The Design Improvement of Airfoil for Flying Wing UAV

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Abstract: - This paper intends to presents the design improvement of airfoil for flying wing UAV (Unmanned Aerial Vehicle) when the Author works with Universiti Putra Malaysia. The design was performed using XFOIL code (an interactive program for the design and analysis of subsonic isolated airfoils) and the wind tunnel test results for verification. Eppler E334 (thickness to chord ratio, t/c = 11.93%) is used as a based airfoil. The final design was using Eppler E334 with t/c = 13.5%. It was shown from this work that the result from XFOIL is fairly accurate.

Key-Words: - airfoil design, flying wing, UAV (Unmanned Aerial Vehicle), aerodynamic design

1 Introduction

The importance of UAV in operations and the unprecedented variety deployed today is growing. The UAVs can be used both for military and non-military purposes including coastal surveillance and monitoring of open burning, illegal logging, piracy, the movement of illegal immigrants, agricultural and crop monitoring, search and rescue, weather observations and tracking cellular phones. Indications are that there is a growing market for this type of aircraft.

Like most other next-generation aircraft, UAVs will require low-cost and efficient configurations. Many of existing UAV use conventional (i.e. : low/mid/high-wing, fuselage tail and tractor engine) and unconventional (i.e. : flying wing, three-surfaces, low/mid/high-wing, high aspect ratio wing, fuselage tail/canards/inverted V-tail and pusher engine) configurations. The design of low-cost and efficient configurations of UAV becomes increasingly more important for improving the performances, flight characteristics, handling qualities and UAV operations. Most of small UAV fly at low Reynolds number, this allow to uses fuselage-wing-tail with laminar flow technology, to improve its cruise performance. Therefore, the understanding of and ability to design and analyze those configuration and technology [1, 2 & 3] for UAV is a problem that must be solved in order to allow the UAV designer to develop a UAV which satisfy the prescribe design requirements and objectives.

However, the presence of unconventional configuration and laminar flow technology seriously complicates design and analysis procedures because of important and often complex interaction between the individual elements of UAV often present very different and distinct challenges.

Common people when asked what an airplane looks like and most will answer a tube with wing. But flying wing aircraft is different, flying wing body does not have a conventional aircraft tail, used to control pitch (up and down) and yaw (side to side) motions. Instead it uses a combination of control surface on the trailing edge of the wing to maneuver the airplane. It also does not have a conventional tube type fuselage for payload. All structure, engine and payload are fixed inside the wing. The wing is everything.

Figure 1. Flying Wing Unmanned Aerial Vehicle.

Flying wing have the advantage of having less air drag, hence increasing the lift over drag coefficient, making it more fuel efficient and environment friendly aircraft. For a same engine and fuel capacity, flying wing will have a better range and endurance compared to the conventional aircraft. Figure 1 shows what a flying wing aircraft looks like.

The most importance task in designing a flying wing UAV is the design of the airfoil itself. Since the wing is everything, then the airfoil must be carefully designed. The most important aerodynamic characteristic in flying wing airfoil is to have the coefficient of moment to be zero or close to zero. There are a lot of patented flying wing airfoil can be found flying wing, for example is the Eppler E325 to E343 flying wing airfoil series [4]. Figure 2 shows one of the flying wing airfoil. For the rest of this project, Eppler E334 (thickness to chord ratio, t/c = 11.93%) will be used because it was designed specifically for flying wings with no tail surfaces, and it has the highest coefficient of lift at low Reynolds numbers in the Eppler flying wing airfoil series.

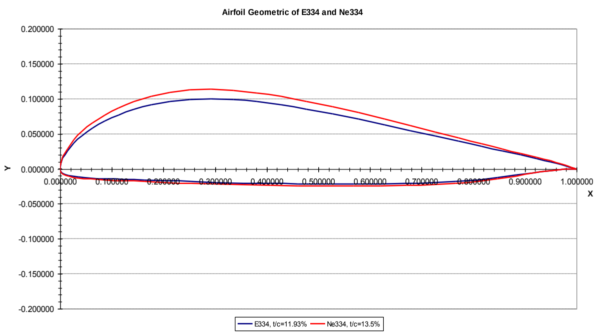

Figure 2. Eppler E334 and new Ne334 airfoil

The first patented airfoil shapes were developed by Horatio F. Phillips in 1884. Phillips was an Englishman who carried out the first serious wind tunnel experiments on airfoil. In 1902, the Wright brothers conducted their own airfoil test in a wind tunnel, developing relatively efficient shapes which contributed to their successful first flight on December 17, 1903.

