.796088	20.86	0.042	0.87612
46.313	0.042	1.945146	21.498	0.042	0.902916
50.24	0.042	2.11008	22.121	0.042	0.929082
55.892	0.042	2.347464	22.869	0.042	0.960498
61.074	0.042	2.565108	23.418	0.042	0.983556
65.08	0.042	2.73336	23.759	0.042	0.997878
68.3	0.042	2.8686	23.986	0.042	1.007412
74.209	0.042	3.116778	24.302	0.042	1.020684
76.528	0.042	3.214176	24.395	0.042	1.02459
80.973	0.042	3.400866	24.505	0.042	1.02921
85.585	0.042	3.59457	24.604	0.042	1.033368
94.432	0.042	3.966144	24.64	0.042	1.03488
111.26	0.042	4.67292	23.991	0.042	1.007622
117.123	0.042	4.919166	23.578	0.042	0.990276
124.782	0.042	5.240844	23.031	0.042	0.967302
132.553	0.042	5.567226	22.335	0.042	0.93807
141.181	0.042	5.929602	21.443	0.042	0.900606
150.849	0.042	6.335658	20.298	0.042	0.852516
161.792	0.042	6.795264	18.824	0.042	0.790608
174.314	0.042	7.321188	16.914	0.042	0.710388

188.825	0.042	7.93065	14.414	0.042	0.605388
207.215	0.042	8.70303	10.725	0.042	0.45045
215.492	0.042	9.050664	8.977	0.042	0.377034
220.45	0.042	9.2589	7.892	0.042	0.331464
225.4	0.042	9.4668	6.658	0.042	0.279636
230.343	0.042	9.674406	5.425	0.042	0.22785
238.566	0.042	10.019772	3.3	0.042	0.1386
241.85	0.042	10.1577	2.498	0.042	0.104916
250	0.042	10.5	0.002	0.042	0.000084

LOWER INTERSECTION POINT					
X			y		
0.938	0.042	0.039396	-1.874	0.042	-0.078708
1.357	0.042	0.056994	-2.38	0.042	-0.09996
1.752	0.042	0.073584	-2.687	0.042	-0.112854
2.126	0.042	0.089292	-2.953	0.042	-0.124026
2.863	0.042	0.120246	-3.416	0.042	-0.143472
3.683	0.042	0.154686	-3.85	0.042	-0.1617
5.505	0.042	0.23121	-4.595	0.042	-0.19299
6.741	0.042	0.283122	-5.027	0.042	-0.211134
7.947	0.042	0.333774	-5.344	0.042	-0.224448
9.632	0.042	0.404544	-5.7	0.042	-0.2394
10.228	0.042	0.429576	-5.82	0.042	-0.24444
13.547	0.042	0.568974	-6.35	0.042	-0.2667
16.104	0.042	0.676368	-6.59	0.042	-0.27678
18.723	0.042	0.786366	-6.796	0.042	-0.285432
21.432	0.042	0.900144	-6.965	0.042	-0.29253
24.27	0.042	1.01934	-7.1	0.042	-0.2982
27.27	0.042	1.14534	-7.198	0.042	-0.302316
30.565	0.042	1.28373	-7.256	0.042	-0.304752
34.197	0.042	1.436274	-7.268	0.042	-0.305256
38.332	0.042	1.609944	-7.224	0.042	-0.303408
43.186	0.042	1.813812	-7.105	0.042	-0.29841
49.096	0.042	2.062032	-6.885	0.042	-0.28917
56.621	0.042	2.378082	-6.533	0.042	-0.274386
66.782	0.042	2.804844	-6.025	0.042	-0.25305
70.44	0.042	2.95848	-5.86	0.042	-0.24612
74.851	0.042	3.143742	-5.687	0.042	-0.238854
78.985	0.042	3.31737	-5.45	0.042	-0.2289
87.064	0.042	3.656688	-5.065	0.042	-0.21273
94.362	0.042	3.963204	-4.765	0.042	-0.20013
102.42	0.042	4.30164	-4.414	0.042	-0.185388
106.467	0.042	4.471614	-4.242	0.042	-0.178164
113.56	0.042	4.76952	-3.948	0.042	-0.165816

125.389	0.042	5.266338	-3.459	0.042	-0.145278
129.384	0.042	5.434128	-3.3	0.042	-0.1386
113.335	0.042	4.76007	-3.144	0.042	-0.132048
144.102	0.042	6.052284	-2.725	0.042	-0.11445
151.061	0.042	6.344562	-2.468	0.042	-0.103656
155.757	0.042	6.541794	-2.291	0.042	-0.096222
162.527	0.042	6.826134	-2.043	0.042	-0.085806
169.379	0.042	7.113918	-1.807	0.042	-0.075894
177.72	0.042	7.46424	-1.53	0.042	-0.06426
182.718	0.042	7.674156	-1.394	0.042	-0.058548
191.061	0.042	8.024562	-1.215	0.042	-0.05103
204.443	0.042	8.586606	-0.871	0.042	-0.036582
216.188	0.042	9.079896	-0.587	0.042	-0.024654
227.971	0.042	9.574782	-0.5	0.042	-0.021
238.101	0.042	10.000242	-0.39	0.042	-0.01638
250	0.042	10.5	-0.002	0.042	-0.000084

