Modelling Flow around a NACA 0012 foil

A report for 3rd Year, 2nd Semester Project

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Abstract

The third year project consisted of using open source software (OpenFoam) to model 2D foils – in particular the NACA 0012. It was found that although the flow seemed to simulate what should be happening around the foil, the results did not agree with test programs and approximate theoretical values. Using X-Foil, a small program that uses a panel method to find the lift, drag and pressure distribution by a boundary layer evaluation algorithm we could compare the results obtained from OpenFOAM. It was determined that the discrepancies in the lift coefficient, drag coefficient and pressure coefficient could be due the mesh not accurate enough around the leading and trailing edge or that unrealistic values were used. This can be improved by refining the mesh around these areas or changing the values to be close matching to a full size helicopter. Experimental work was also completed on a 65-009 NACA foil. Although the data collected from this experiment could not be used to compare any results made in OpenFOAM, the techniques learnt could be applied to future experiments to improve the quality of data taken.

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1.0 Introduction

The short-term aim of this project is to model stall patterns at varying angles of attack on helicopter NACA foils. This was done using open source software OpenFOAM; a program established in 2004 using a Linux based system to be able to do 3-D models of objects. In the long term, modelling the flow around a 3 dimensional rotating helicopter blade will be the goal.

OpenFOAM is an open source computational fluid dynamics (CFD) which solves and analyses problems and simulates the effects. This is useful when the problems get hard to solve using calculations alone. The way OpenFOAM works is by using a steady-state solver for incompressible, turbulent flow (OpenFOAM User Guide 2010) using Bernoulli's equation ($1/2\ v^2 + gz + P/p =$ constant where v is the velocity and P is the pressure) so that conservation of matter, energy and momentum can be conserved. The program calculates the users' interest (pressure, lift, drag, separation) at each intersection of the mesh; so the closer the mesh is made, the higher the accuracy in each point of data will be. This is because ideally, the mesh should be continuous, however it is simulated discretely and so the closer the points are: the closer it will be to simulating (but never reaching) a continuous analysis of the problem.

The way in which this project was completed was by a step-by-step basis. Using OpenFOAM, a blockMesh was designed that simply outlined the NACA 0012 foil inside a 3-D block. However, this first step that I've taken is only a pseudo 3-D case; as the 3rd dimension (z axis) was just given constant values. This is shown using paraView in Figure 1: using paraView to view the blockMesh, a viewing tool of OpenFoam. 5 blocks were used to create the blockMesh. Block 5 was created for the purpose of defining a tighter mesh around the leading edge so that the flow would be as smooth as possible.

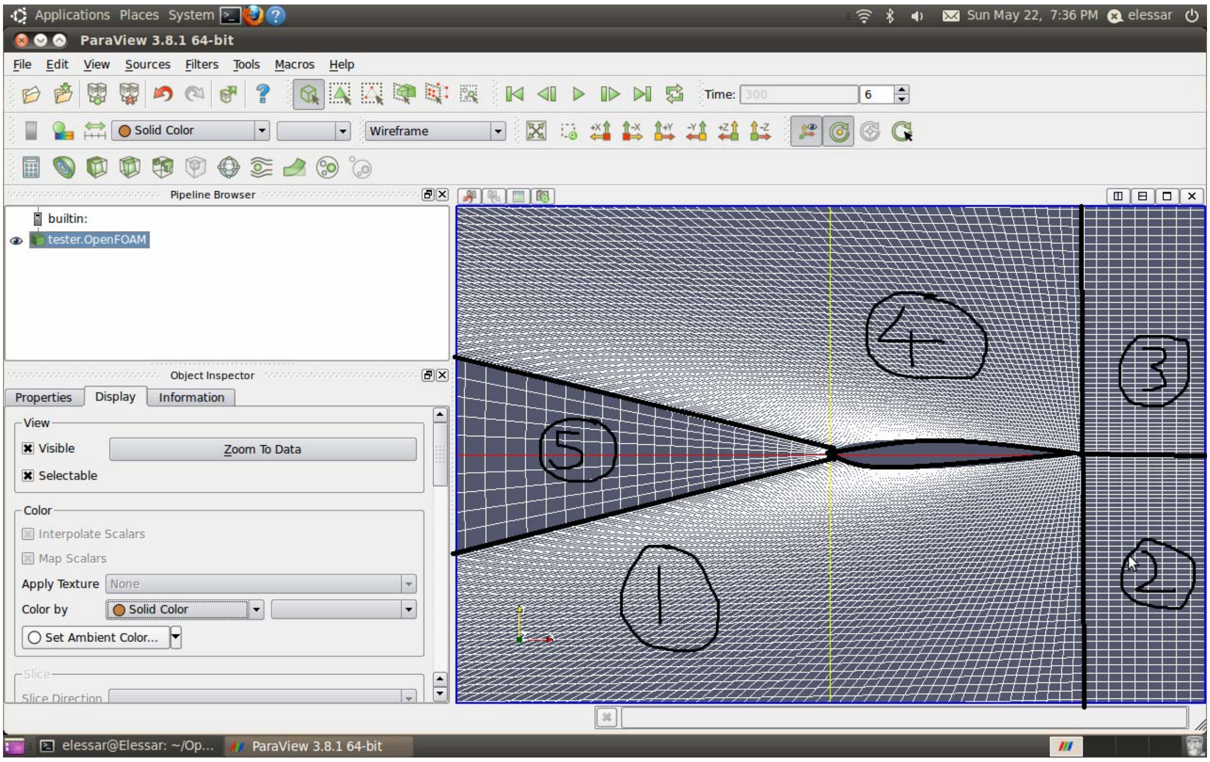

Figure 1: using paraView to view the blockMesh

The next stepis to use a function called snappy-hex mesh which would create a hexagon 3-D mesh, and then start to pull back the lines to create the desired shape. This would give a true 3-D model. Observing the stalling patterns which includes the pressure distribution, lift/drag coefficients and separation effects when using different angles of attack, these can then be compared to the patterns obtained using a wind tunnel, X-foil (a 2D analysis program) or other researchers work. Using this 3D model, a rotating selection of 4 blades should be possible. Although, given the limited amount of time on the project we did not get to this.

2.0 Theory

When an object is immersed in a fluid, usually water or air, it has certain flow patterns around it. This object is called a foil and has a number of characteristics. The boundary layer on a foil is the thin layer of fluid, which will be air in the case of this project, where the speed is virtually zero next to the surface of the foil, and full speed at the edge of the layer (White 2008). In between is what can be described as sheets of air moving at different speeds over each other. How they move is what makes up the different sections in the boundary layer. There is typically 3 sections (see Figure 2for the location of each on a foil); laminar, turbulent, and a separated boundary layer. The laminar boundary layer is generally where the fluid is a smooth flow around the surface of the object; most typically at the leading edge, and also has lower resistance than the other regions. Before the turbulent boundary layer, there is a transition period. The transition period is very short and is related to the Reynolds Number; a coefficient that is the velocity multiplied by length on resistance, and roughness of the foil. The turbulent boundary layer is where the fluid is described as chaotic, and this is normally occurring when the air speed is high. The separated boundary layer occurs when the fluid near the surface of the object reverses direction and can lift the boundary layer off the surface; it is the breakaway of a boundary layer from the foil. The boundary layer and the positions of the components are important when looking at the air flow around a foil, as it can determine what will happen at higher and lower speeds and what will happen to the lift and drag coefficients.

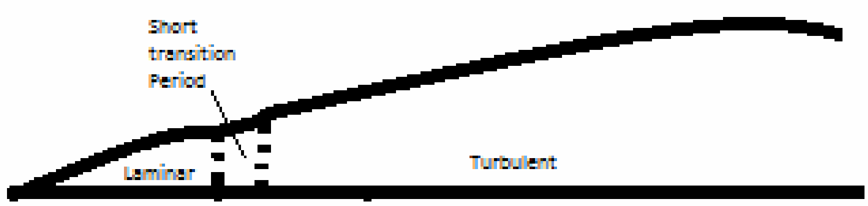

Figure 2: A basic picture showing where the boundary layers are.

Foils are designed in a vast amount of ways. One difference in each is the camber, also called the curvature, on the upper and lower surfaces (upper and lower camber in Figure 3). Cambered foils tend to have a higher maximum coefficient of lift as it takes higher angles of attack to stall. A symmetric foil has zero camber and works much better than a highly cambered foil at lower angles of attack (Airfoils and Airflow 2005). These foils are often assigned numbers from the NACA corresponding to their properties. NACA, the National Advisory Committee for Aeronautics was a research group which tested and developed many series of foils – this group is now known as NASA. For the four digit numbers, the first number describes the maximum camber as a percentage of the chord length. The second number is the position of the maximum camber in tenths of the chord and the third and fourth number corresponds to the maximum thickness of the foil as a percentage of the chord length (NACA Profiles 2010). The well-known NACA 0012 foil which will be used in this project is symmetrical as both first and a second number are zero, and has maximum thickness of 12% of the chord length.

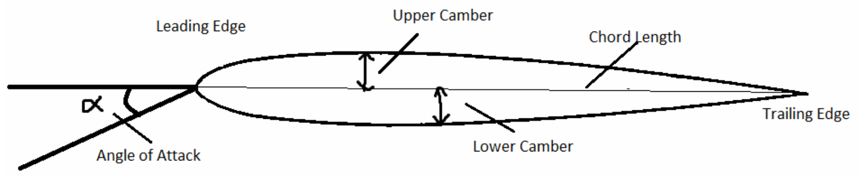

Figure 3: An image showing the various components of a foil .

Helicopter blades use relatively thick airfoils and are symmetrical. This is primarily because of the stability they provide. This is done by keeping the centre of pressure a constant along the blade, even as the angle of attack changes and hence no unnecessary movement. Where the flow meets the foil and separates to the upper camber and lower camber, this is called a stagnation point. This point has the highest pressure and a pressure coefficient of 1. For lift on a symmetrical foil, there must be an angle of attack, from Bernoulli's principle (Equation 6) and White (2008, 495). This is so that there is a higher pressure on the lower surface and a much lower pressure on the upper surface of the foil. The lift can be increased flow speed and also the angle of attack. Ideally a bit of both to optimise the lift, without having a stall effect and to also decrease the drag.

In three dimensional flows, and the ends are finite, an equalisation of pressure at the end causes some of the flow from the high pressure region go to the low pressure region; a tip vortex as seen in Figure 4. This leads to loss of lift force and induced drag.

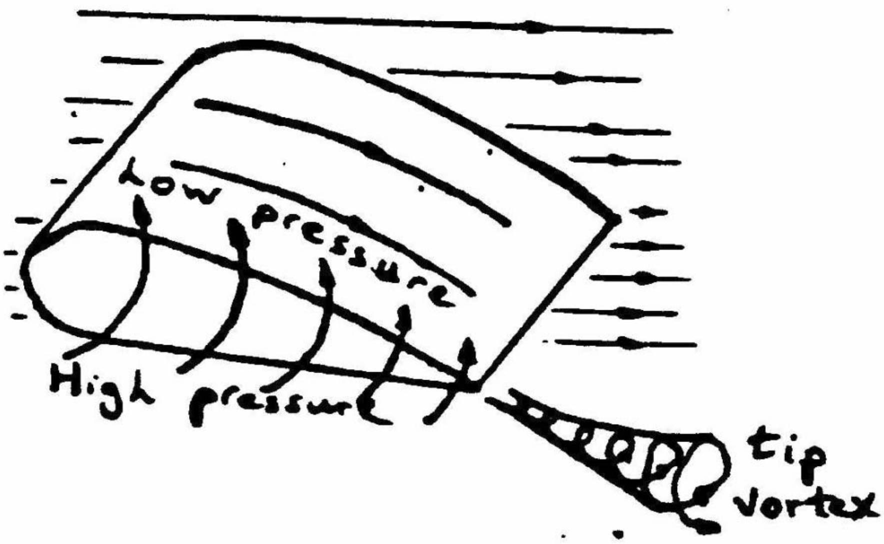

Figure 4: A figure showing the basic flow a 3D foil with finite span (courtesy CMST)

There are some equations that were used in the project (White, 2008).

The Reynolds number is the non-dimensional frictional resistance. Where μ is the dynamic viscosity ($1.86 * 10^{-5}$ Pa·s), V is the flow speed (150 m/s), L is the camber length (3m) and ρ is the density of the fluid (1.204kg/m^3).