In the period 1912-1918, the analysis of airplane wings took a giant step forward when Ludwig Prandtl and his colleagues at Göttingen, Germany, showed that the aerodynamic consideration of wings could split into two parts: (1) the study of the section of a wing – an airfoil and (2) the modification of such airfoil properties to account for the complete, finite wing. The approach still used today.

Indeed, the theoretical calculation and experimental measurement of the modern airfoil properties have been a major part of the aeronautics research carried out by the National Aeronautics and Space Administration (NASA) in the 1970s and 1980s.

The questions of whether more advanced configuration and technology would produce significantly better results for UAV remains open. This justifies the need to carryout such a basic scientific investigation.

This paper intends to presents the design of airfoil for flying wing UAV when the Author work with Universiti Putra Malaysia [5].

2 Airfoils Design

For Unmanned Aerial Vehicle (UAV), one of the basic aerodynamic performance objectives is to achieve the highest value of $M(L/D)_{max}$ at the cruise Mach number. Climb and descent performance, especially for short range missions, is also important and may suggest the "cruise" design conditions be compromised.

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XFOIL 1.0 was written by Mark Drela in 1986. XFOIL is an interactive program for the design and analysis of subsonic isolated airfoils. It consists of a collection of menu-driven routines which perform various useful functions such as :

- Viscous (or inviscid) analysis of an existing airfoil, allowing forced or free transition transitional separation bubbles limited trailing edge separation
- Lift and drag predictions just beyond CLmax Karman-Tsien compressibility correction fixed or varying Reynolds and/or Mach numbers
- Airfoil design and redesign by interactive modification of surface speed distributions, in two

methods :
  - Full-Inverse method, based on a complex-mapping formulation
  - Mixed-Inverse method, an extension of XFOIL's basic panel method
- Airfoil redesign by interactive modification of geometric parameters such as : max thickness and camber, highpoint position, LE radius, TE thickness, camber line via geometry specification, camber line via loading change specification, flap deflection and explicit contour geometry (via screen cursor)
- Blending of airfoils
- Writing and reading of airfoil coordinates and polar save files
- Plotting of geometry, pressure distributions, and multiple polars

Over the past few years, bug reports and enhancement suggestions have slowed to practically nil, and so after a final few enhancements from version 6.8, XFOIL 6.9 is officially "frozen" and being made public. Although any bugs will likely be fixed, no further development is planned at this point. Method extensions are being planned, but these will be incorporated in a completely new next-generation code. For this research XFOIL 6.94 code was used.

XFOIL program is using a numerical panel method on the input airfoil geometry to determine the pressure distribution around the surface of the airfoil. The pressure distribution is important to calculate the airfoil aerodynamic characteristics.

2.1 Verification

Verification of reliability of XFOIL program is done using the NACA 4415 airfoil (Figure 3). The NACA 4415 airfoil aerodynamic characteristics, both from XFOIL and reference [6], are shown in Figure 4.

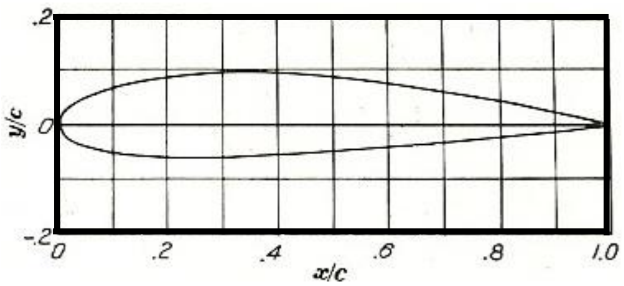

Figure 3. The geometry of NACA 4415 airfoil

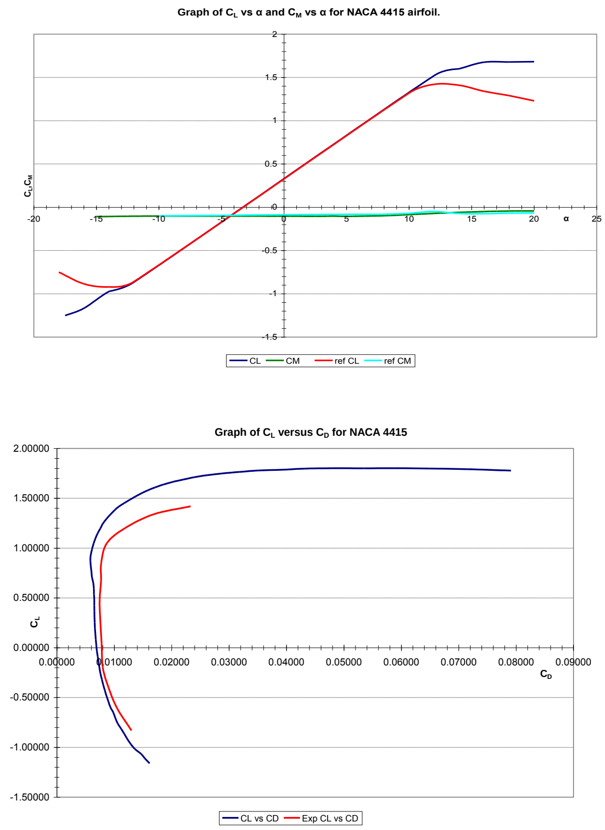

Figure 4. The NACA 4415 airfoil aerodynamic characteristics, both from XFOIL and reference [3] at Re = 3000000

