Determination of the Aerodynamic Performance of a Low-Speed Airfoil based on Pressure Distribution Measurements

Aerodynamics and Propulsion Laboratory

Section 2

Tyler Cascalho Cox

Iowa State University
Undergraduate Aerospace Engineering

Abstract

In this report the aerodynamic performance of a GA(W)-1 airfoil is analysed at various angles of attack. Pressure taps around the airfoil are used to find the pressure distribution. Which is used to find the lift, drag and moment coefficients at each of the angles of attack. This is then used to determine the movement of the stagnation point as angle of attack is varied and the angle of attack at which flow separation and stall start at.

Variables and Symbols

P - Pressure (Pa)

C_p - Pressure Coefficient

P_A - Contraction Section Pressure (Pa)

P_E - Inlet Pressure (Pa)

ρ - Density of Air $\left(\frac{\text{kg}}{\text{m}^3}\right)$

α - Angle of Attack (Degrees)

C_D - Drag Coefficient

C_L - Lift Coefficient

C_M - Moment Coefficient

D - Drag Force (N)

L - Lift Force (N)

M_{LE} - Leading Edge Moment (Nm)

K - Calibration Constant

Contents

Abstract **3**

1 Introduction **4**

2 Theory **5**
2.1 The Closed Loop Wind Tunnel 5
2.2 Bernoulli's equation and The Pitot-Static Probe 5
2.3 The Calibration Constant 7
2.4 Estimating the Pressure Integral 8

3 Experimental Setup **10**
3.1 General Description 10
3.2 Case Study 10

4 Results **11**
4.1 C_P distribution for $\alpha = -4°$ 11
4.2 C_P distribution for $\alpha = 0°$ 12
4.3 C_P distribution for $\alpha = 4°$ 13
4.4 C_P distribution for $\alpha = 6°$ 14
4.5 C_P distribution for $\alpha = 8°$ 15
4.6 C_P distribution for $\alpha = 10°$ 16
4.7 C_P distribution for $\alpha = 12°$ 17
4.8 C_P distribution for $\alpha = 14°$ 18
4.9 C_P distribution for $\alpha = 16°$ 19
4.10 C_L variation with changes to α 20
4.11 C_D variation with changes to α 21
4.12 C_M variation with changes to α 22
4.13 The Calibration Constant and Plot between q_T and Δp 23
4.14 Flow Velocity vs. Motor Speed 24
4.15 Reynolds Number 24
4.16 General Discussion of Results and of Error 25

5 Conclusion **26**

6 Work Cited **27**

A Appendix of Data Tables **28**
A.1 Average Pressure Measurements 28
A.2 Values for C_L, C_D, and C_M 29
A.3 C_P Data 30
A.4 Estimated Location of Stagnation Point 31
A.5 Location of Pressure Taps on GA(W)-1 airfoil 32

B Appendix of Matlab Code **33**
B.1 Code for Plots and Data Manipulation 33

1 Introduction

For this experiment a GA(W)-1 airfoil has been outfitted with 43 pressure taps and tested at nine different angles of attack with the wind tunnel velocity held constant. Three pressure transducers were attached to pressure taps around the airfoil to collect the raw data. The data was time-averaged and then used to obtain plots of the lift, drag, moment, and pressure coefficients vs. angle of attack.

2 Theory

2.1 The Closed Loop Wind Tunnel

The closed loop wind tunnel is comprised of seven main sections/components. These are the Test Section, Contraction Section, Diffuser Section, Settling Chamber, Screens/Flow management, Cooling System, and a Motor/Fan. These are depicted below (Figure 1).