Equation 1: Reynolds number

$$Re = \frac{\mu V L}{\rho}$$

The lift calculation is lift produced by the foil. Where A is the area of the foil and C_L is the lift coefficient.

Equation 2: Lift calculation

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

The approximate lift coefficient is defined for thin foils only where α is the angle of attack in degrees.

Equation 3: The approximate lift coefficient for thin foils

$$\sim C_L = 2 * \pi * \sin(\alpha)$$

The drag of the foil can be calculated. C_D is the drag coefficient.

Equation 4: Drag calculation

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

The pressure coefficient is calculated where P is the actual pressure and P_∞ is the free stream pressure.

Equation 5: Pressure coefficient calculation

$$C_p = \frac{P - P_\infty}{\frac{1}{2}\rho V^2}$$

Equation 6: Bernoulli's equation

$$\frac{V^2}{2} + gz + \frac{P}{\rho} = Constant$$

4.0 X-Foil Results

X-Foil makes a good comparison program as it is a simple program that analyses 2D subsonic foils, including the NACA 0012 which has already implemented coordinates (X-Foil, 2008). Written in FORTRAN and using the panel method, boundary layer evaluation algorithm, the program is able to find the lift, drag and pressure distribution. X-Foil is also very accurate in predicting the transition period to turbulent.

Using constant values and boundary conditions for both OpenFOAM and X-Foil, analysis of both could be completed and comparable.At the hub of a helicopter blade, the speed around the foil is generally very low, yet at the tip it is close to the speed of sound. For the sake of simplicity and for comparison, a medium value has been used; the stream velocity is 150 m/s. A constant value of 3m for the length has been chosen and the density and dynamic viscosity are at 20 degrees Celsius. The inputs are outlined in Table 1.

Table 1: Inputs and boundary conditions of OpenFOAM and X-Foil.

Inputs and Boundary Conditions	OpenFOAM	X-Foil
Speed	150 m/s	150 m/s
Length	3m	3m
Turbulence Model	Spalart-Allmaras model	N/A
Flow solver	simpleFoam	Panel Method
Density	1.204 kg/m^3	1.204 kg/m^3
Dynamic Viscosity	1.86 $*10^{-5}$ Pa·s	1.86 $*10^{-5}$·s

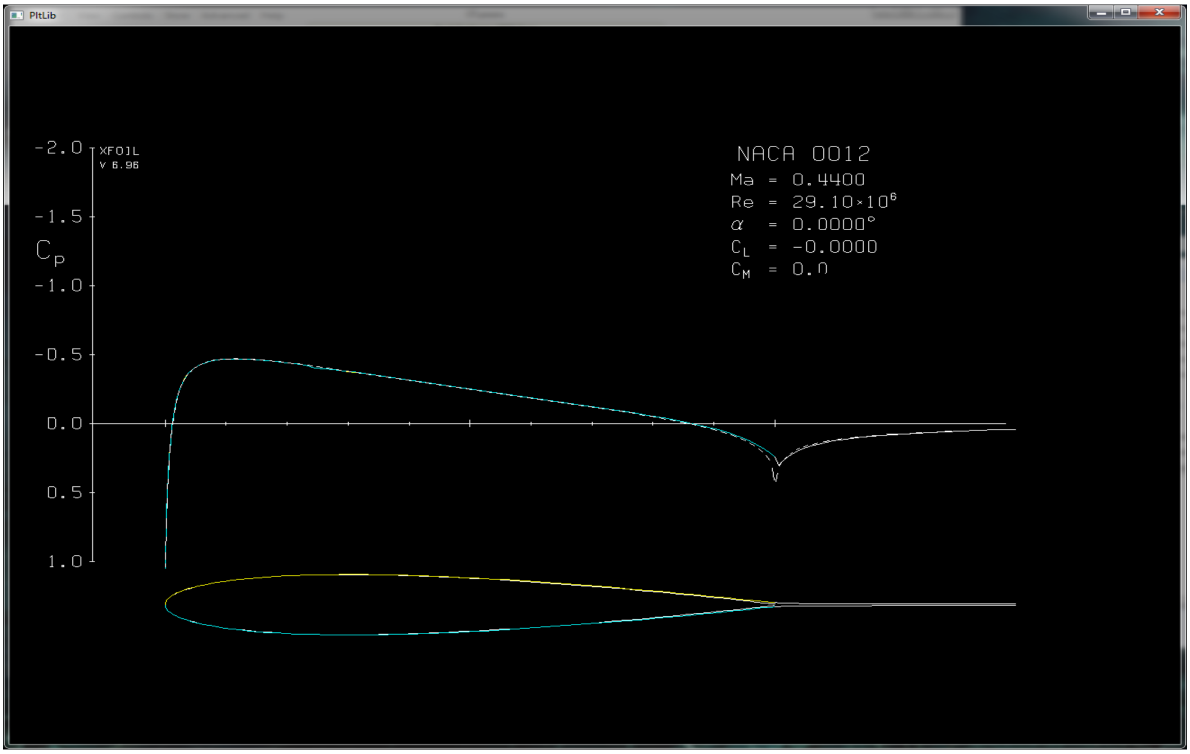

Figure 5: The X-Foil output of a NACA 0012 foil at 0 degrees angle of attack.

In Figure 5, we see the output of X-Foil. This is for an angle of 0 degrees. For this angle, we find that C_L, the lift coefficient is 0. The lift coefficient is a dimensionless number which is relationship between pressure, velocity and the reference area of the foil; Equation 2. We note that the foil as observed in the bottom half of the figure has a yellow outline for the upper surface and blue for the lower surface of the foil. The plot, which is of the pressure coefficient, has maximum pressure coefficient of 1 on the bottom of the vertical axis, and negative on the top. For this angle, both the lower and upper surfaces have the exact same pressure (symmetrical) and hence there is no lift being produced.From the output of the X-Foil program,the transition period starts at 22.5% of the length of chord.

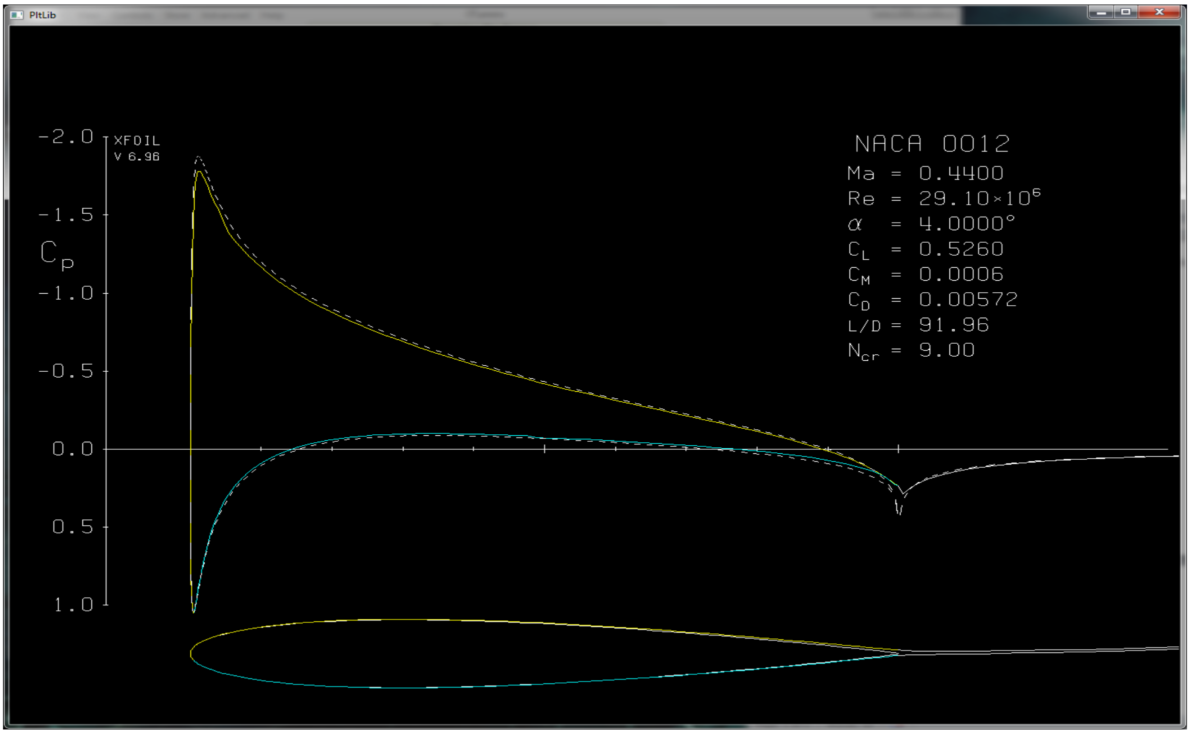

Figure 6: The X-Foil output of a NACA 0012 foil at 4 degrees angle of attack.

Figure 6 is the plot output for an angle of 4 degrees. The lift coefficient is 0.5260 and can note that there is a higher pressure on the lower surface than the top surface, thus producing lift. From the output of the X-Foil program,the transition period starts at 4.5% of the length of chord.

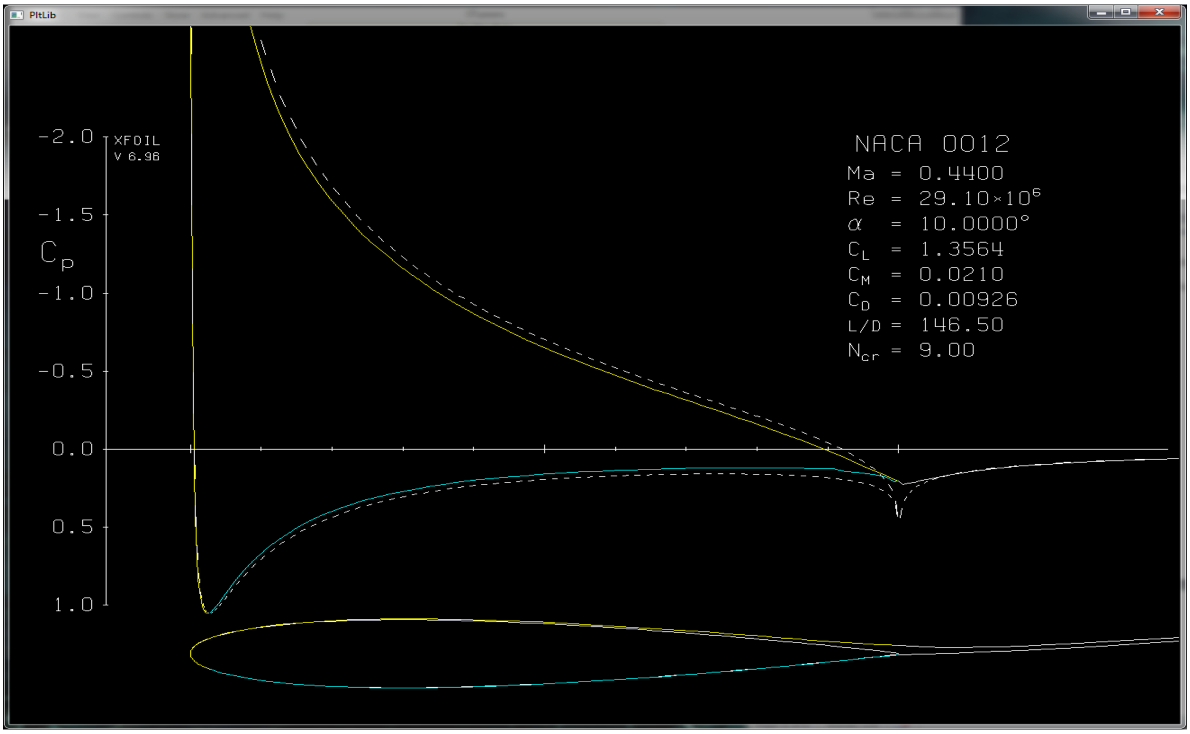

Figure 7: The X-Foil output of a NACA 0012 foil at 10 degrees angle of attack.

Figure 7 is the plot output for an angle of 10 degrees. The lift coefficient is 1.3564, an increase from the lower angles. However, can also note the drag coefficient, C_D, has also increased. The stagnation point is lower than the leading edge, and therefore producing lift. From the output of the X-Foil program, the transition period starts at 0.79% of the length of the chord.