From the above figure, the NACA 4415 airfoil aerodynamic characteristics, predicted from XFOIL is fairly accurate (lift and moment vs angle of attack), especially in the linear region.

2.2 Analysis for a Better Design

In order to increase the structure effectiveness, the new airfoil with 13.5% thickness of E334 airfoil had been designed and named as Ne334 in this project.

The comparison of the geometry and the aerodynamic characteristics (lift, drag and moment) between E334 and Ne334 airfoil are shown in Figure 2, 5 and 6.

Based on Figure 5 and 6, by observation, the pattern of each Reynolds number of $0.8*E^6$, 0.9*E6, $1*E^6$, $1.1*E^6$ and $1.2*E^6$ the variation for the different comparison of aerodynamic characteristic is about the same.

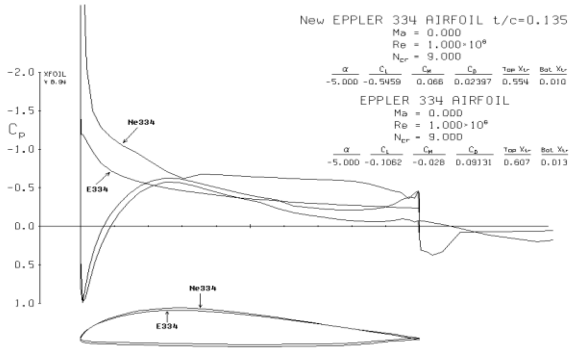

Figure 5a. Graph of pressure distribution over E334 and Ne334 airfoil at α = -5 at R_e = 1*e[6]

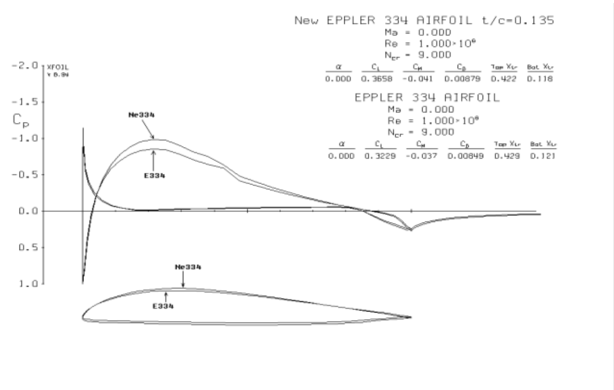

Figure 5b. Graph of pressure distribution over E334 and Ne334 airfoil at α = 0˚ at R_e = 1*e[6]

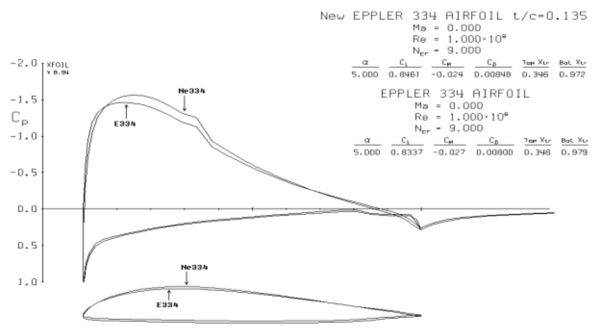

Figure 5c. Graph of pressure distribution over E334 and Ne334 airfoil at α = 5˚ at R_e = 1*e[6]

The maximum lift coefficient of the Ne334 airfoil had significantly increased for every variation of Reynolds number in the same angle of attack to the original Eppler 334 airfoil. This is the most desired results when a new design thickness is applied to an airfoil. If there are no any changing in maximum lift coefficient, the design can be said unsuccessful.