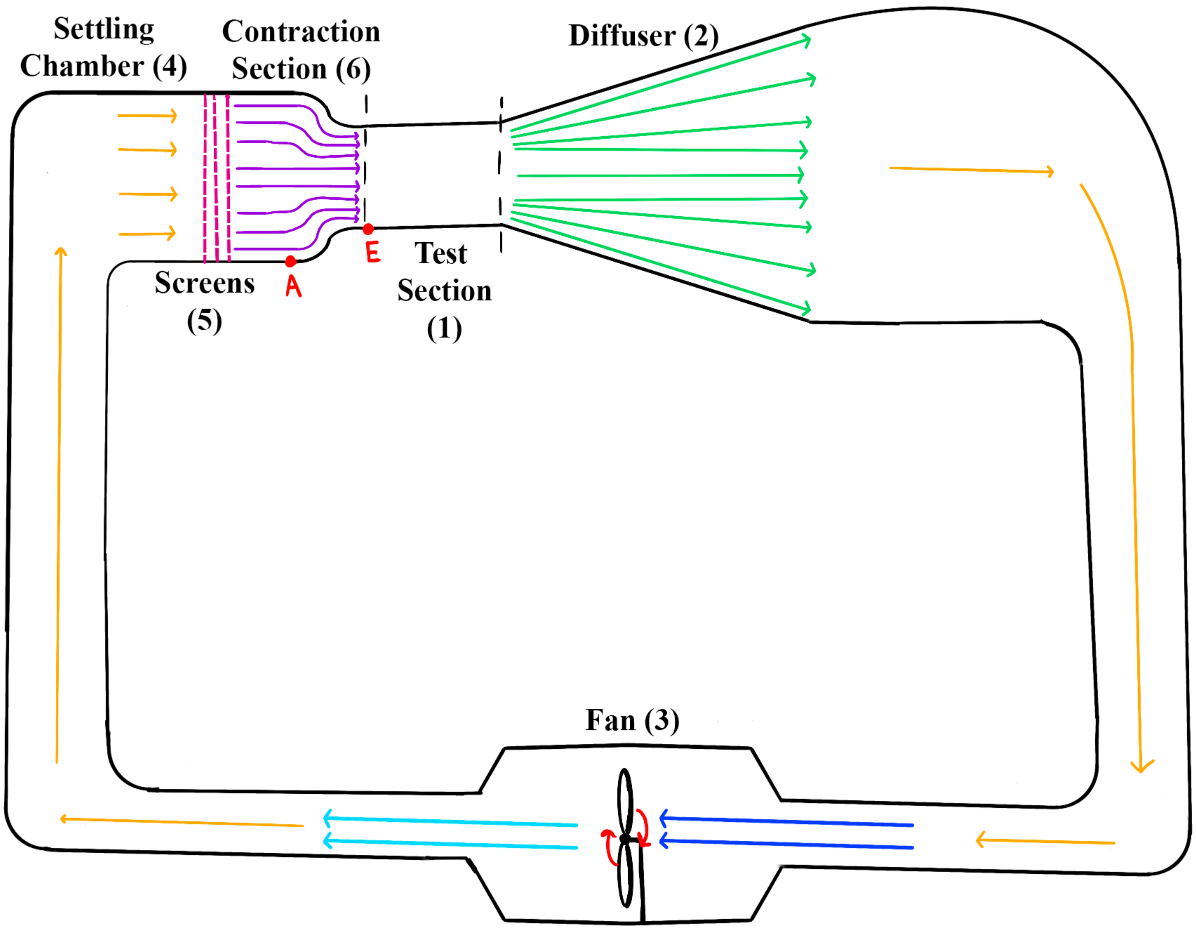

Figure 1: Closed Loop Wind Tunnel

A closed loop wind tunnel is a tool often used in field of Aerospace to determine the flow field around objects of interest (i.e. things like cars, airfoils, ect). In a low speed wind tunnel things are particularly nice since it satisfies the criteria required for Bernoulli's equation to be applicable. This allows for easier measurement of the flow velocity within the wind tunnel and also results in simpler flow fields in general.