Table 2: The start of the transition period as a percentage of the chord length.

Angle of attack (α)	Transition period starts (% of chord length)
0	22.5
2	10.9
4	4.5
6	2.0
8	1.1
10	0.79

Table 2 shows percentage of the chord length of when the transition period starts. This is the point along the foil where the flow becomes turbulent. It can be observed that after 4 degrees, very close to all the flow is turbulent.

5.0 OpenFOAM Results

I have used OpenFOAM to model the flow around a NACA 0012 foil for various angles of attack. For the values used, we can see from the X-Foil transition periods (Table 2) that most of flow is turbulent, indicated by the transition period being very close to the leading edge and hence used an all-turbulent model in OpenFOAM: simpleFoam.

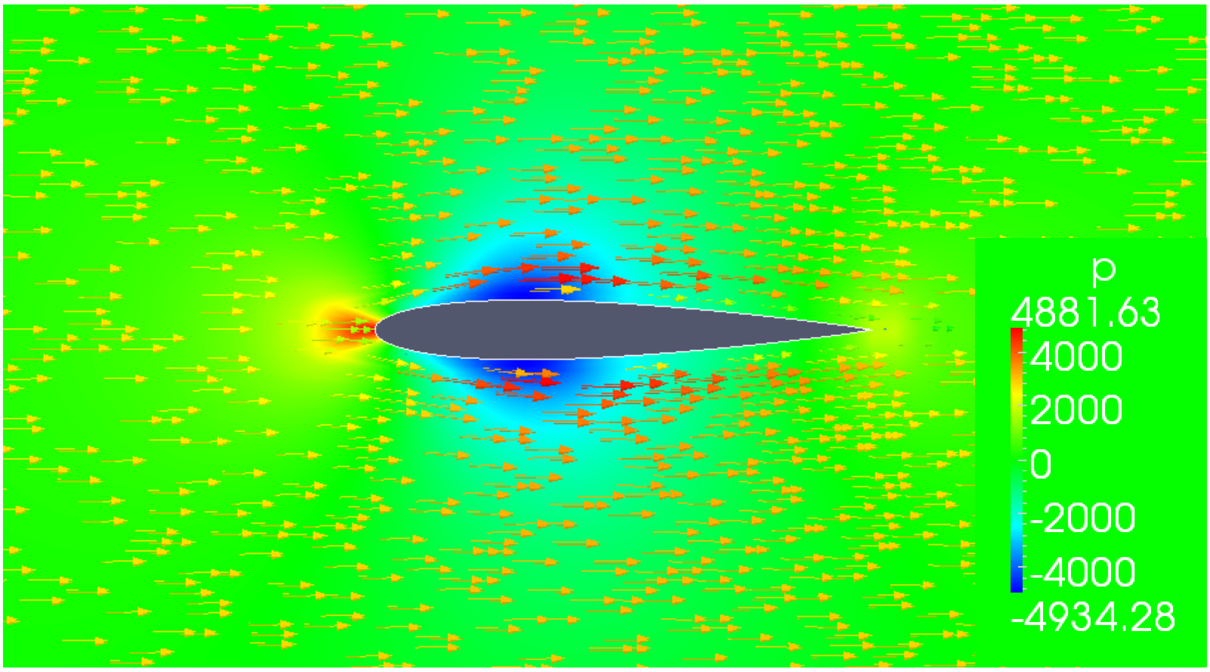

Figure 8: The flow representation of a NACA 0012 foil at 0 degrees angle of attack.

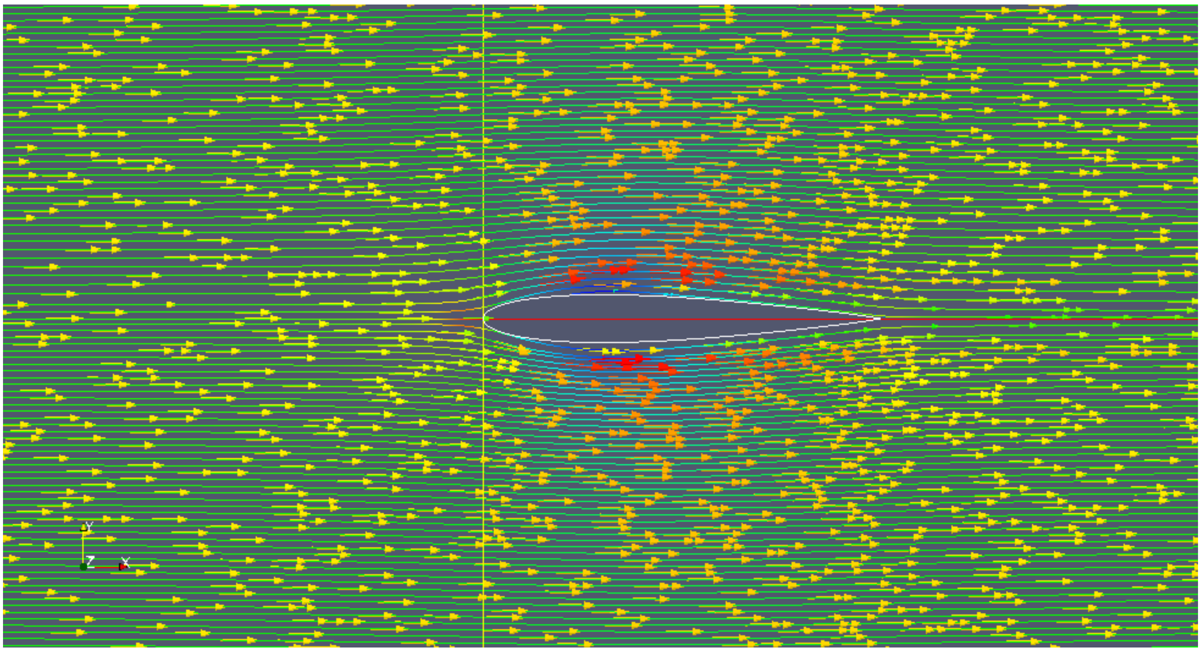

Figure 9: Streamline flow around a NACA 0012 foil at 0 degrees angle of attack.

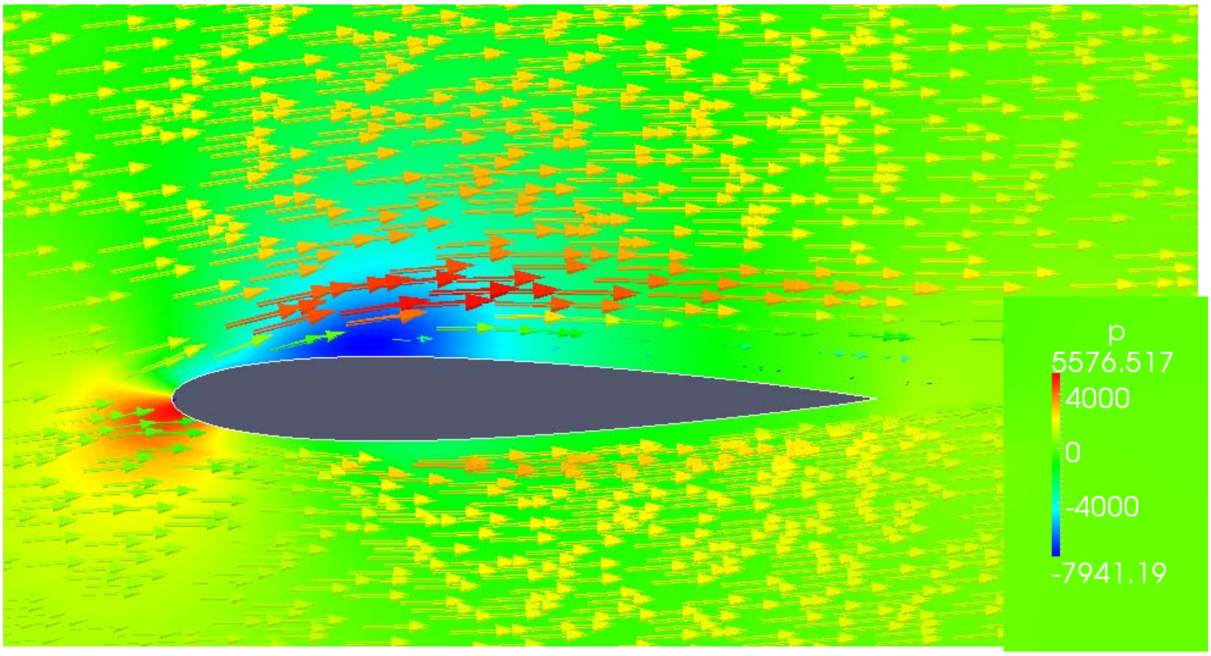

Figure 10: The flow representation of a NACA 0012 foil at 4 degrees angle of attack.

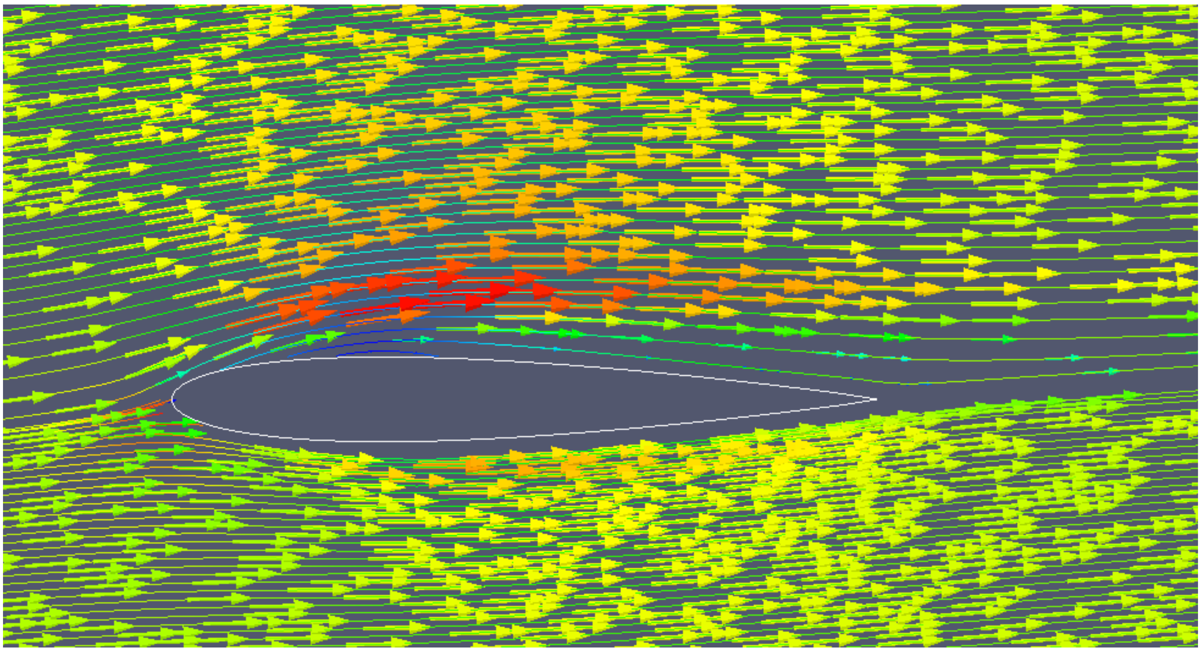

Figure 11: Streamline flow around a NACA 0012 foil at 4 degrees angle of attack.