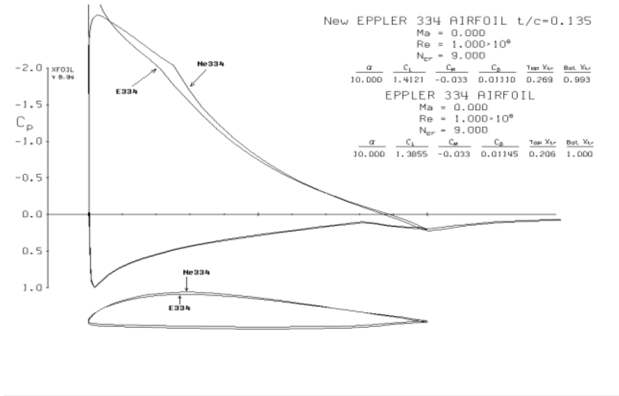

Figure 5d. Graph of pressure distribution over E334 and Ne334 airfoil at α = 10˚ at R_e = 1*e[6]

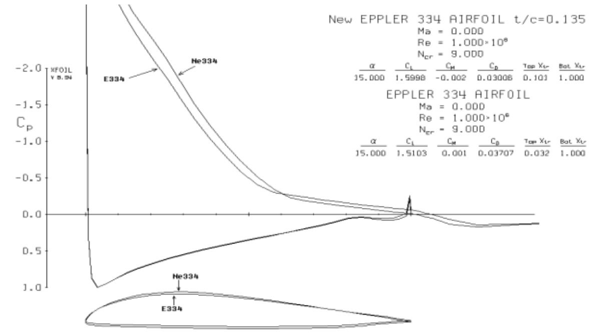

Figure 5e. Graph of pressure distribution over E334 and Ne334 airfoil at α = 15˚ at R_e = 1*e[6]

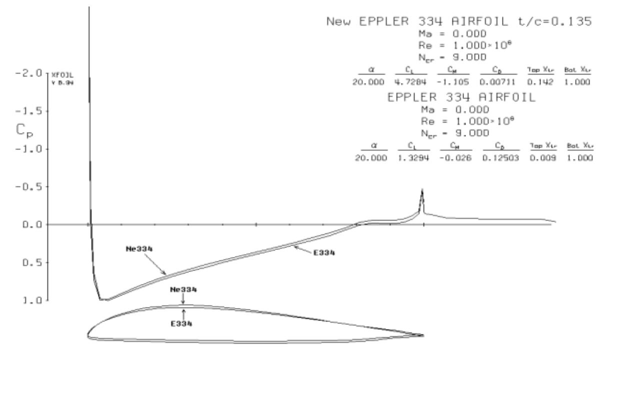

Figure 5f. Graph of pressure distribution over E334 and Ne334 airfoil at α = 20˚ at R_e = 1*e[6]

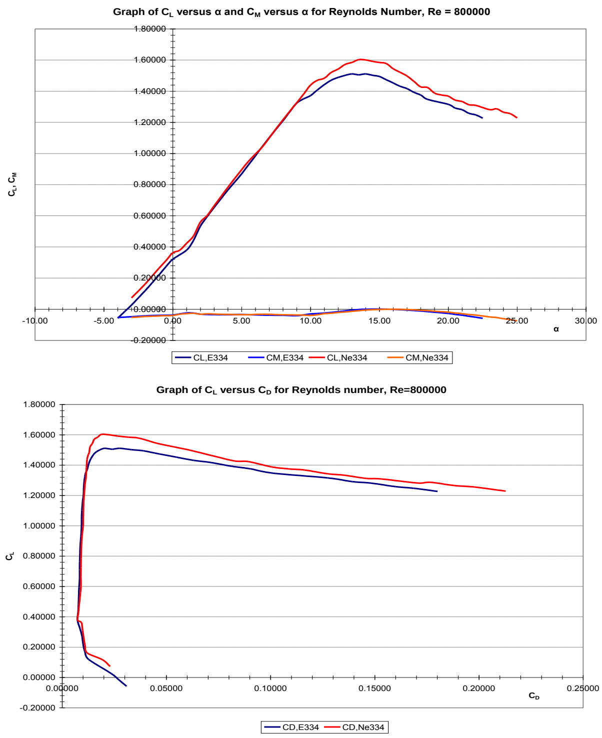

Figure 6a. Graph of comparison between E334 and Ne334 airfoil for C_L versus α, C_M versus α and C_D versus C_L at Reynolds number of 0.8*E^6