2.2 Bernoulli's equation and The Pitot-Static Probe

There are three criteria that must be satisfied for Bernoulli's equation to be valid. These criteria are as follows, a given flow must be steady (velocity at a point cannot change with time), it must be incompressible (density along a steamline must remain constant), and friction due to viscous forces must be negligible. In a low speed wind tunnel these criteria are satisfied. Now, Bernoulli's equation is as follows:

$$p + \frac{1}{2}\rho v^2 + \rho g h = \text{constant} \tag{1}$$

For our purposes we can ignore the $\rho g h$ term since we are taking our flow inside the area of interest to be horizontal. This gives us the following:

$$P_T = p + \frac{1}{2}\rho v^2 \tag{2}$$

Where P_T represents total pressure, which is constant. We can then solve this equation for the velocity of the flow.

$$v = \sqrt{\frac{2\left(P_T - p\right)}{\rho}} \tag{3}$$

This means that if we have the total pressure P_T (a.k.a stagnation pressure) and the static pressure p then we can find the velocity of the flow. Fortunately, we have measurement tool that does just that and it's called a pitot-static probe (Figure 2).

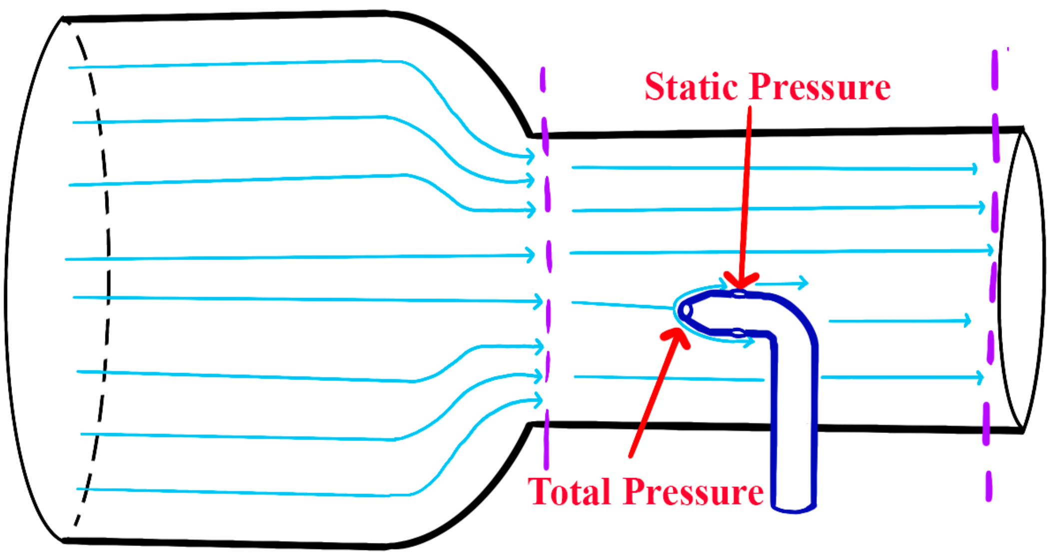

Figure 2: Pitot-Static Probe

Unfortunately, the pitot-static probe is quite intrusive and disrupts the flow quite a bit and thus cannot be used to determine flow velocity while trying to find the flow profile of another object. Now, the alternate method to this is to take static pressure measurements at points A and E as shown in Figure 1. In theory the pressure difference between A and E should be linearly related to dynamic pressure in the test section. Which means we can find a calibration constant relating the dynamic pressure to the pressure difference between points A and E.

2.3 The Calibration Constant

As discussed above there should exist a calibration constant that when multiplied by the pressure difference between points A and E (Figure 1) you get dynamic pressure inside the test section. To find this constant we need to start with Bernoulli's equation.

$$P_i = p_i + q_i$$

Applying this to our points A and E

$$P = p_A + q_A = p_E + q_E$$

Now we need to account for the pressure loss due to the boundary layer effect at A and E

$$P_A = p_A + q_A = p_E + q_E + (P_A - P_E)$$

Now we define a pressure loss coefficient

$$C_1 = \frac{P_A - P_E}{q_E}$$

Substituting this into the equation above:

$$p_A - p_E = q_E + q_E C_1 - q_A \tag{4}$$

Lets let A_A, A_E, and A_T denote the cross sectional area at points A, E, and the test section respectively. We then equate the mass flow rate equations using the conservation of mass.