Appendix 3

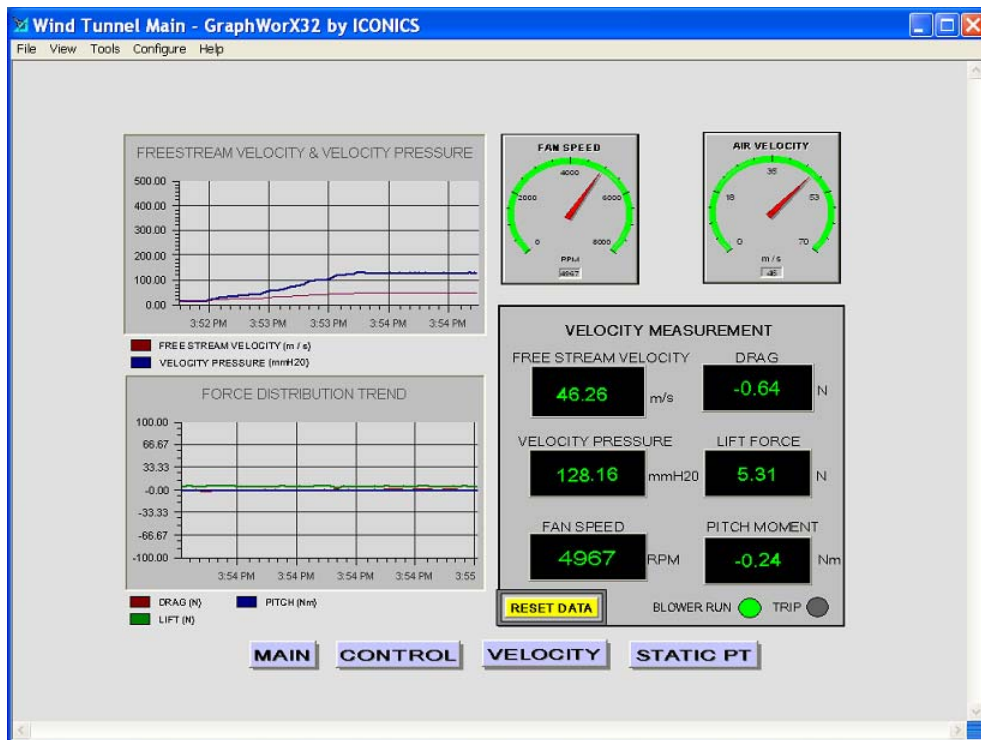


Figure A3.1: -4° angle of attack

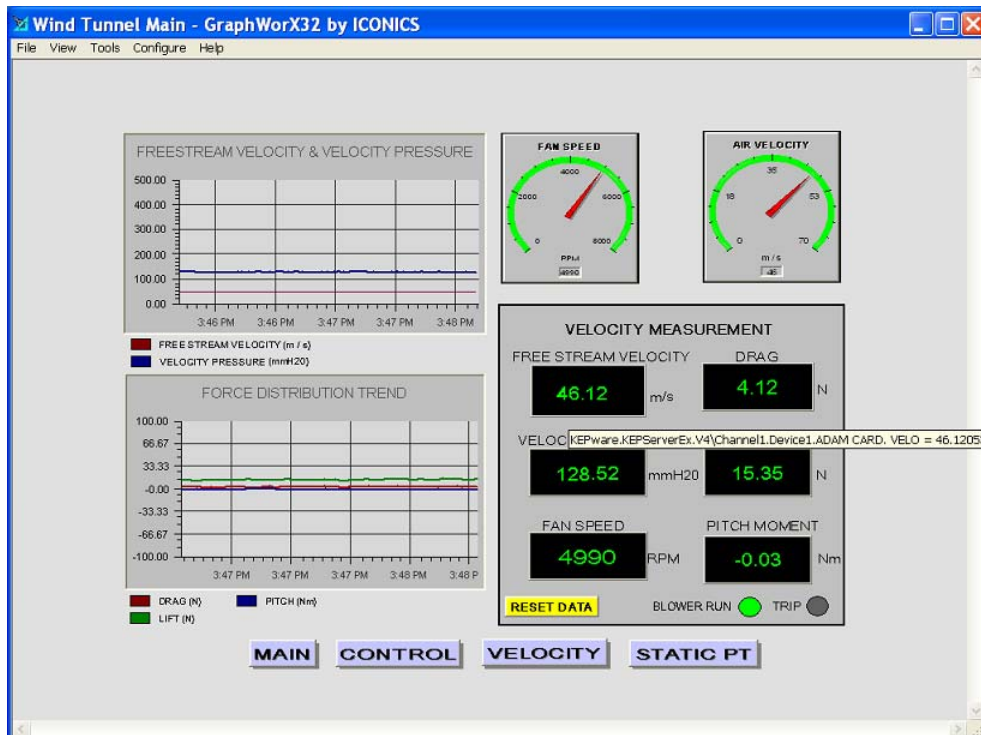


Figure A3.2: 0° angle of attack

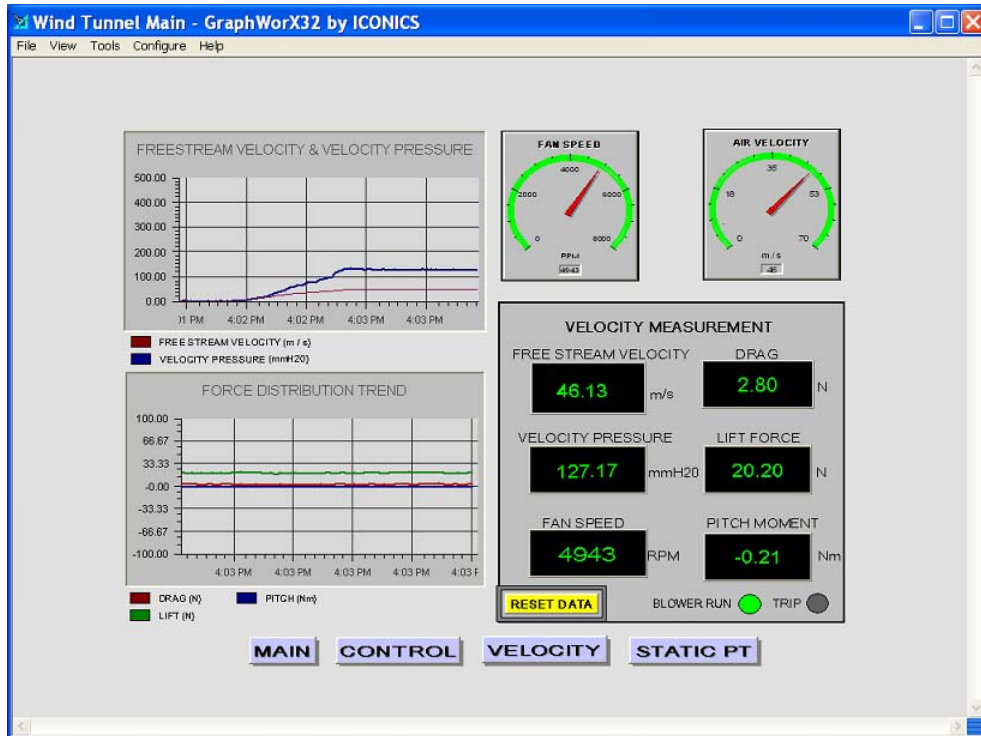