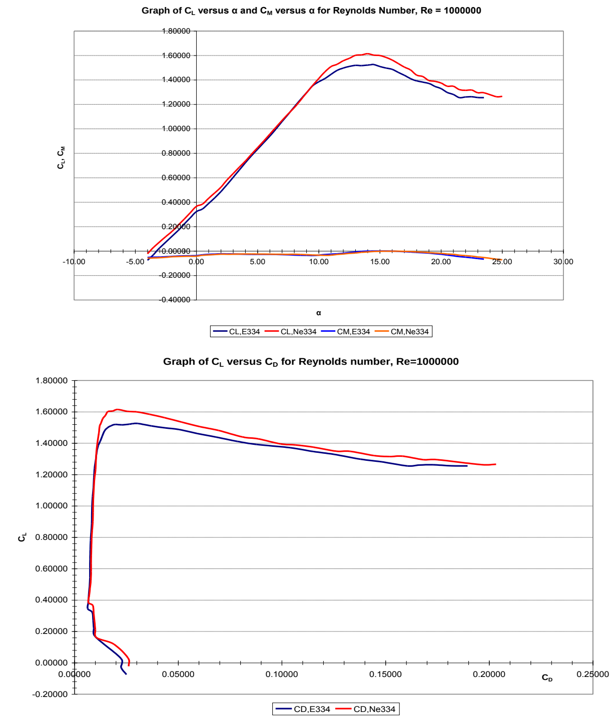

Figure 6c. Graph of comparison between E334 and Ne334 airfoil for C_L versus α, C_M versus α and C_D versus C_L at Reynolds number of 1*E^6

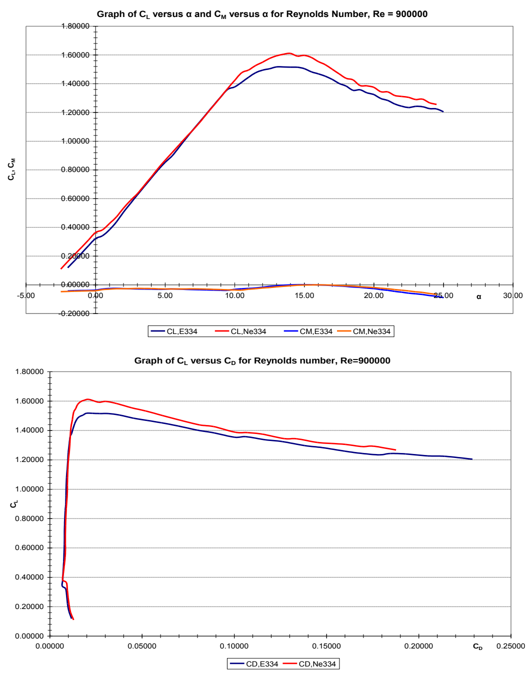

Figure 6b. Graph of comparison between E334 and Ne334 airfoil for C_L versus α, C_M versus α and C_D versus C_L at Reynolds number of 0.9*E6

Figure 6d. Graph of comparison between E334 and Ne334 airfoil for C_L versus α, C_M versus α and C_D versus C_L at Reynolds number of 1.1*E^6

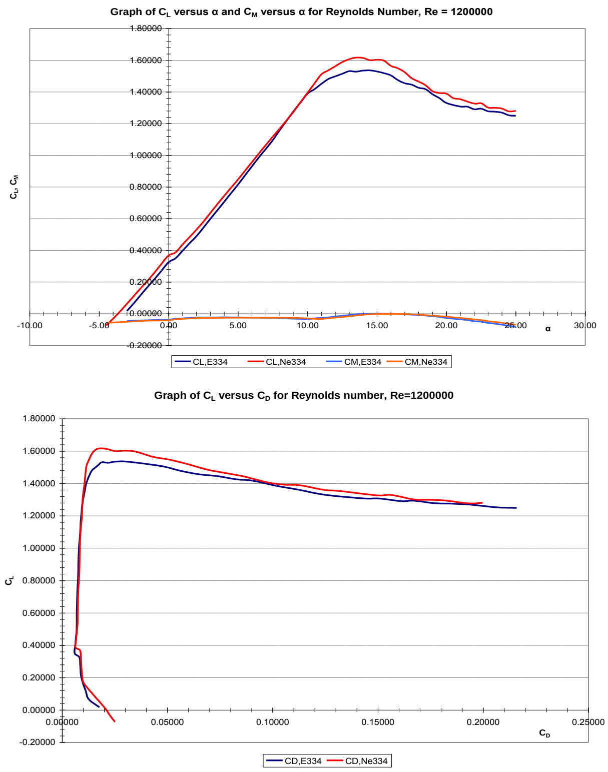

Figure 6e. Graph of comparison between E334 and Ne334 airfoil for C_L versus α, C_M versus α and C_D versus C_L at Reynolds number of 1.2*E^6

Another desired results obtained are that the increased thickness of the new design does not increase the coefficient of moment much. It can be said remaining zero or closed to zero in a certain range of angle of attack. The same results applied to different Reynolds number as well. Since this is a flying wing airfoil, keeping the coefficient of moment as zero as possible is very important because the flying wing UAV needed a moment coefficient of zero during cruise and other operation.

From the results, the Author also found that the zero coefficient of moment is located in an angle of attack that is in the same time, closed to the maximum lift coefficient. The same pattern also occurs in other Reynolds number. This result bring a meaning that the flying wing UAV will able to cruise close to maximum lift while having zero pitching moment.