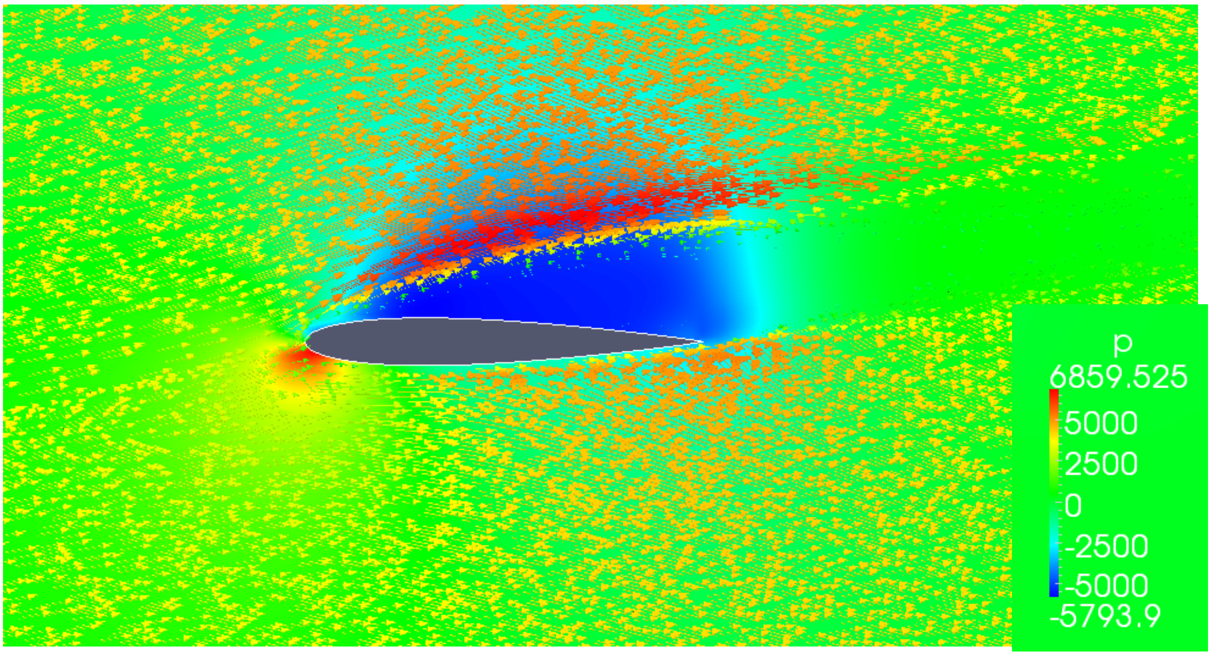

Figure 12: The flow representation of a NACA 0012 foil at 10 degrees angle of attack.

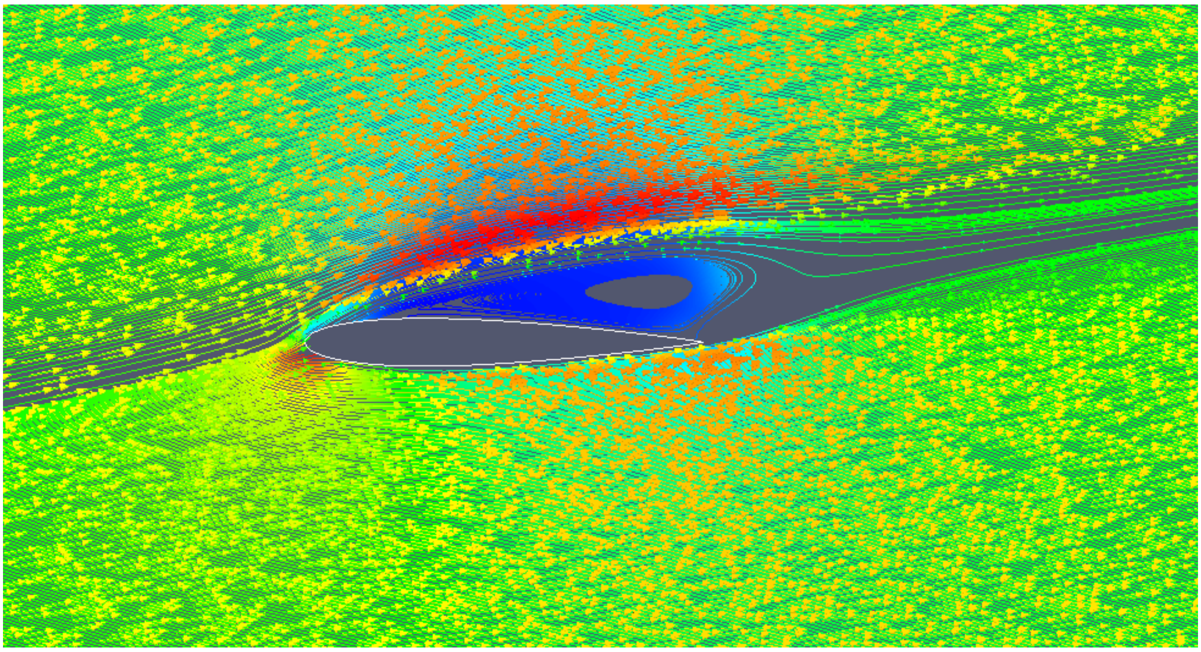

Figure 13: Streamline flow around a NACA 0012 foil at 10 degrees angle of attack.

6.0 Results Comparison and Discussion

The lift coefficient and drag coefficient calculated from OpenFOAM and X-foil can be compared against each other and also to an approximate formula for thin foils. As the NACA 0012 foil is fairly thick, we should be expecting the lift coefficient to above this approximate value.

Table 3: Comparison of lift coefficients at various angles of attack.

Angle of attack (α)	**OpenFOAM lift coefficient**	**X Foil lift coefficient**	**Approximate Lift coefficient (**Equation 3**)**
0	0	0	0
2	0.1642	0.2618	0.2193
4	0.2765	0.5260	0.4383
6	0.3103	0.7947	0.6568
8	0.3466	1.0705	0.8745
10	0.3947	1.3564	1.0911
12	0.4498	Could not converge	1.3063

Table 4: Comparison of drag coefficients at various angles of attack.

Angle of attack (α)	OpenFOAM drag Coefficient	X-Foil drag Coefficient
0	0.0158	0.0050
2	0.0374	0.0052
4	0.0707	0.0057
6	0.1106	0.0065
8	0.1309	0.0076
10	0.1494	0.0093
12	0.1695	Could not converge

The pressure in OpenFOAM is the actual pressure whereas X-Foil uses pressure coefficient. The OpenFOAM actual pressure has been converted to a pressure coefficient (Equation 5).

Table 5: Comparison of pressure coefficients at various angles of attack.

Angle of attack (α)	OpenFOAM pressure coefficient (max)	OpenFOAM pressure coefficient (min)	X-Foil pressure coefficient (max)	X-Foil pressure coefficient (min)
0	0.43	-0.44	1.0	-0.5
2	0.45	-0.62	1.0	-1.0
4	0.50	-0.71	1.0	-1.75
6	0.53	-0.56	1.0	-3.0
8	0.57	-0.51	1.0	-3.6
10	0.61	-0.52	1.0	-4.4
12	0.66	-0.53	N/A	N/A

Table 6: The comparison of the separation effects at various angles of attack.

Angle of attack (α)	Separation of OpenFOAM	Separation of X-Foil
0	None	None
2	None	None
4	none	None
6	Partial	Partial
8	Fully	partial
10	Fully	Fully

The key result in this project was to analyse the flow around a NACA 0012 helicopter foil. This was done using open source software, OpenFOAM. The lift coefficient, drag coefficient and maximum/minimum pressure coefficients for each angle of attack were then compared to X-Foil. It was found that the results did not agree and this will be discussed in more detail.

In OpenFOAM, the Lift coefficient and drag coefficient were calculated using a function in the control dict of the OpenFOAM files and output to a text file after the execution of the program. This was done for angles 0 degrees to 12 degrees. Post-processing the data using ParaView, we found that the flow appeared to be moving correctly around the foil. For 0 degrees (no angle of attack), we find that the stagnation point is in the centre of the upper and lower camber on the leading edge (Figure 3 and 4). At the stagnation point there is a high pressure and a symmetrical flow around the foil, producing low pressure on both top and bottom surfaces. Therefore, there is no lift being produced; consistent with teachings of White (2008, 295). Values recorded in Table 2 show that for no angle of attack, the results agree with each other.However, the drag coefficient in OpenFoam is calculated to be 0.0158 whereas in X-Foil it is 0.0050; a difference of 316%. This is a substantial difference and is not only for this angle of attack.

For an angle of attack of 4 degrees, we see that the flow now has a stagnation point just under the leading edge and hence producing lift as there is a low pressure region on the upper surface of the foil (Figure 5 and 6). We can also observe that Bernoulli’s principle is holding true; the velocity is high (denoted by the red arrows) at the low pressure region and vice-versa. At 4 degrees, $C_L \sim 0.4383$, OpenFoam $C_L = 0.2765$ and X-Foil gives $C_L = 0.5260$. We should expect a higher lift than the approximate as the NACA 0012 is a fairly thick foil and therefore in the range X-Foil is producing. However, we find that OpenFoam is 48% less than the expected value. We can also note that the OpenFOAM drag coefficient does not agree with the value that X-Foil has computed.

For an angle of 10 degrees, the stagnation point has moved further below the leading edge producing more lift, but now a noticeable separation effect (Figure 7 and 8). We can also observe that in Figure 8, the low pressure is spread along the length of the foil, whereas the X-Foil output for angle of 10 degrees (Figure 11) suggests there is a sharp peak of low pressure just after the leading edge. This is an adverse pressure gradient and is due to the flow pushing back from the trailing edge towards the leading edge in the form of recirculation.

Table 6 outlines the effect of the separation at the various angles of attack. Using the boundary layer analysis in X-Foil and visual post analysis for OpenFOAM we find that partial separation happens at 6 degrees for both. We observe that the flow is fully separated at 8 degrees for OpenFOAM, and 10 degrees for X-Foil.

The lift and drag coefficients do increase as the angle of attack increases, however they do not agree with the values produced by X-Foil, or the approximate theoretical ones. This does suggest there is something wrong with the function to calculate the coefficients – or that the mesh of the foil is not correct. However, another comparison of the maximum and minimum pressure coefficients was produced with OpenFOAM and X-Foil (Table 3). It is found that the pressure coefficient is also significantly less than the expected. As this coefficient is not calculated in OpenFOAM using the same function we can assume that it is indeed the mesh that is causing the discrepancies in the coefficients. More specifically the mesh should be refined around the leading and trailing edge so that the flow can go around the foil smoother. The leading edge can be refined by making the length smaller, but the width of the mesh wider. This will ensure a better line-up with the other blocks (Figure 1) and smaller cell sizes in the x direction. For the pressure coefficient in OpenFoam, we should expect that it will be slightly lower than X-Foil as it is more distributed along the foil, rather than in just one sharp peak at higher angles of attack. However, we should have a coefficient of 1 at the stagnation point, and this should be the maximum. This should relate to an actual pressure of 11 250 Pa above free stream pressure.

It can be also noted that the constant value of the length chosen is relatively higher than realistic helicopter would have. A more realistic value would be approximately tenfold smaller. This would reduce the Reynolds number by the same amount, and possible reduce the amount of time convergence would take to complete. By reducing this value the conversion factor would have to be changed; to reflect the smaller length. This unrealistic length could also be a possible discrepancy between OpenFOAM and X-Foil results.

In order to test if the mesh is the only problem, independent changes can be made to OpenFOAM to ensure that the problem is fixed. This can be achieved by refining the mesh until the results don't change. If after refining the mesh multiple times and not noticing any changes in the lift/drag/pressure coefficients then we can adopt a different modification to OpenFOAM in order to attain the required results. Small changes would be using different variables such as speed or length in order to see if it the values chosen that are affecting the results. Else, using a different model to the current one (Spalart–Allmaras model) may prove worthwhile.

Table 4 showed the comparison of drag between OpenFoam and X-Foil. X-Foil uses a panel method, a method which is inviscid and thus does not take into account any viscous forces. However, X-Foil also uses a boundary layer method which is a viscous method and can determine the drag. But as the Reynolds number is high, most of the flow is turbulent, as we saw by the transition period close to the leading edge; the fluid will be dominated by inertial force acting on the fluid (Symscape, 2007). This led to X-foil having a much smaller drag than perhaps what it should have had.

7.0 Wind Tunnel Tests

The experiment performed in this project involved using a wind tunnel in an engineering laboratory. Using a glue coated foil which represented a 65-009 NACA foil, we were able to vary the speed and angle of attack to see when the flow started to separate. As the foil is based on a RS-X racing fin, a project another honours student is working on;the results were relevant towards her work and not so much mine. However, it did provide some excellent considerations to be undertaken if doing a similar experiment with a NACA 0012 foil.