Figure A3.3: 4° angle of attack

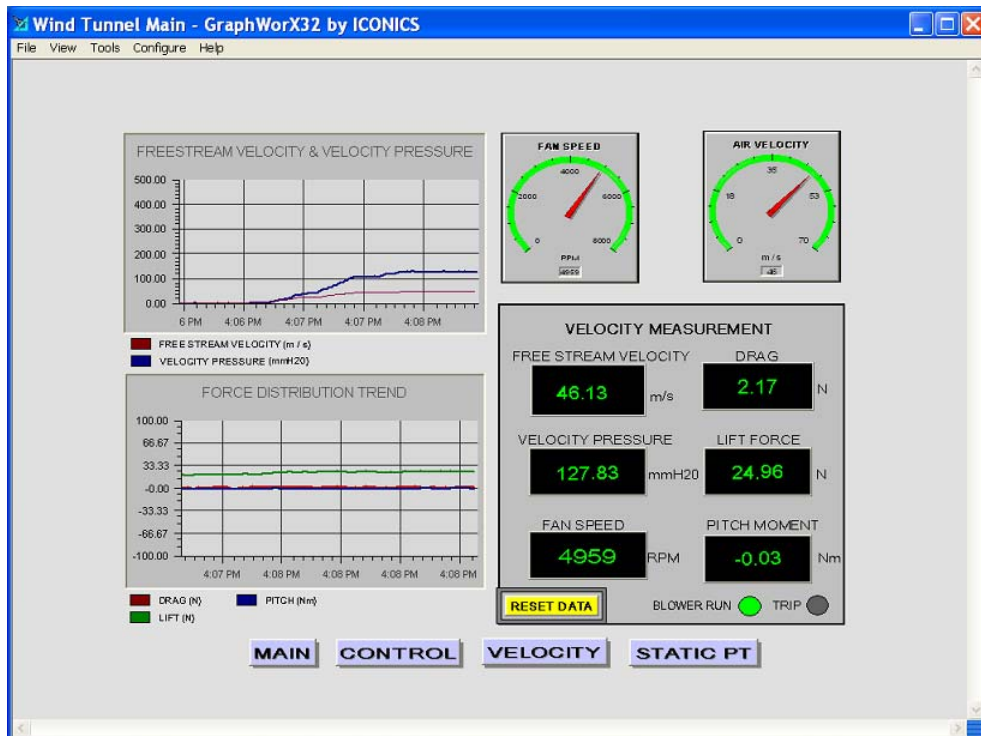


Figure A3.4: 8° angle of attack

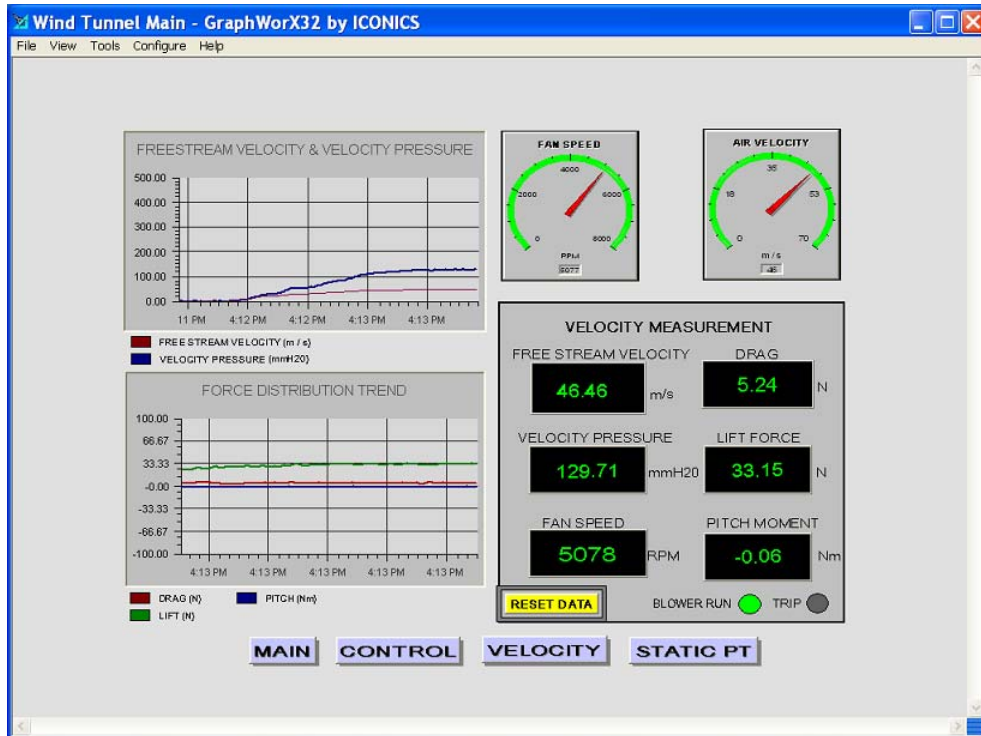


Figure A3.5: 12° angle of attack