2.3 Comparison of NACA 44-series with the Ne334 for Different of Thickness

Figure 7 shows the graph of comparison of NACA 44-series with the new Ne334 for different of thickness.

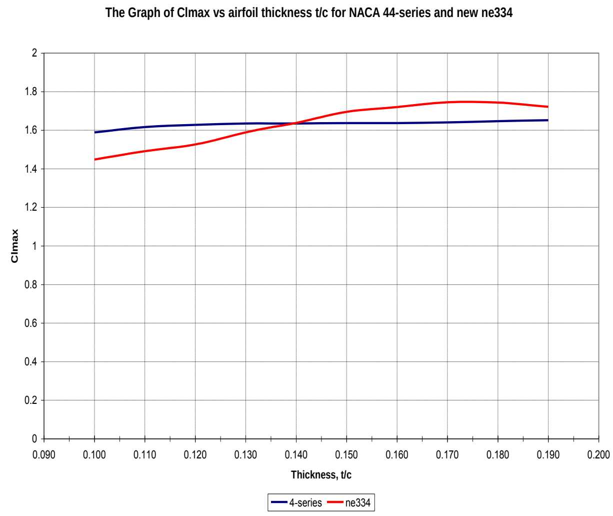

Figure 7. Graph of comparison of NACA 44-series with the new Ne334 for different of thickness

By observation, it can be seen that both of the above airfoils has the same trend, i.e. the maximum lift coefficient has increase with increasing t/c. The maximum lift coefficient of NACA 44-series is continue to increase while the maximum lift coefficient of Ne334 airfoil has reached its maximum value at t/c = 17.4. In this project, the Author had chosen the 13.5% thickness of Ne334 because it has the high coefficient of lift against the drag coefficient [5]. The more the increasing of thickness (higher then 14%) will eventually not giving more lift but induced more drag and higher pitching moment.

3 Wind Tunnel Test

The wind tunnel test used in this research is open loop type, the size of the test section is 1m*1m*1.5m, the maximum velocity at the test section is 50 m/s (Figure 8).

Figure 8. The wind tunnel test at UPM

3.1 Airfoil Model

For this work the velocity at the test section is 24 m/s, the airfoil length is 0.3m, so the Reynolds number (R_N) is 457,261.

The development of the airfoil model is shown in Figure 9. Figure 10 shows the airfoil model in the test section.

Figure 9a. Airfoil is cut to section

Figure 9b. Airfoil is scale to 30cm of chord

Figure 9c. Spar added

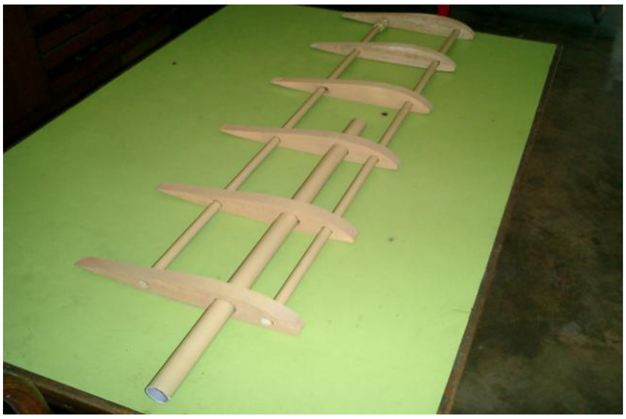

Figure 9d. Center hole is to put the test tube out

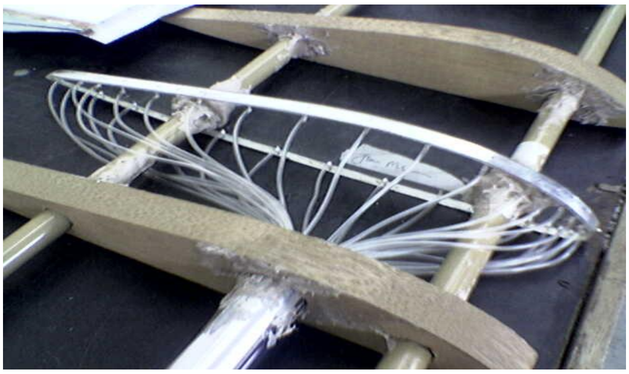

Figure 9e. Test tube added

Figure 9f. Final assembly of airfoil model

Figure 9g. Flush orifices, there are total of 32 orifices in the test model

Figure 10. The test model is fixed in the test chamber of wind tunnel.

3.2 Results of Wind Tunnel Test Model

The wind tunnel computer during the experiment had been encountered breakdown. So the Researcher have to use a manometer to do the pressure different of each different orifice (Figure 11).