The experiment was completed twice. The first time the foil was screwed into the side of the tunnel and calibrated with a wheel which measured the angle. In order to see when the flow separates, tell-tales were attached to the foil. Tell-tales which are essentially pieces of string will remain calm and won't move when the flow is smooth. However, when the flow is starting to separate, the tell-tales will begin to move chaotically and lift up or whirl around. Pictures were taken through the various windows around tunnel and used to record what angle the separation happened. However, it was observed that there was flow on the sides of the tunnel hitting the metal rod used to hold the foil and causing the flow to become turbulent. Moreover, the string used for the tell-tales was a bit too heavy and hard to see when the photo was taken. Therefore the experiment was re-done a different day.

The second time the experiment was conducted a few improvements were made. A thin metal plate was put between the foil and the metal rod holding the foil in place. This would stop the flow becoming turbulent when hitting the rod. The tell-tales were also changed to a different colour and also a bit lighter in mass. The camera was now able to clearly pick up the changes in flow from smooth to separated (comparison of Figure 14andFigure 15). Noting down when the tell tales first began to fluctuate, this resulted in finding the separation to be approximately at 12 degrees angle of attack at a speed of 20.9 m/s.

If this experiment was to be completed with a NACA 0012 foil, many of the techniques used for the NACA 65-009 experiment would be adopted. It is important to get the coordinates as close to the model as possible and well as a getting a smooth leading edge. Placing tell-tales at the leading edge would also help determine what is happening to the flow when there is a tip vortex. One of the better improvements could include adding smoke to the air. This would ideally tell us exactly what the flow is doing at every part of the foil.

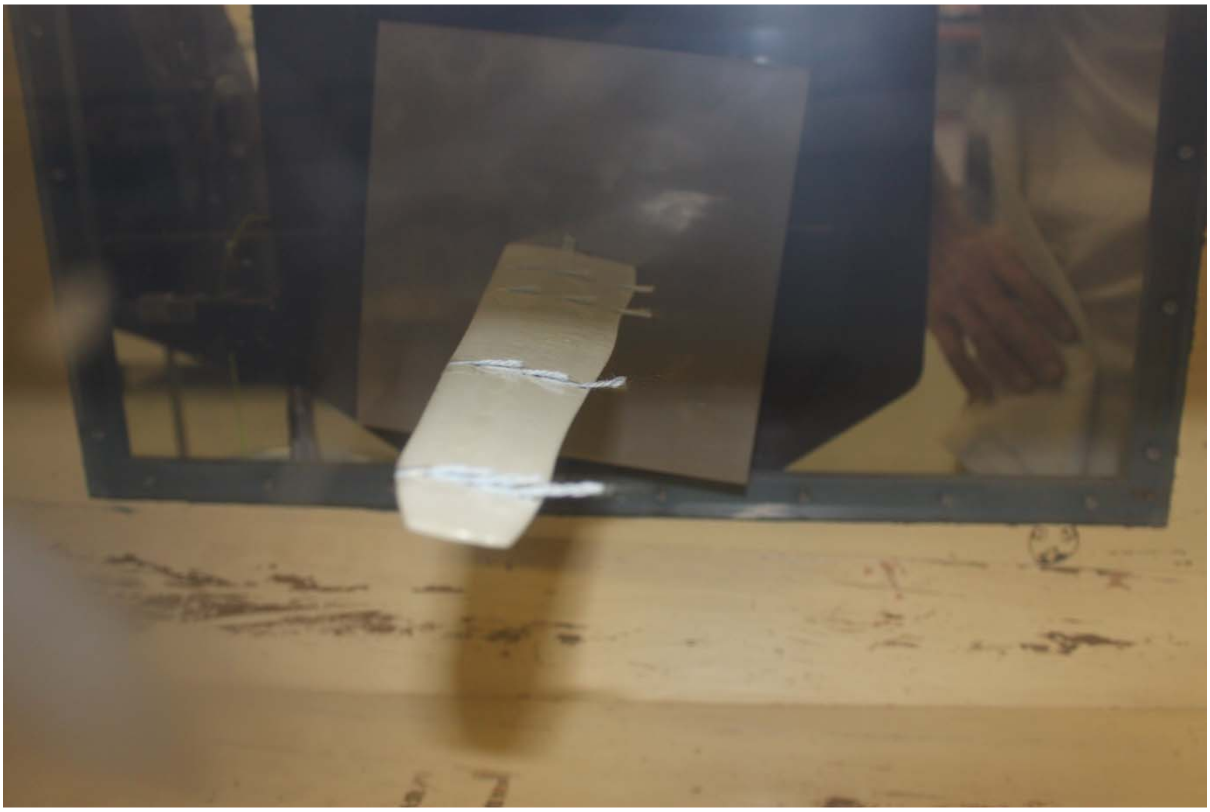

Figure 14: Picture of the tell-tales at angle of attack of 8 degrees (trial 2).

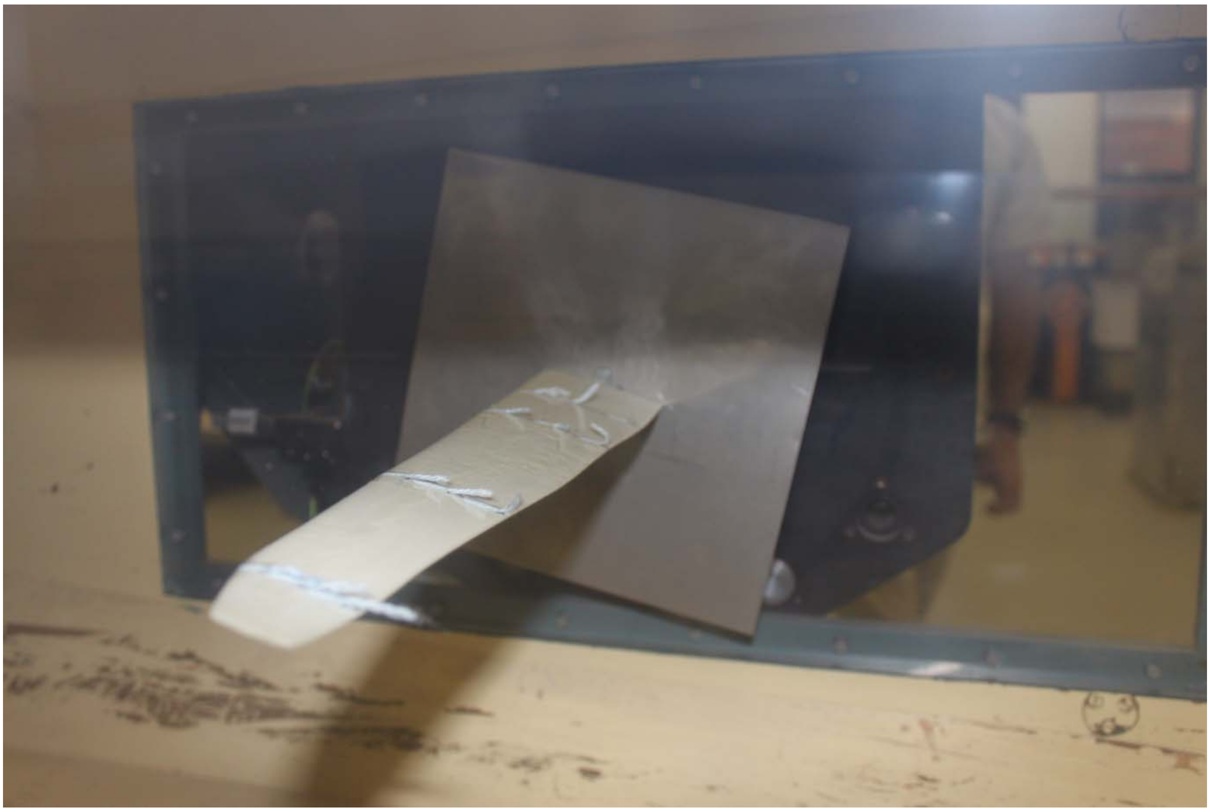

Figure 15: Picture of the tell-tales at an angle of 12 degrees indicating separation of flow around the foil (trial 2).

8.0 Conclusion

This project is a long process and thus has been done in steps. Using OpenFOAM to model the flow around a NACA 0012 foil, it has increased my understanding of the effects angle of attack has on a foil. We can determine the lift coefficient, drag coefficient and pressure coefficient at different angles of attack and hence find the stalling angle. Making comparisons to literature and other programs, we have accurately been able to determine the strengths and weaknesses of OpenFOAM. By conducting experimental work, we can successfully apply the same techniques in the future to produce quality results.

Future work will include refining the mesh to obtain accepted values of the three coefficients. This will involve making the leading edge and trailing edge smoother so that flow is not being disrupted. We can also hope to improve results by making realistic assumptions for a full length helicopter. Additional research will include modelling in 3D such that a more accurate representation can be used. Also to apply my understanding of flow to optimise helicopter blades further.

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10.0 Glossary

Drag Coefficient: The dimensionless drag force with respect to the foil area.

Lift Coefficient: The dimensionless lift force with respect to the foil area.

NACA: acronym for National Advisory Committee for Aeronautics.

OpenFOAM: an open source program to do modelling of flow.

ParaView: an add-on of OpenFOAM to view the model and to do analysis on the data.

Reynolds Number: It is the non-dimensional frictional resistance. It is the ratio of speed*length and kinematic viscosity.

Stagnation Point: The point the flow meets the foil and separates.

Stalling: Referring to when a foil reaches a point when the angle of attack is high enough that the lift starts to decrease. Separated flow is generated on the upper surface.

11.0 Appendix; Additional Plots

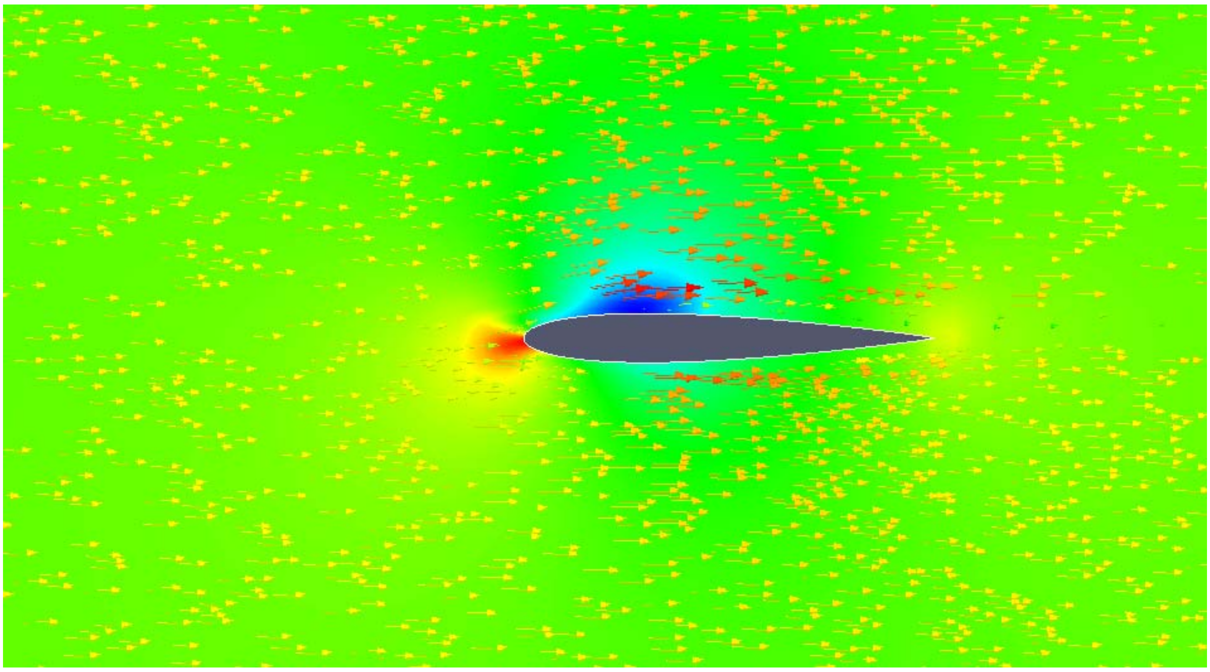


Figure A1: Flow representation at 2 degrees in OpenFOAM.