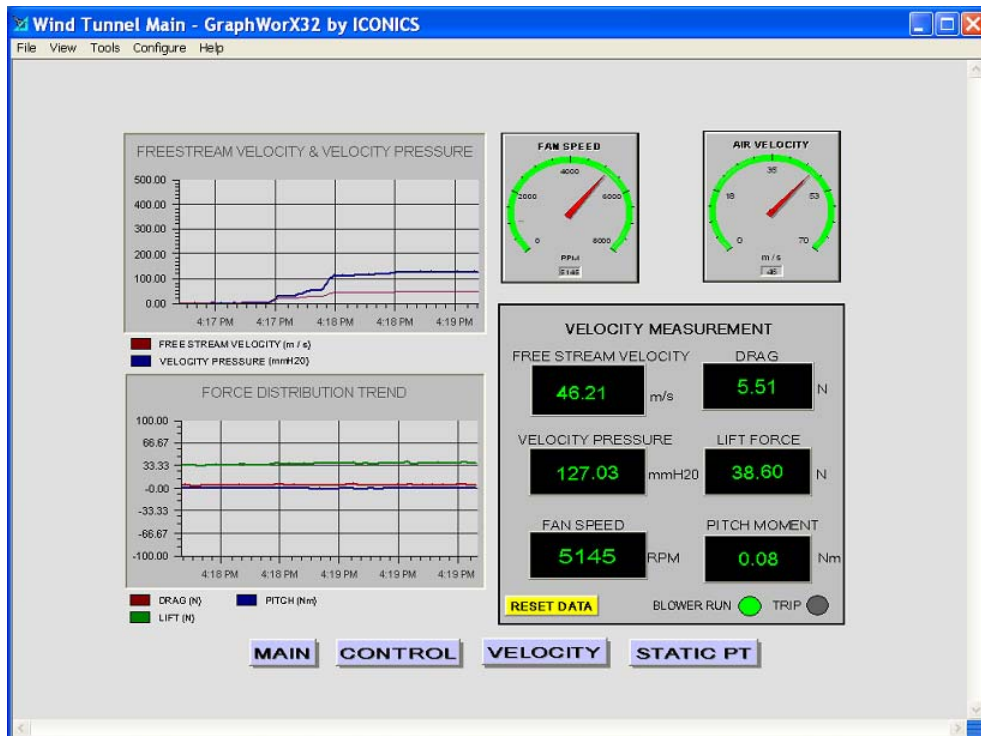


Figure A3.6: 16° angle of attack

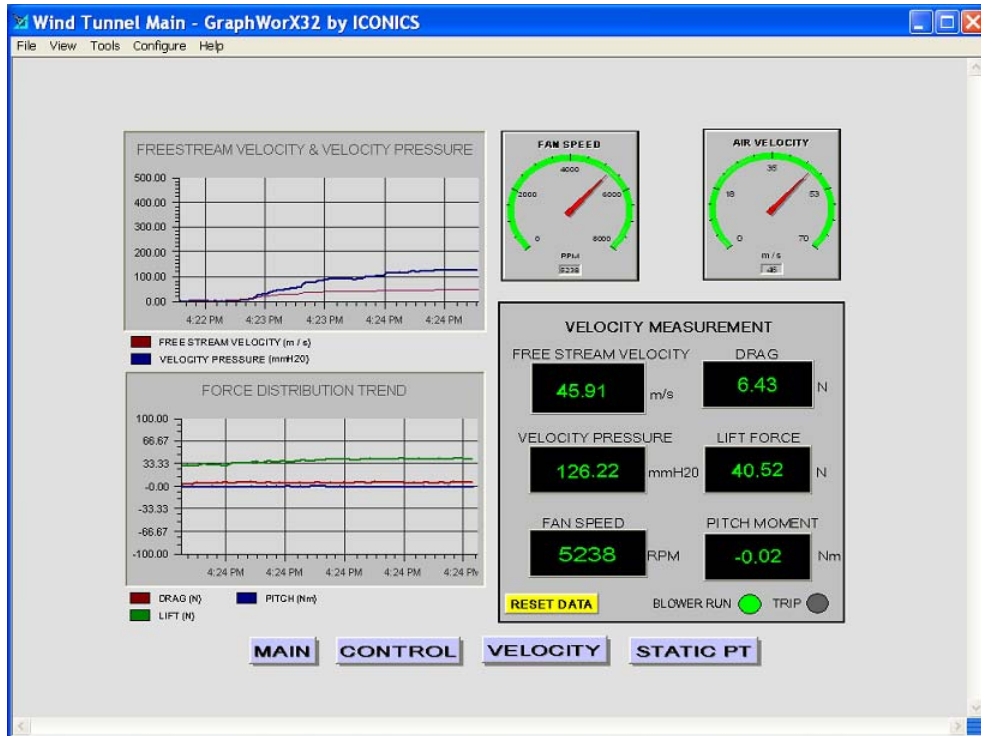


Figure A3.7: 20° angle of attack

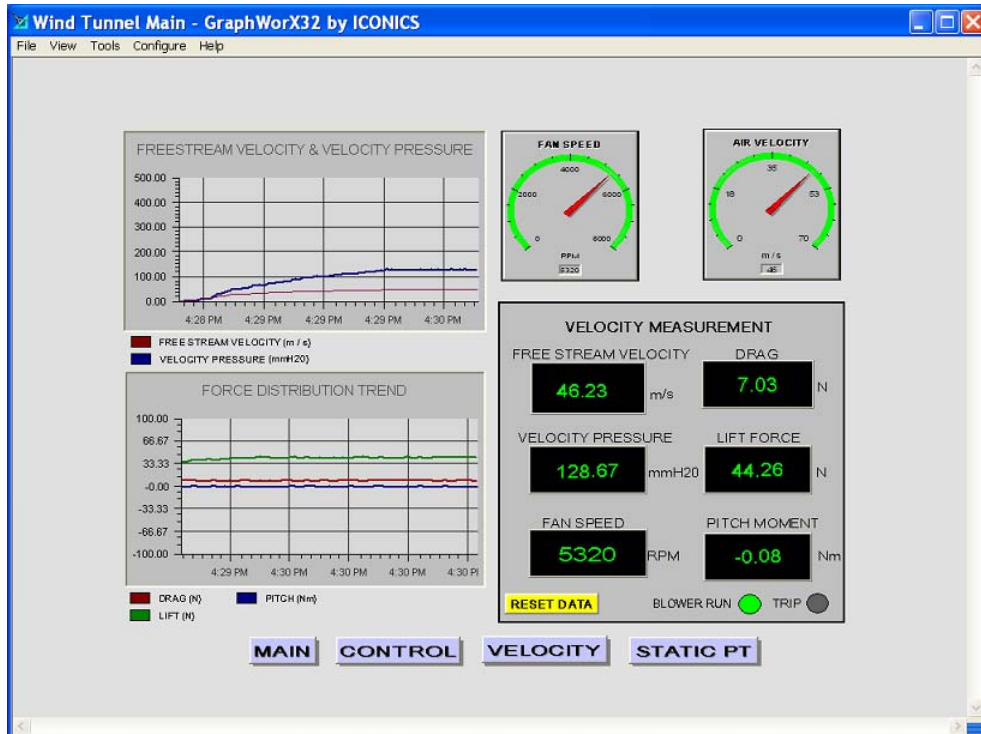


Figure A3.8: 22.5° angle of attack