Figure 11. Taking reading from the manometer

Figure 12 shows the airfoil pressure distribution, for airfoil Ne334 test model at angle of attack, $\alpha = -5^o, 0^o, 5^o, 10^o, 15^o$ and 20^o.

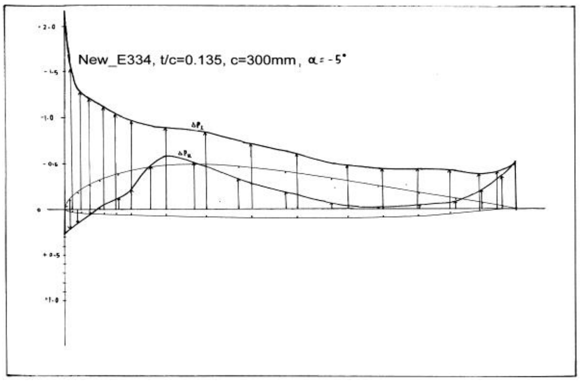

Figure 12a. The pressure distribution of airfoil Ne334 test model at angle of attack, $\alpha = -5^o$.

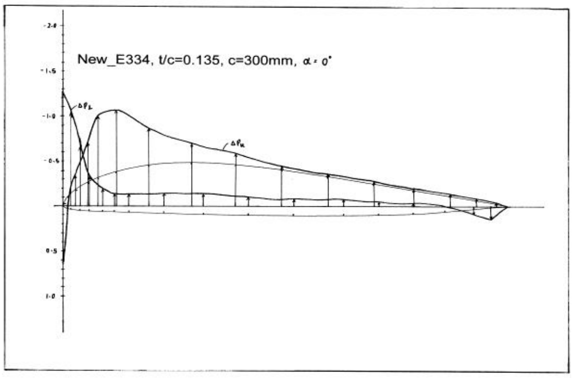

Figure 12b. The pressure distribution of airfoil Ne334 test model at angle of attack, $\alpha = 0^o$.

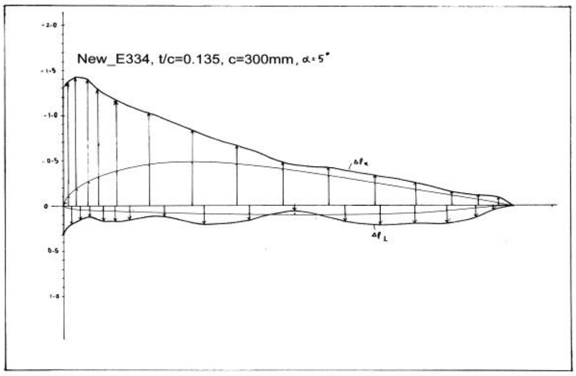

Figure 12c. The pressure distribution of airfoil Ne334 test model at angle of attack, $\alpha = 5^o$.

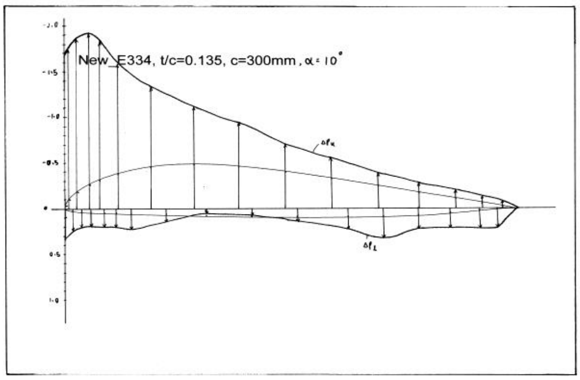

Figure 12d. The pressure distribution of airfoil Ne334 test model at angle of attack, $\alpha = 10^o$.

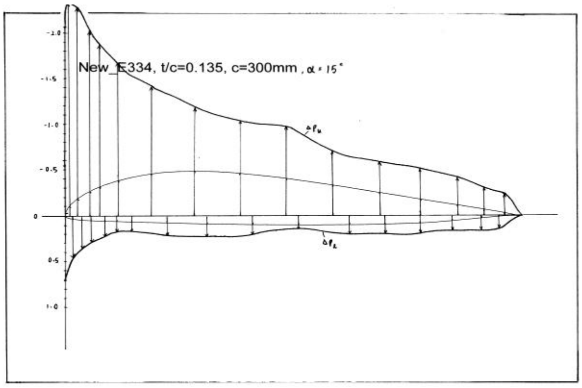

Figure 12e. The pressure distribution of airfoil Ne334 test model at angle of attack, α = 15°.