$$\rho_A v_A A_A = \rho_E v_E A_E = \rho_T v_T A_T$$

Since this is a low-speed flow, we can assume that it is inviscid. Which means that $\rho_A = \rho_E = \rho_T$ and therefore get the following equation:

$$v_A A_A = v_E A_E = v_T A_T$$

After squaring and multiplying by $\frac{\rho}{2}$ we get the following equation:

$$\frac{1}{2}\rho_A {v_A}^2 {A_A}^2 = \frac{1}{2}\rho_E {v_E}^2 {A_E}^2 = \frac{1}{2}\rho_T {v_T}^2 {A_T}^2$$

Simplifying:

$$q_A {A_A}^2 = q_E {A_E}^2 = q_T {A_T}^2$$

Defining more coefficients:

$$C_2 = \frac{{A_E}^2}{{A_A}^2} \text{ and } C_3 = \frac{{A_T}^2}{{A_E}^2}$$

$$\rightarrow q_A = C_3 q_E \text{ and } q_E = C_3 q_T$$

Now plugging this into (4) gives:

$$p_A - p_E = C_3 q_T + C_1 C_3 q_T - C_2 C_3 q_T = (1 + C_1 - C_2) C_3 q_T = C q_T$$

$$\rightarrow K = \frac{1}{C} = \frac{q_T}{p_A - p_E} = \frac{q_T}{\Delta p} \tag{5}$$

Where K is the calibration constant.

2.4 Estimating the Pressure Integral

The lift, drag, and moment coefficients can be calculated by integrating the distribution of surface pressure around the airfoil. If we define the i-th panel as bounded by the i-th and i+1-th taps, then the pressure $p_{i+1/2}$ (acting on the i-th panel) can be calculated using

$$p_{i+1/2} = \frac{1}{2}\left(p_i + p_{i+1}\right)$$

Then we assume the pressure variation is constant and define

$$\Delta x_i = x_{i+1} - x_i$$

$$\Delta y_i = y_{i+1} - y_i$$

From equations 1 and 2 we can define the normal and axial components acting on the i-th panel (with the prime indicating force per unit span):

$$\delta N_i^{'} = p_{i+1/2}\Delta x_i$$

$$\delta A_i^{'} = p_{i+1/2}\Delta y_i$$

These values are visualized on the airfoil surface in the following figure: The moment con-

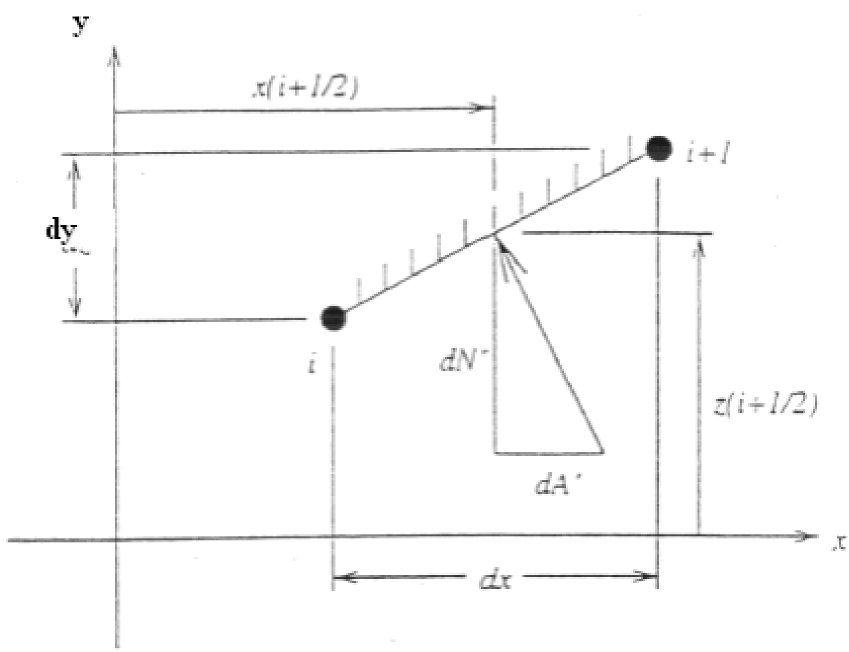

Figure 3: Discrete representation of the airfoil surface element

tribution from the i-th panel to the total leading edge moment can be determined using a similar method (positive in the pitch-up direction):

$$\delta M_{LE,i}^{\prime} = r \times \delta F_i = \left(x_{i+1/2} i + y_{i+1/2} k\right) \times \left(\delta A_i^{'} i + \delta N_i^{'} k\right)$$