Appendix 4

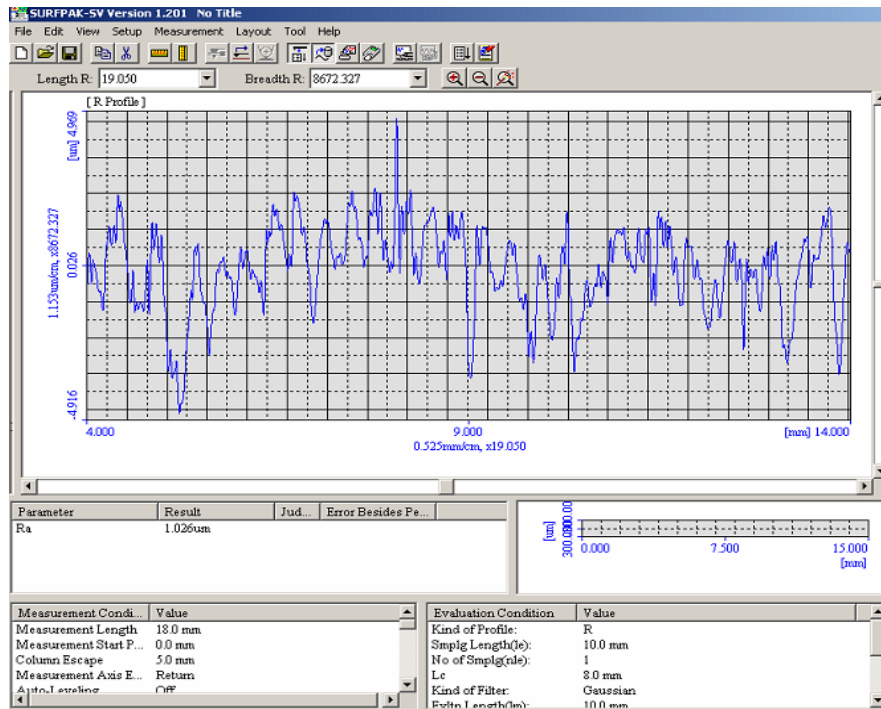


Figure A4.1: Section 1

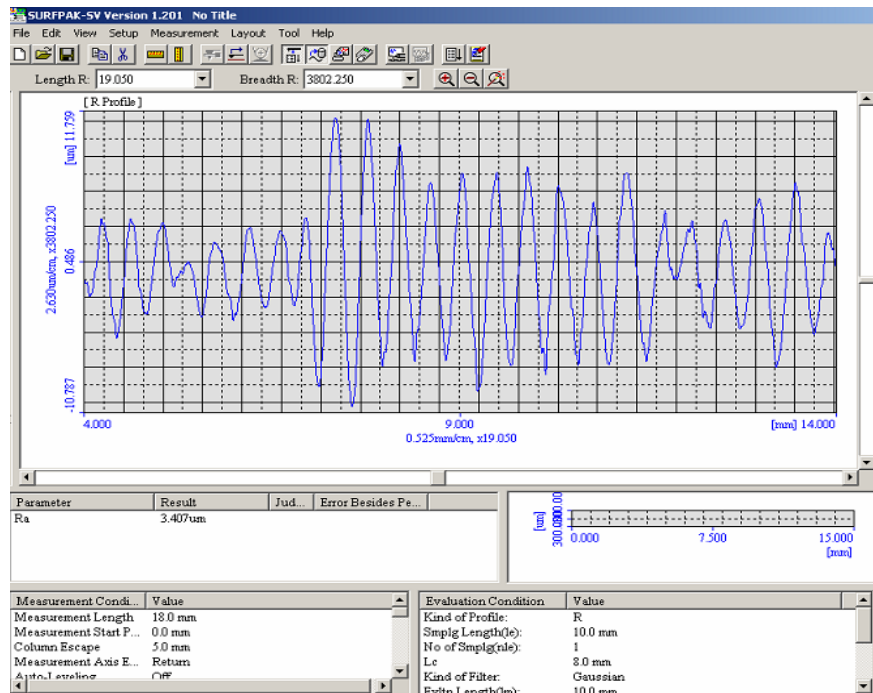


Figure A4.2: Section 2

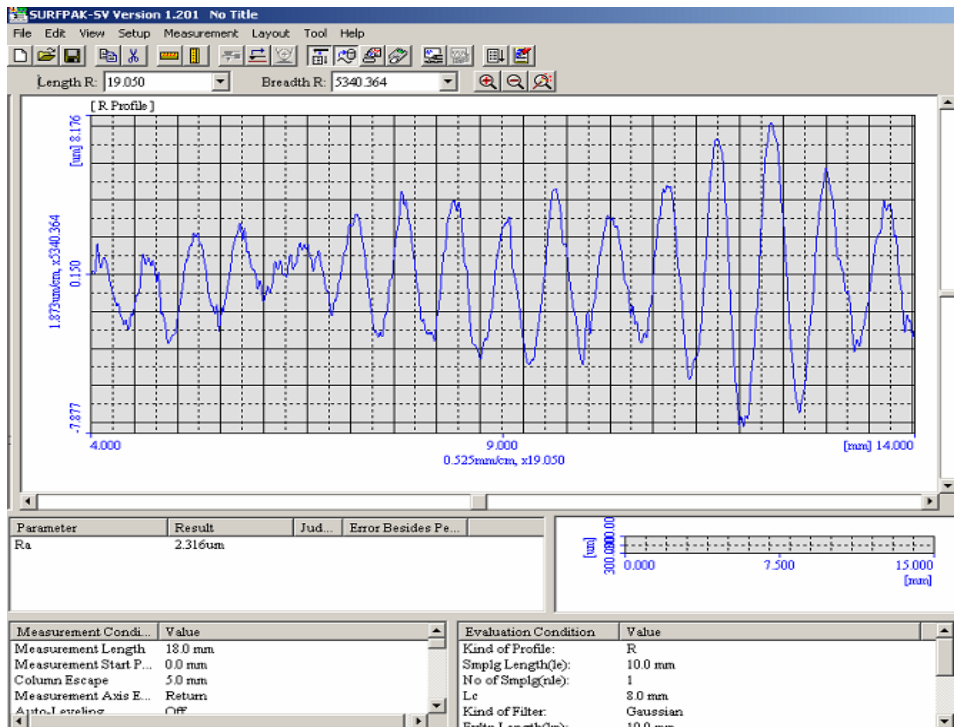


Figure A4.3: Section 3