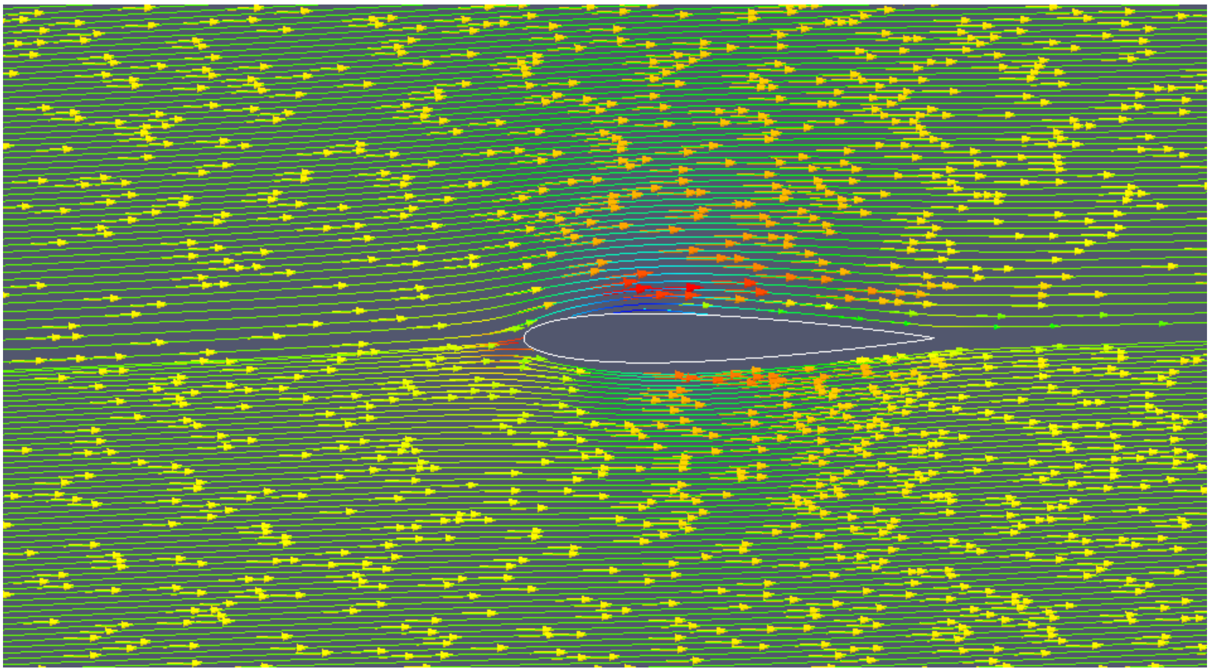


Figure A2: Streamline representation at 2 degrees in OpenFOAM.

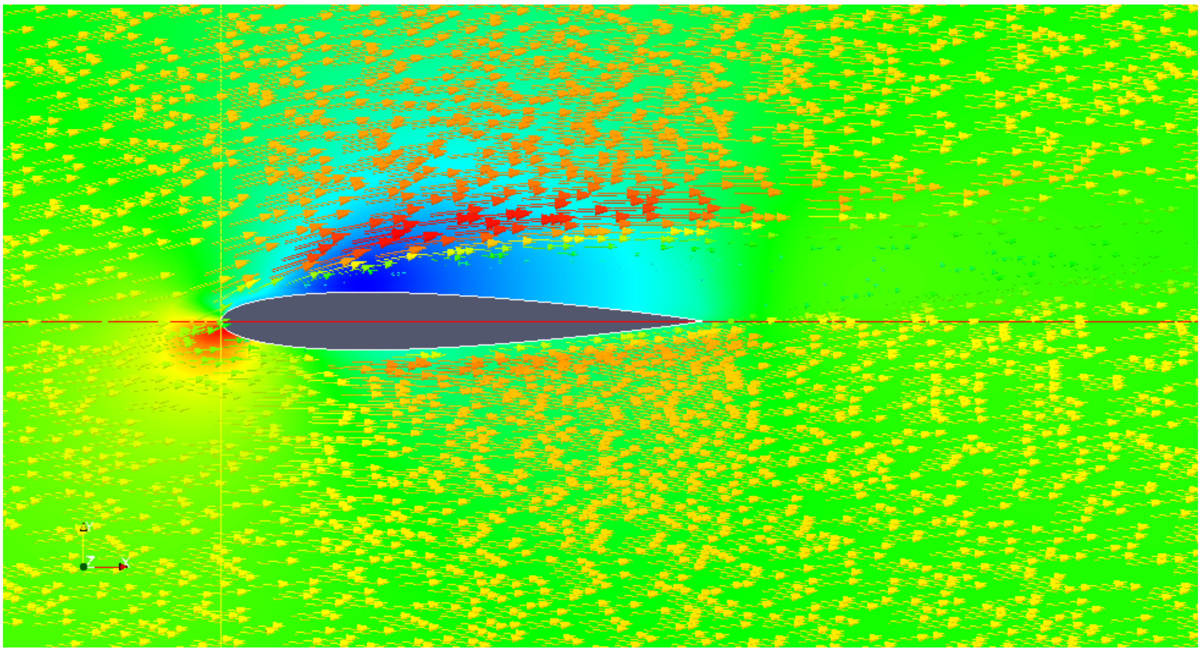


Figure A3: Flow representation at 6 degrees in OpenFOAM.

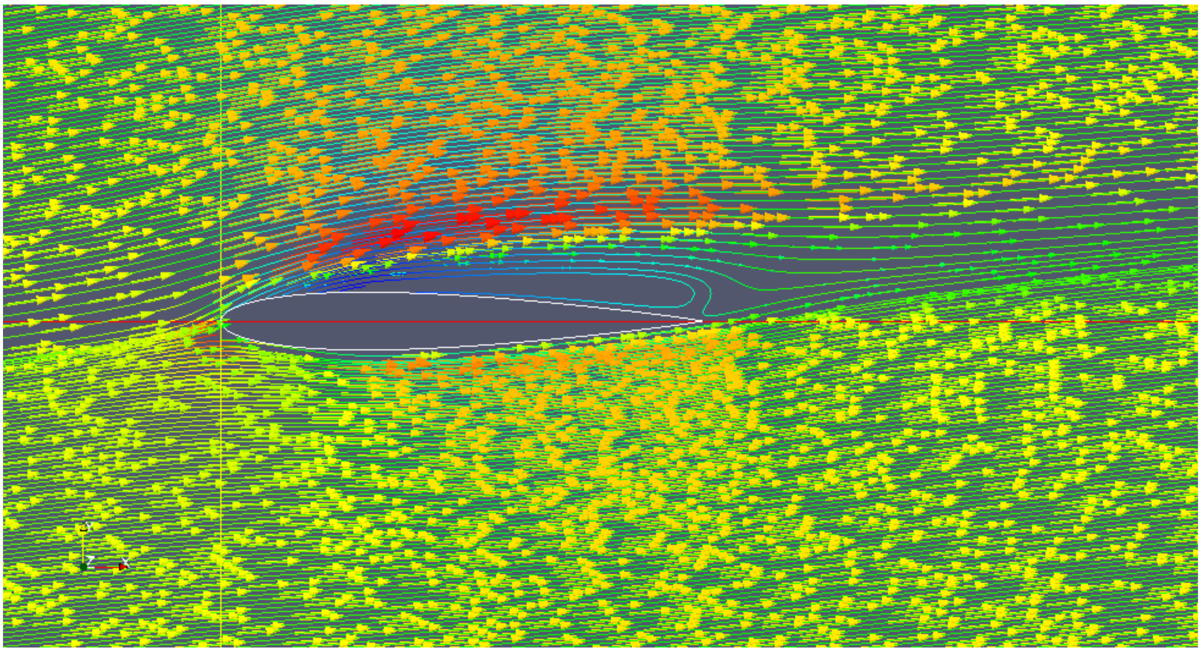
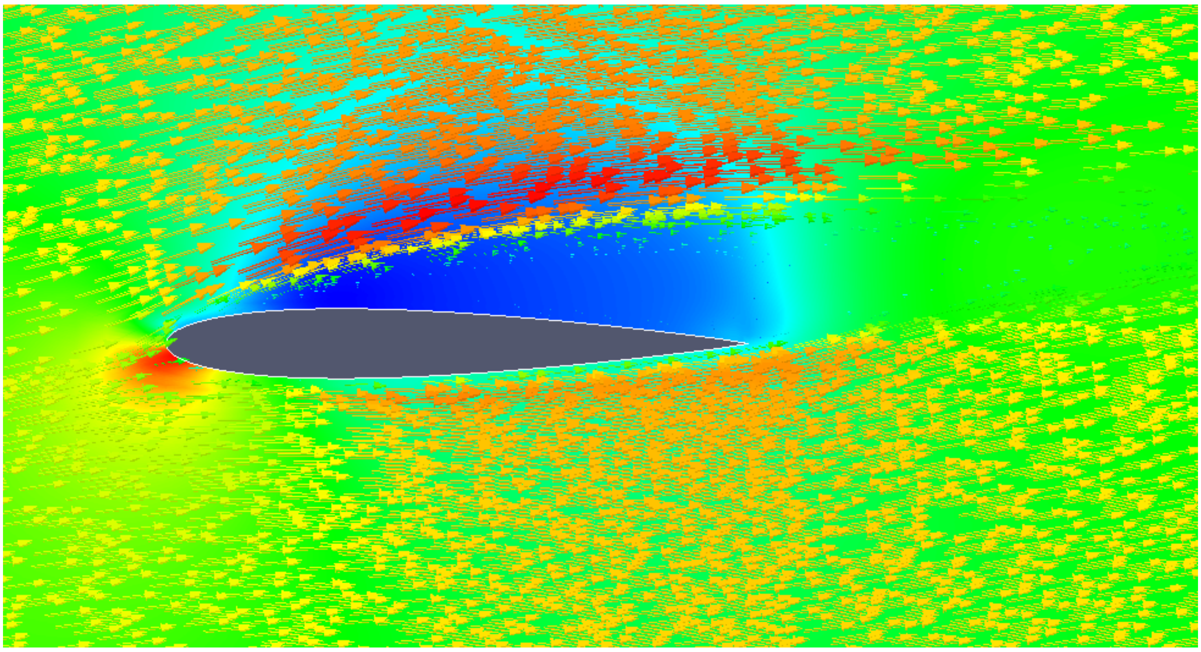


Figure A4: Streamline representation at 6 degrees in OpenFOAM.



Fiugre A5: Flow representation at 8 degree in OpenFOAMs.

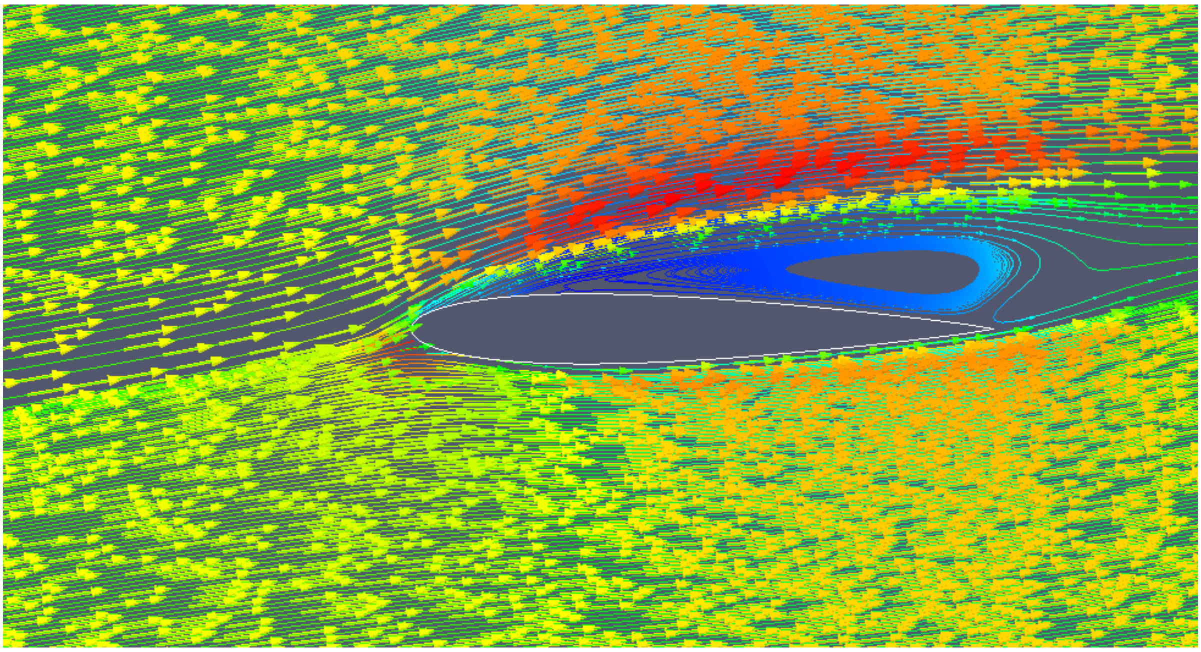


Figure A6: Streamline representation at 8 degrees in OpenFOAM.