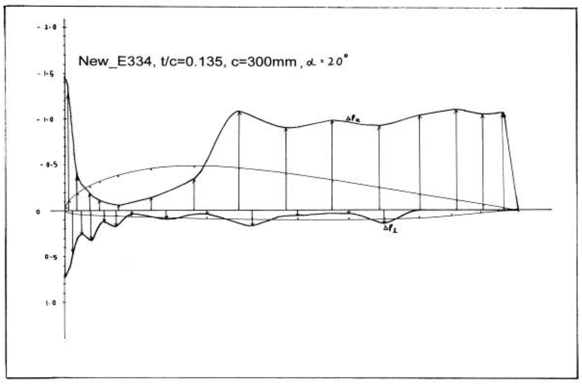

Figure 12f. The pressure distribution of airfoil Ne334 test model at angle of attack, α = 20°.

Based on the calculation of the pressure coefficient, Cp, the coefficient of lift and coefficient of moment in different angle of attack can be obtained, as shown in Table 1 and Figure 13.

	Wind tunnel		XFOIL	
α	CL	Cm	CL	Cm
-5.0	-0.7443	-0.0196	-1.3506	0.2060
0.0	0.5162	0.0158	0.3252	-0.0330
5.0	1.1529	0.0247	1.0315	-0.0640
10.0	1.4757	0.0315	1.3935	-0.0320
15.0	1.7268	0.0349	1.5561	0.0010
20.0	1.1078	0.0905	1.3383	-0.0200

Table 1. Comparison between wind tunnel test model and XFOIL results for C_L versus α and C_M versus C_L for Ne334 airfoil at Re = 457261

By observation, the wind tunnel test results have a very similar results with the computer generated results from XFOIL program. From the above comparisons and the results from Figure 5 and 6, the wind tunnel test is giving a confirmation of the Ne334 have a better performance compare to the original airfoil.

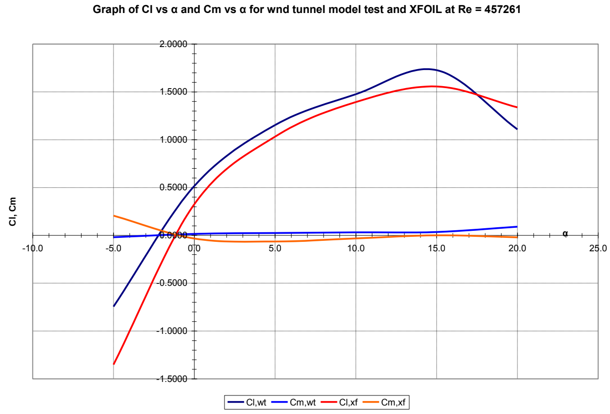

Figure 13. Graph of the comparison between wind tunnel test model (wt) and XFOIL (xf) results for C_L versus α and C_M versus C_L for Ne334 airfoil at R_N = 457,261

The errors which occur at the wind tunnel test can be narrow to some of the effect as following :

a. Due to the wind tunnel computer during the experiment had been encountered breakdown. So human error should happened as taking the wrong results when reading the manometer.
b. The airfoil model test is a hand build model to obtain a cheap model test. So the model unlike some model that had been made by computer using laser cutting, it have some different with the ideal designed airfoil from the computer. In fact, the thickness of the test model is slightly bigger than 13.5%. So it gives in the graph, a higher C_L with the XFOIL results.
c. The scale factor of the manometer has a minimum of 1mm scale. So the pressure different that lower than 1mm can not be read, this will effect the accuracy of the results.
d. Without the computer generated results to get coefficient of pressure, Cp. The reseacher has to manually draw the Cp in the graph paper. The coefficient of lift C_L and coefficient of moment C_M calculation is based on the area of Cp different of upper airfoil surface with lower airfoil surface. So, when using the graph to calculate the area, many errors can occur such as the human reading error, plotting error and area calculating error.

But by the end, the results are satisfied and the comparison of the computer results is consistent with the wind tunnel test results. The design of Ne334 can be said a successful and confirmed of its good performance but yet low pitching moment.

4 Conclusions

With all the results obtained, from aerodynamic point of view, the Author can conclude that a Ne334 with 13.5% thickness is a better design that surpass it original airfoil geometric of Eppler 334. Hence, this new airfoil can be use for the building of low Reynolds number Flying Wing Unmanned Aerial Vehicle.

Regarding to the usage of XFOIL program, from the results, the Author found that XFOIL program is only valid up to a certain range of angle of attack. Hence, when using this program, ones should be careful with the results. However, there are still many part inside XFOIL program are remain unexplored in this project, such as the boundary layer profile and the skin friction coefficient. The Author believed the accuracy of the results can be improved if all the remaining parameter is taken into account.

Finally, the Author hope that this project might make some contributions towards a better understanding for other researcher in the future that are working either the Flying Wing UAV or the XFOIL program.

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