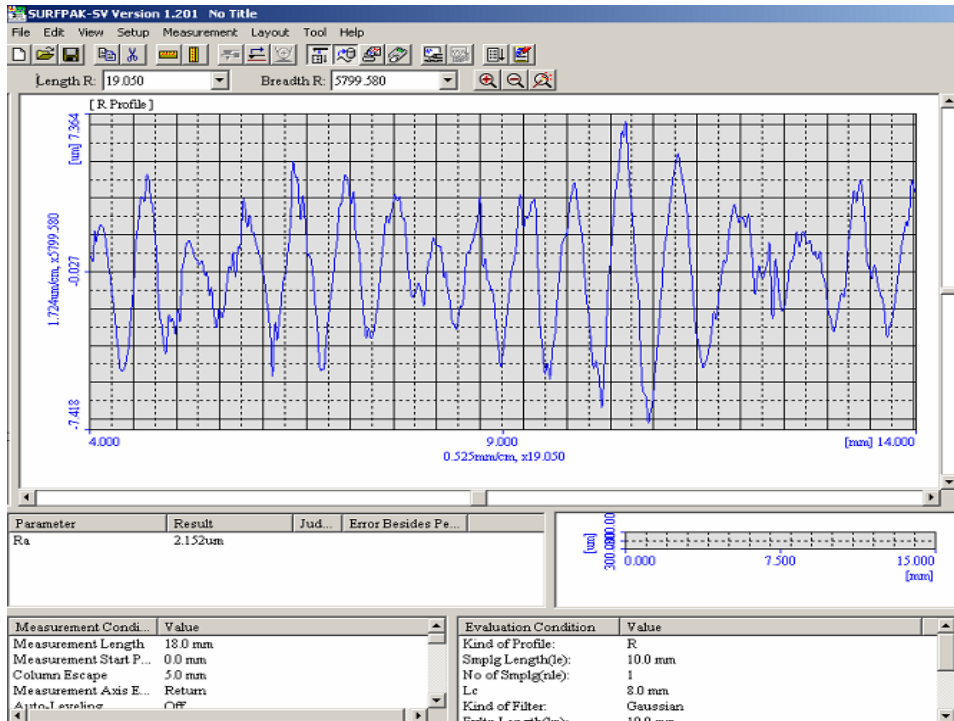


Figure A4.4: Section 4

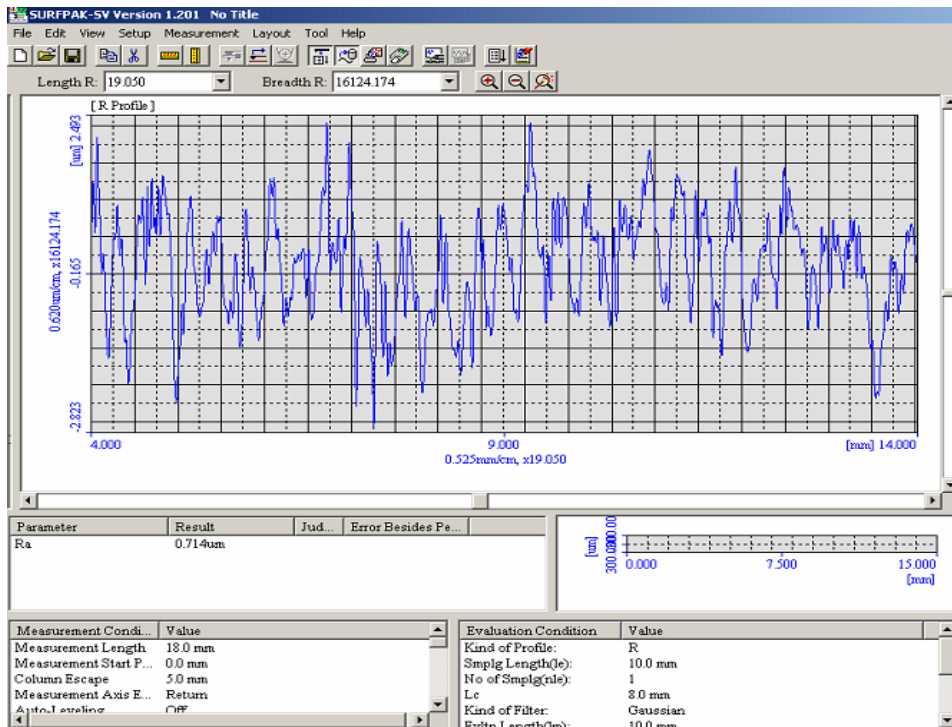


Figure A4.5: Section 5

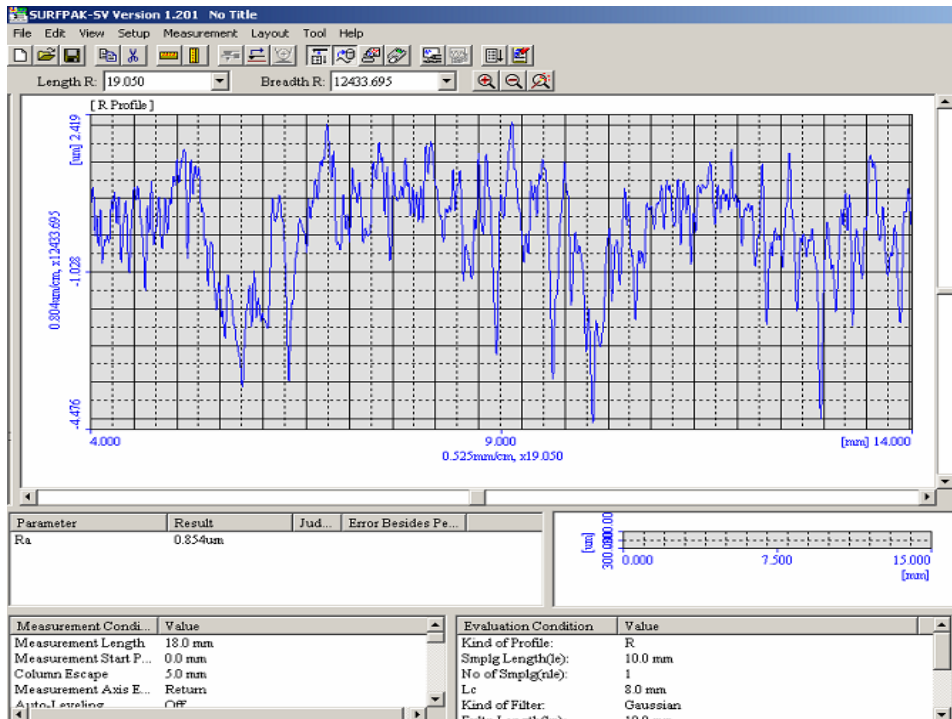


Figure A4.6: Section 6