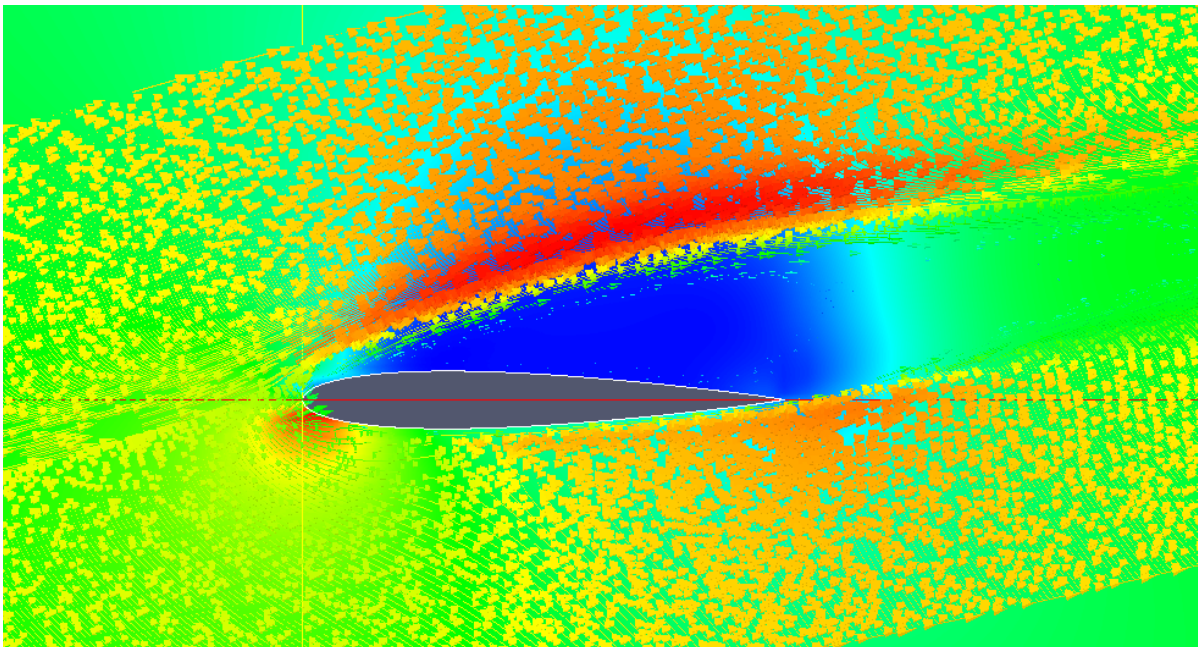


Figure A7: Flow representation at 12 degrees in OpenFOAM.

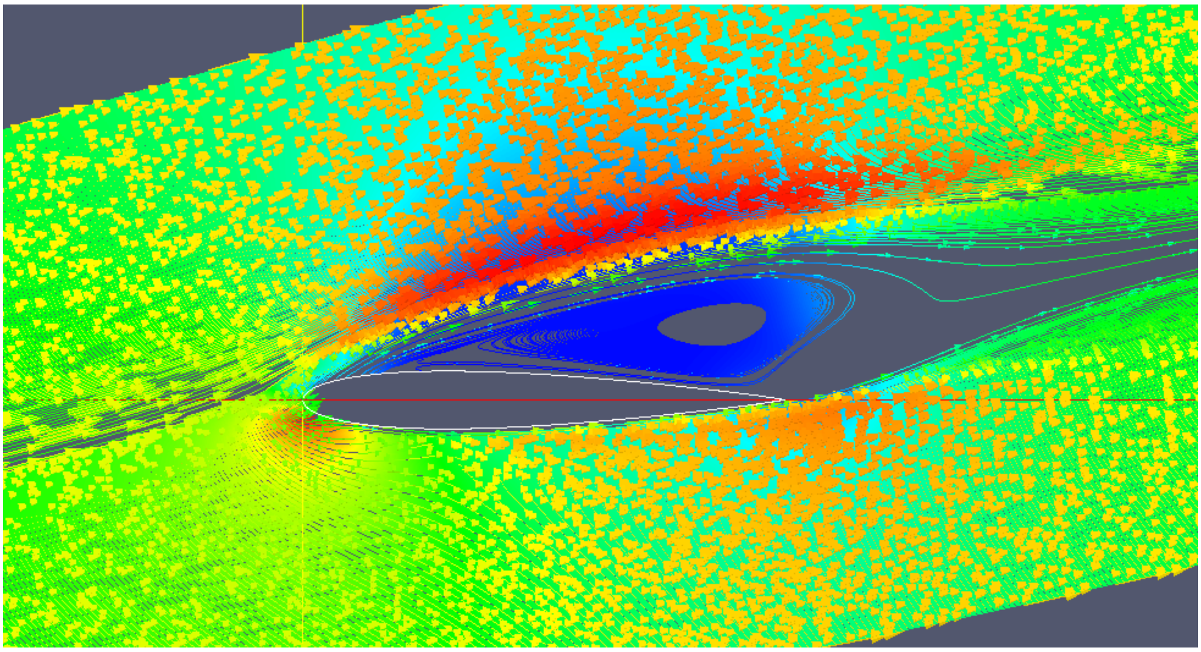


Figure A8: Streamline representation at 12 degrees in OpenFOAM.

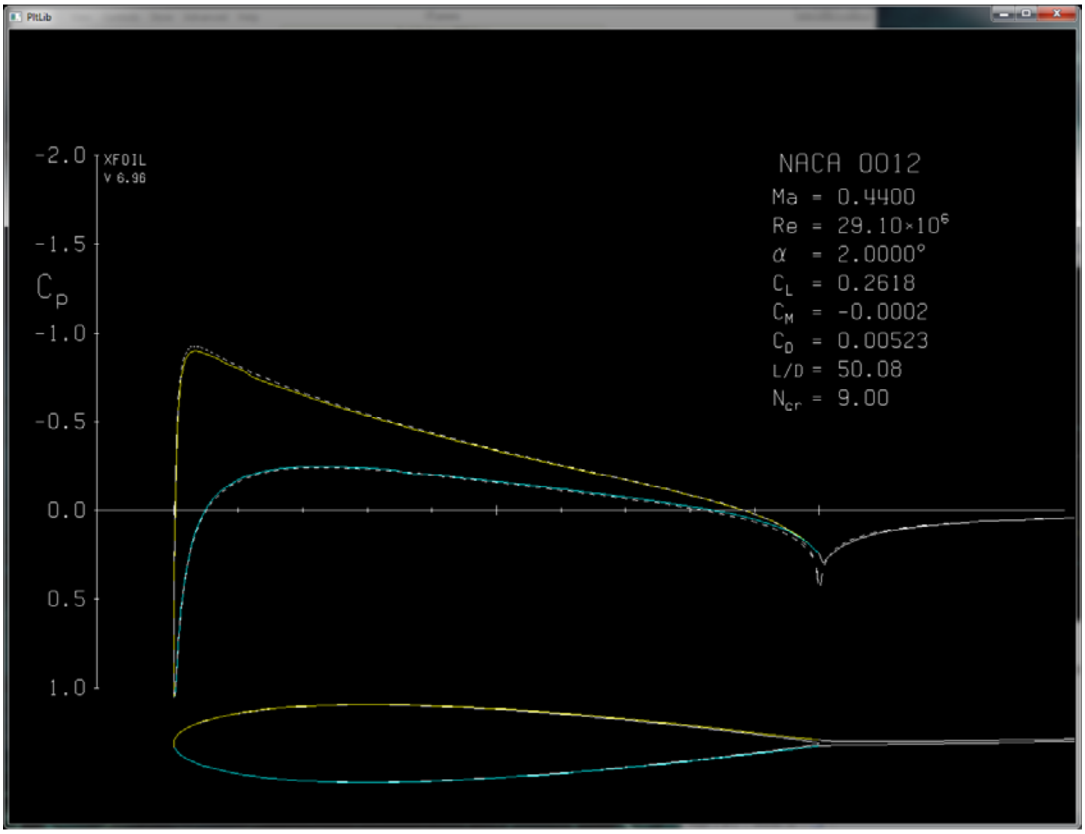


Figure A10: X-Foil output at 2 degrees.

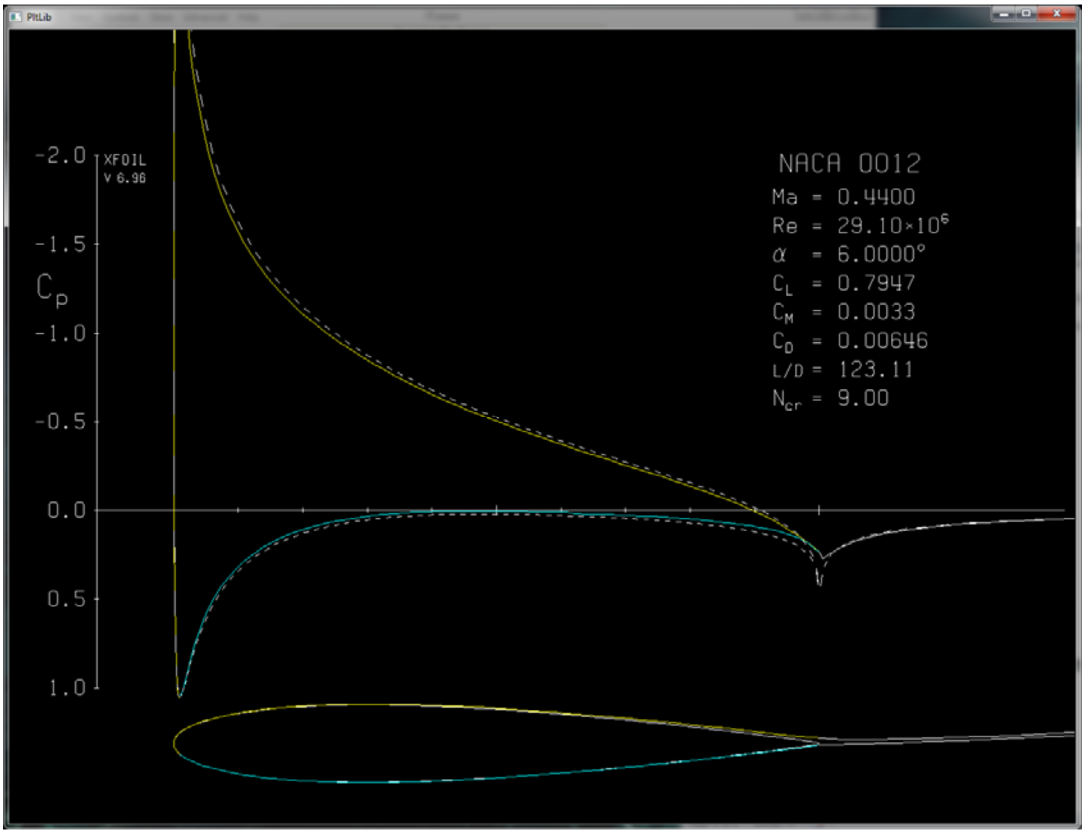


Figure A11: X-Foil output at 6 degrees.