Which can be simplified to

$$\delta M'_{LE,i} = -\left(p_{i+1/2}\Delta x_i\right) x_{i+1/2} - \left(p_{i+1/2}\Delta y_i\right) y_{i+1/2}$$

With

$$x_{i+1/2} = \frac{1}{2}\left(x_i + x_{i+1}\right)$$
$$y_{i+1/2} = \frac{1}{2}\left(y_i + y_{i+1}\right)$$

The expressions for the differential force and moment on each panel can now be integrated over the airfoil surface by using the total sums:

$$N' = \sum_{i=1}^{N} \delta N'_i = \sum_{i=1}^{N} p_{i+1/2}\Delta x_i$$

$$A' = \sum_{i=1}^{N} \delta A'_i = -\sum_{i=1}^{N} p_{i+1/2}\Delta y_i$$

$$M'_{LE} = \sum_{i=1}^{N} \delta M'_{LE} = -\sum_{i=1}^{N} \left(p_{i+1/2}\Delta x_i\right) x_{i+1/2} - \sum_{i=1}^{N} \left(p_{i+1/2}\Delta y_i\right) y_{i+1/2}$$

Using these values we can determine the lift and drag per unit span:

$$L' = N' \cos(\alpha) - A' \sin(\alpha)$$

$$D' = N' \sin(\alpha) + A' \cos(\alpha)$$

$$C_L = \frac{L'}{K(P_A - P_E)}$$

$$C_D = \frac{D'}{K(P_A - P_E)}$$

$$C_M = \frac{M'_{LE}}{K(P_A - P_E)}$$

3 Experimental Setup

3.1 General Description

The low speed wind tunnel and a GA(W)-1 airfoil with 43 pressure taps in it were used to find the pressure distribution at the following angles of attack: $[-4°, 0°, 4°, 6°, 8°, 10°, 12°, 14°, 16°]$. A wind tunnel motor frequency of 15 Hz was used, which produces a test section flow velocity of about 22 $\frac{\mathrm{m}}{\mathrm{s}}$(Figure 17). The pressure taps were hooked up to 3 pressure transducers which were then hooked up to the computer to record the results. At each angle of attack 1000 pressure measurements for each pressure tap was made. During the analysis these were then averaged for each angle of attack. The values of P_A and P_E were used to calculate the dynamic pressure of the system using Bernoulli's equation (Section 2.3). Then the method described in Section 2.4 was used to determine the lift, drag, and moment coefficients.

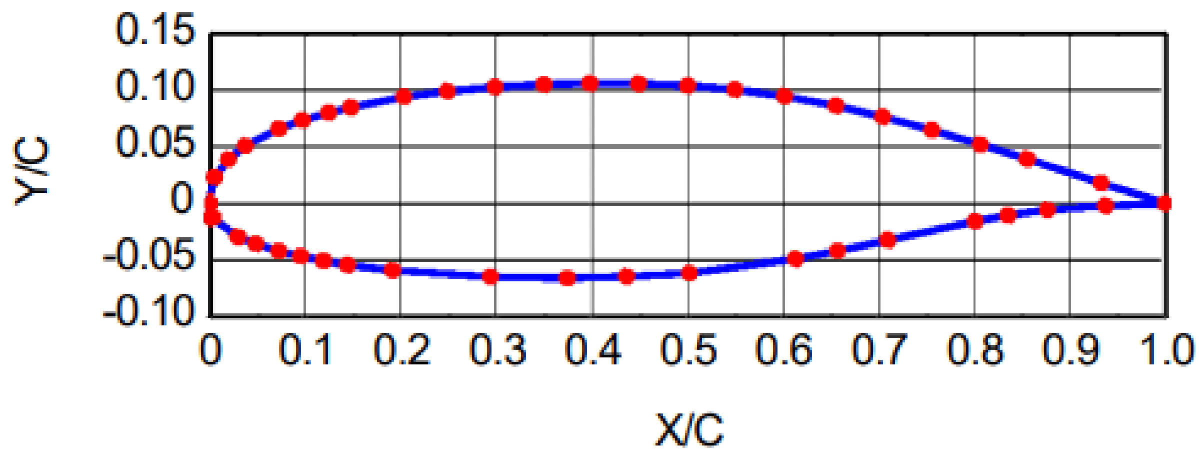

Figure 4: GA(W)-1 Airfoil with Pressure Taps (Red)