Appendix 5

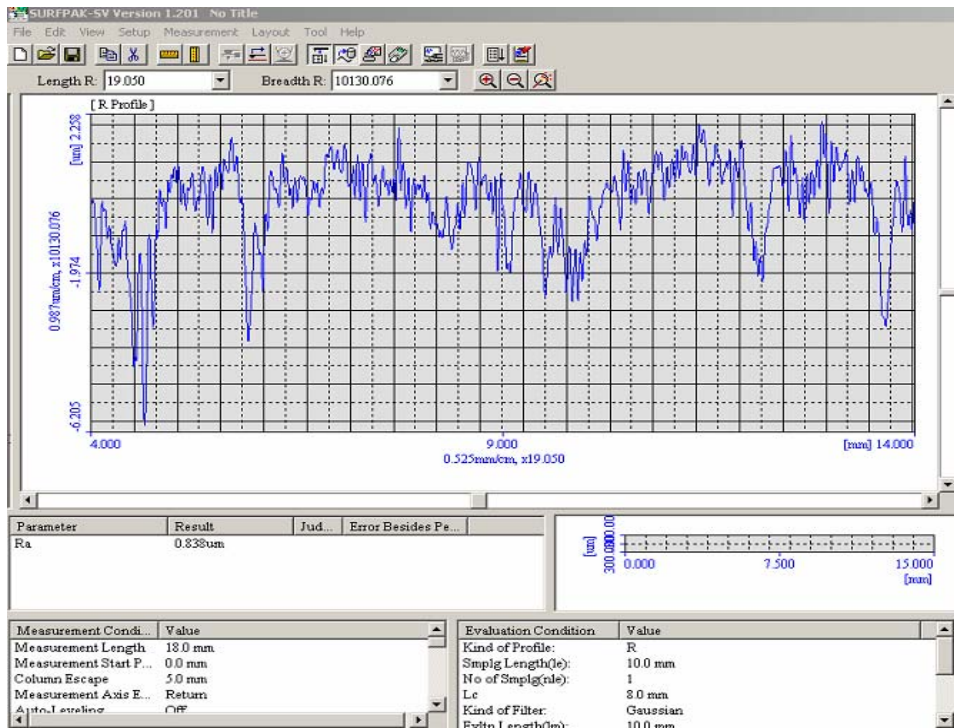


Figure A5.1: Section 1

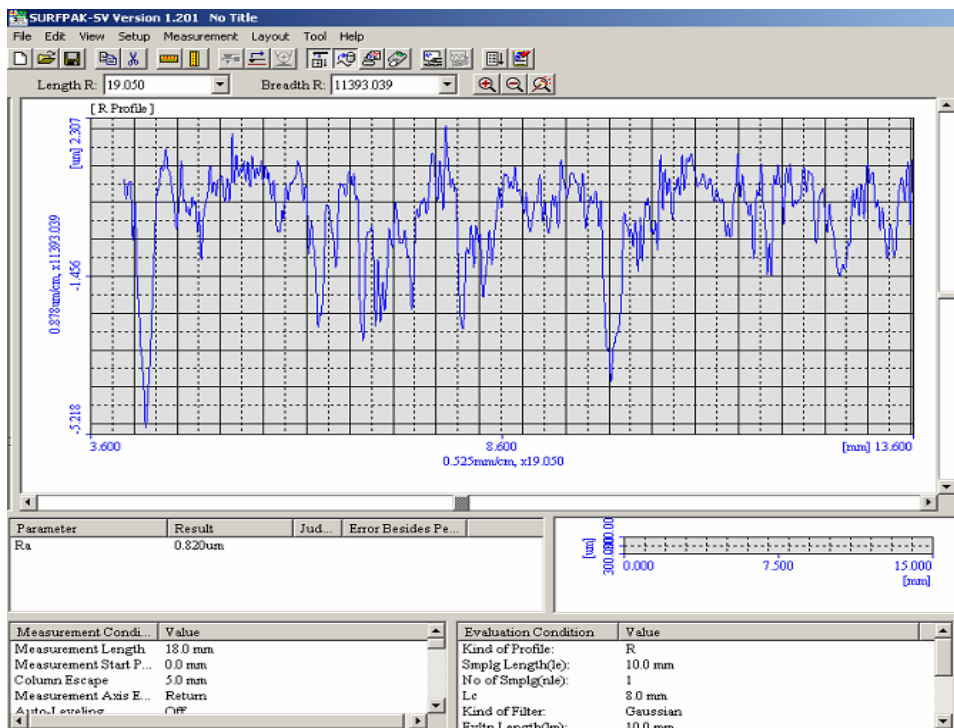


Figure A5.2: Section 2

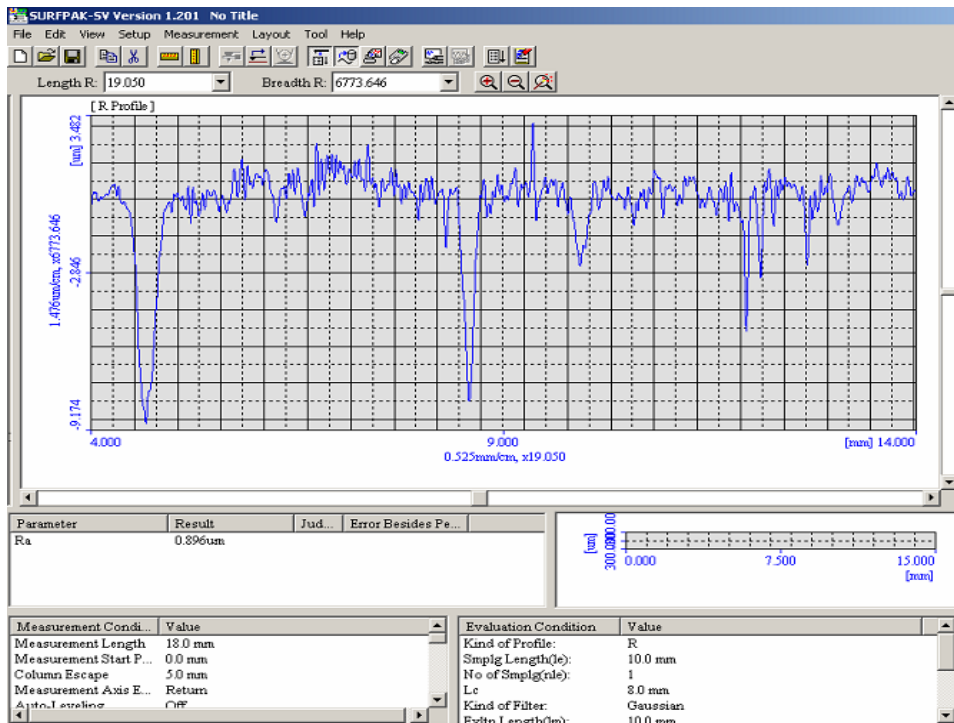


Figure A5.3: Section 3