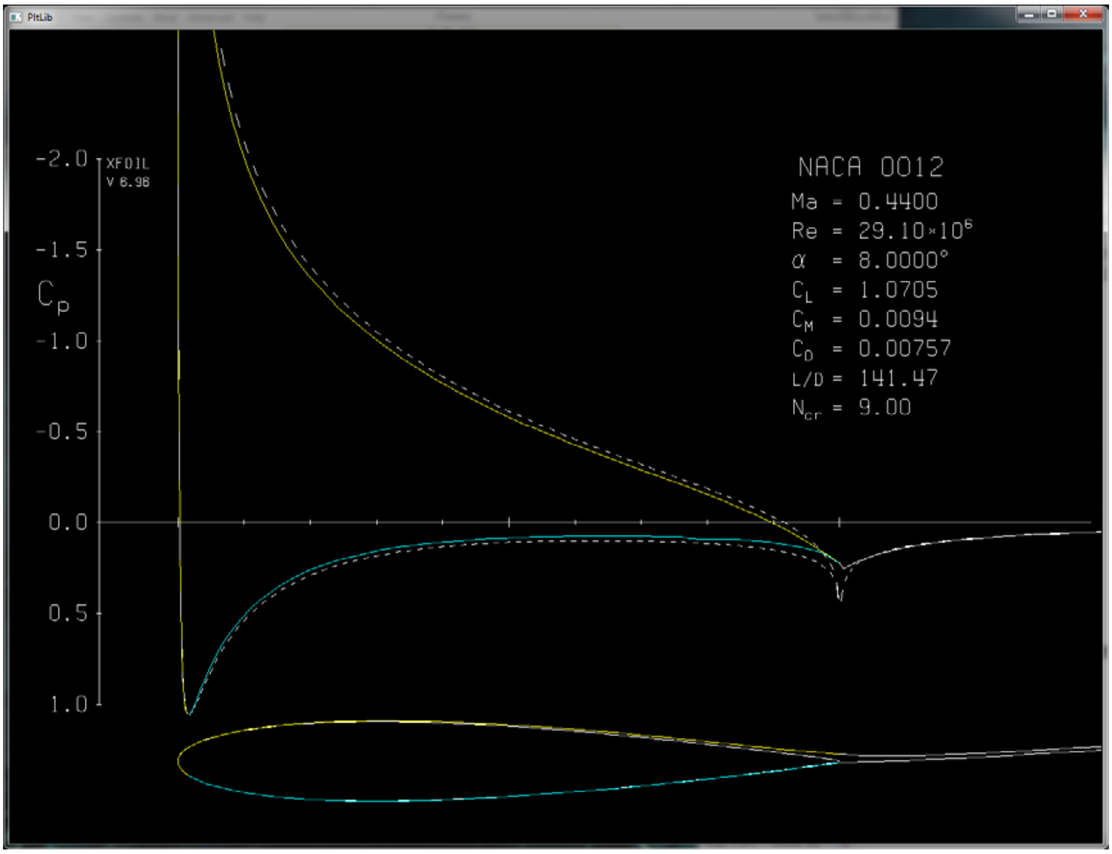


Figure A12: X-Foil output at 8 degrees.

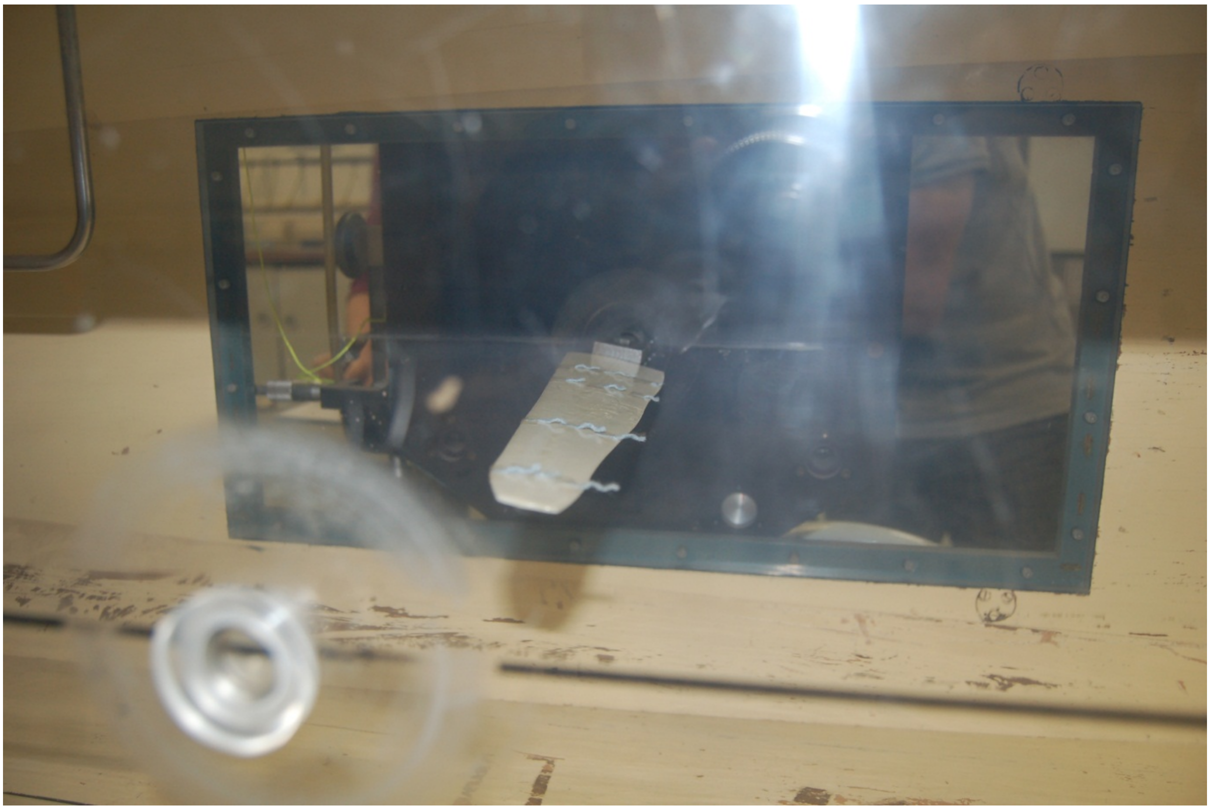


Figure A13: Picture of the tell-tales at an angle of 10 degrees and flow speed 15.4 m/s (trial 1)

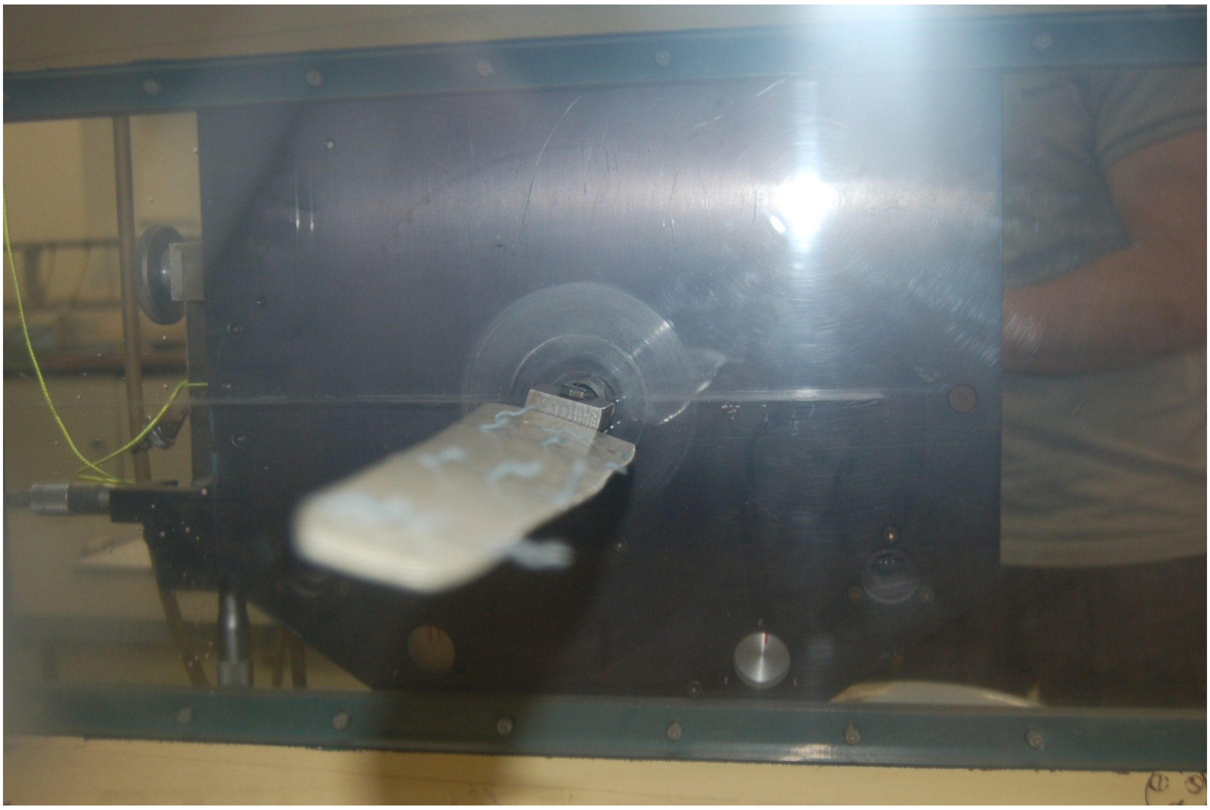


Figure A14: Picture of the tell-tales at an angle of 16 degrees and flow speed 21.2 m/s (trial 1)

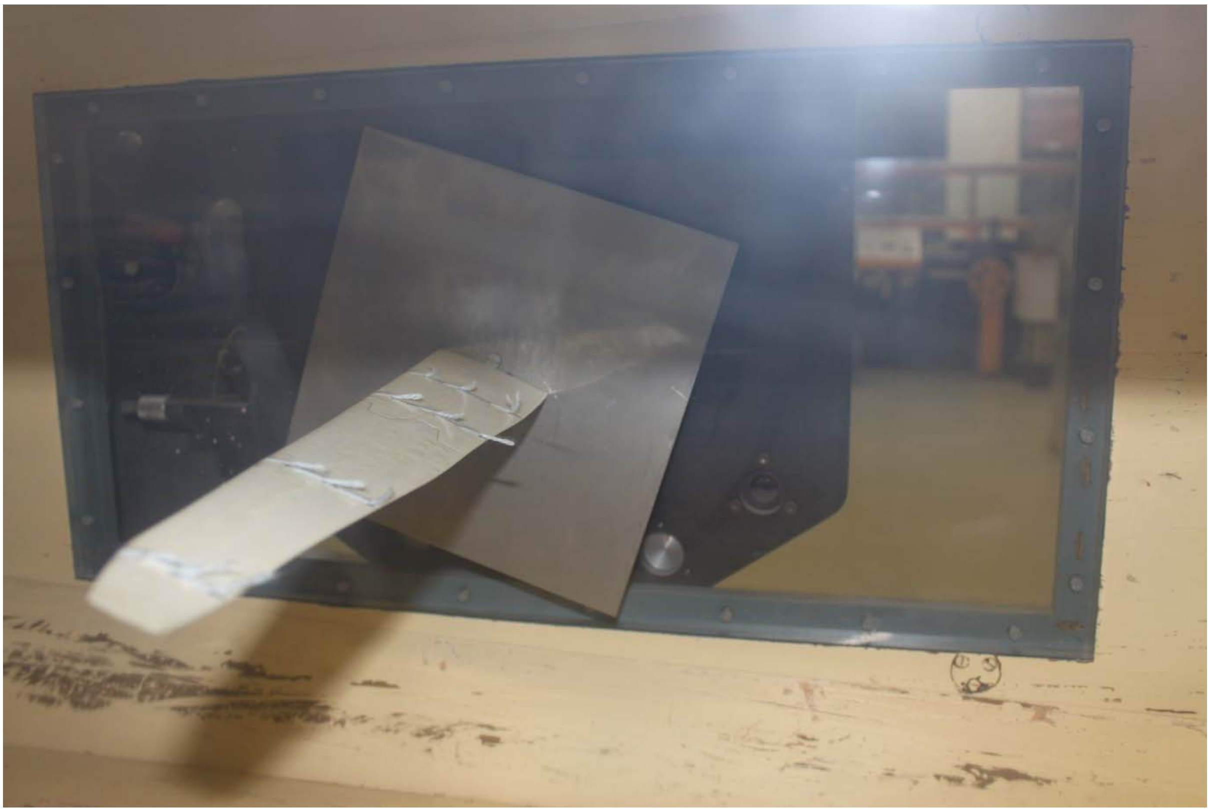


Figure A15: Picture of the tell-tales at an angle of 18 degrees and flow speed 20.9 m/s (trial 2).