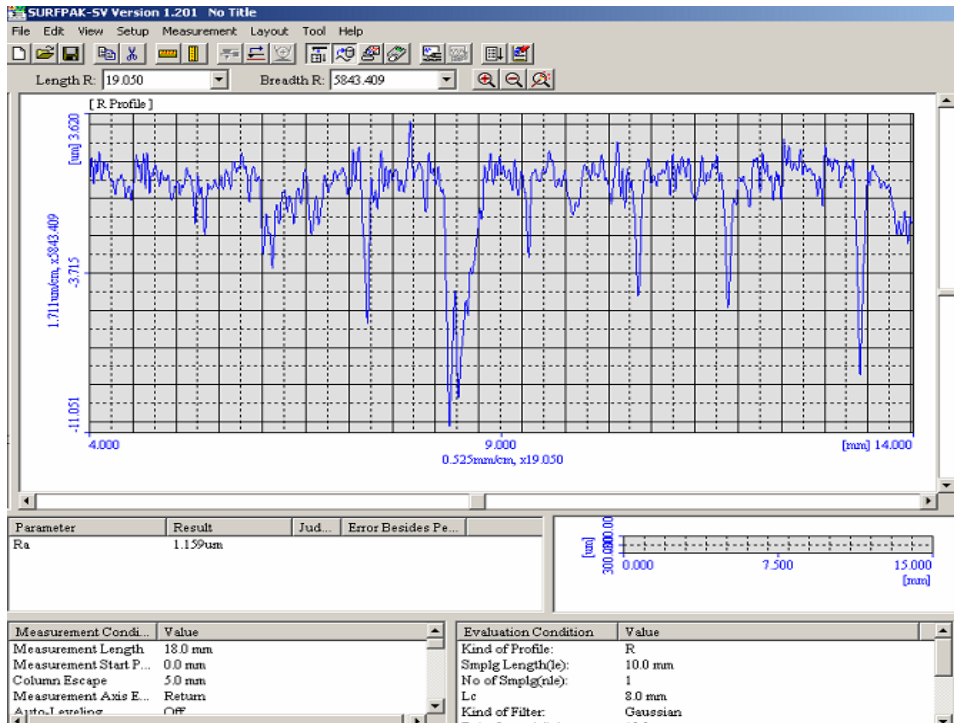


Figure A5.4: Section 4

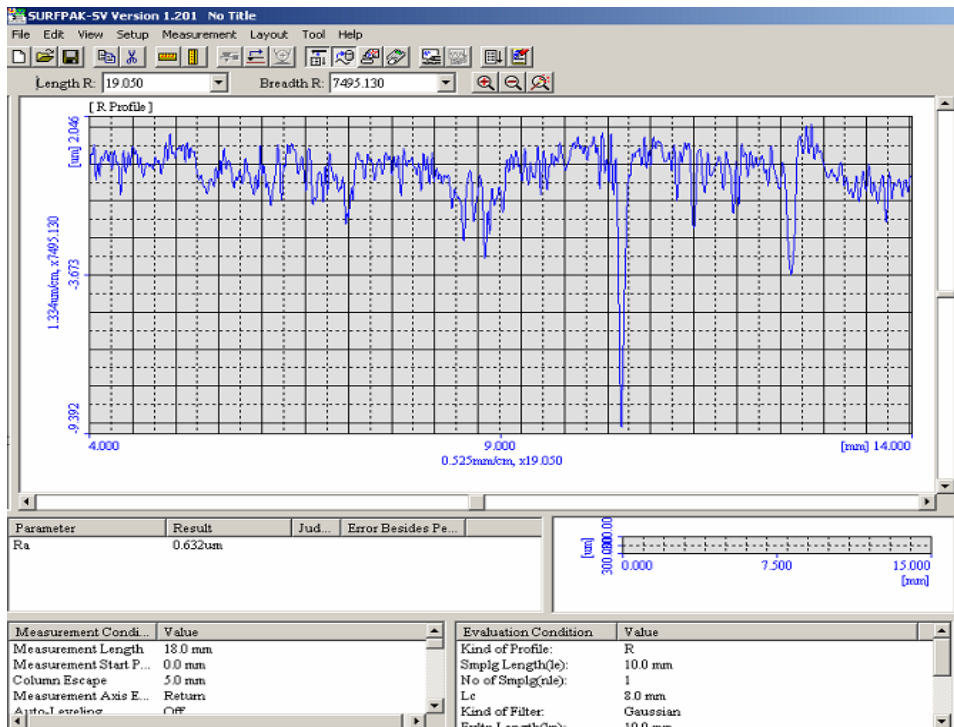


Figure A5.5: Section 5

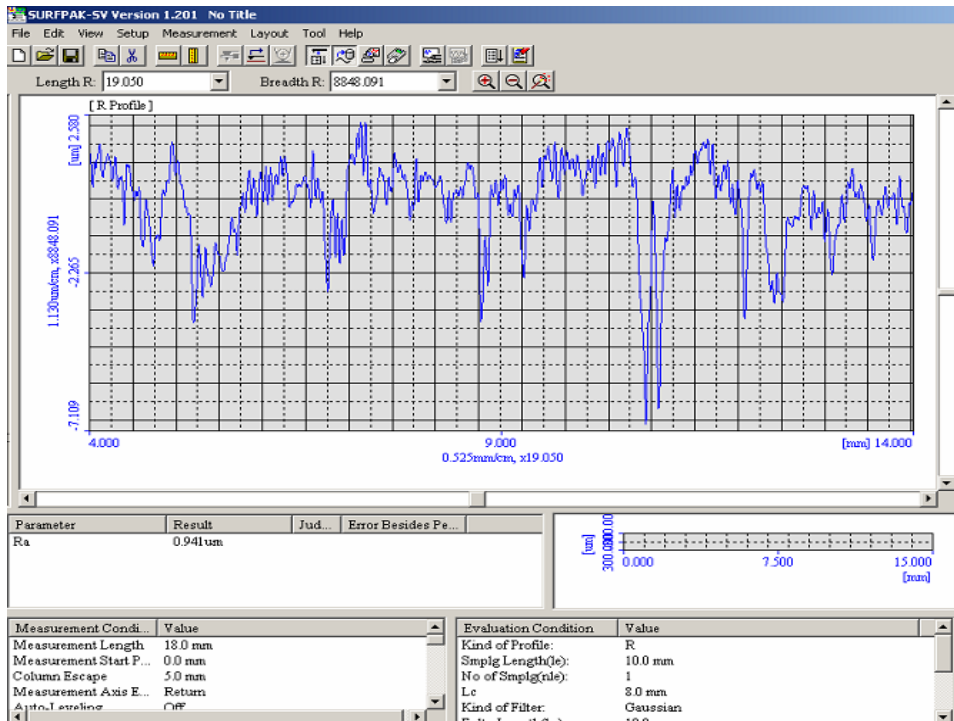


Figure A5.6: Section 6