3.2 Case Study

The lab was at NTP during the experiment

- $P_{ntp} = 1$ atm
- $\rho_{ntp} = 1.204 \, \frac{\mathrm{kg}}{\mathrm{m}^3}$
- $T_{ntp} = 20\,°\mathrm{C}$

4 Results

4.1 C_P distribution for $\alpha = -4°$

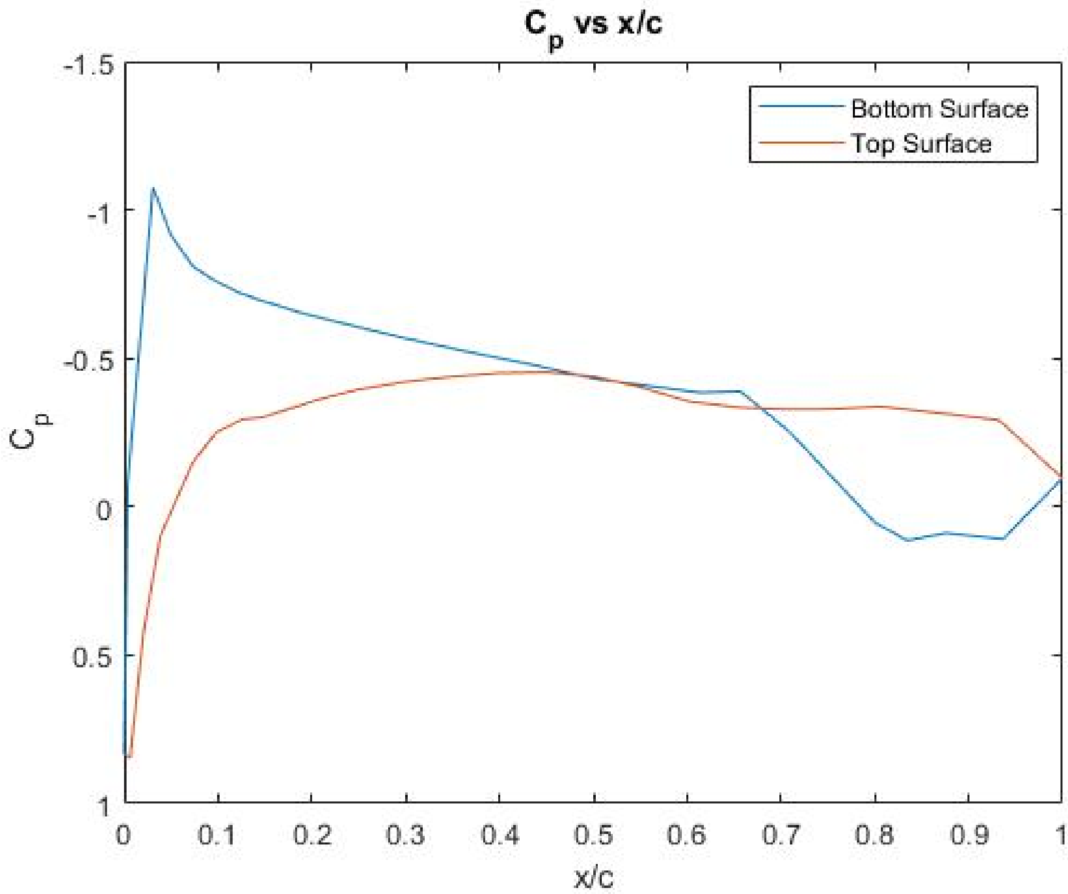

Figure 5: C_P distribution for $\alpha = -4°$

4.2 C_P distribution for $\alpha = 0°$

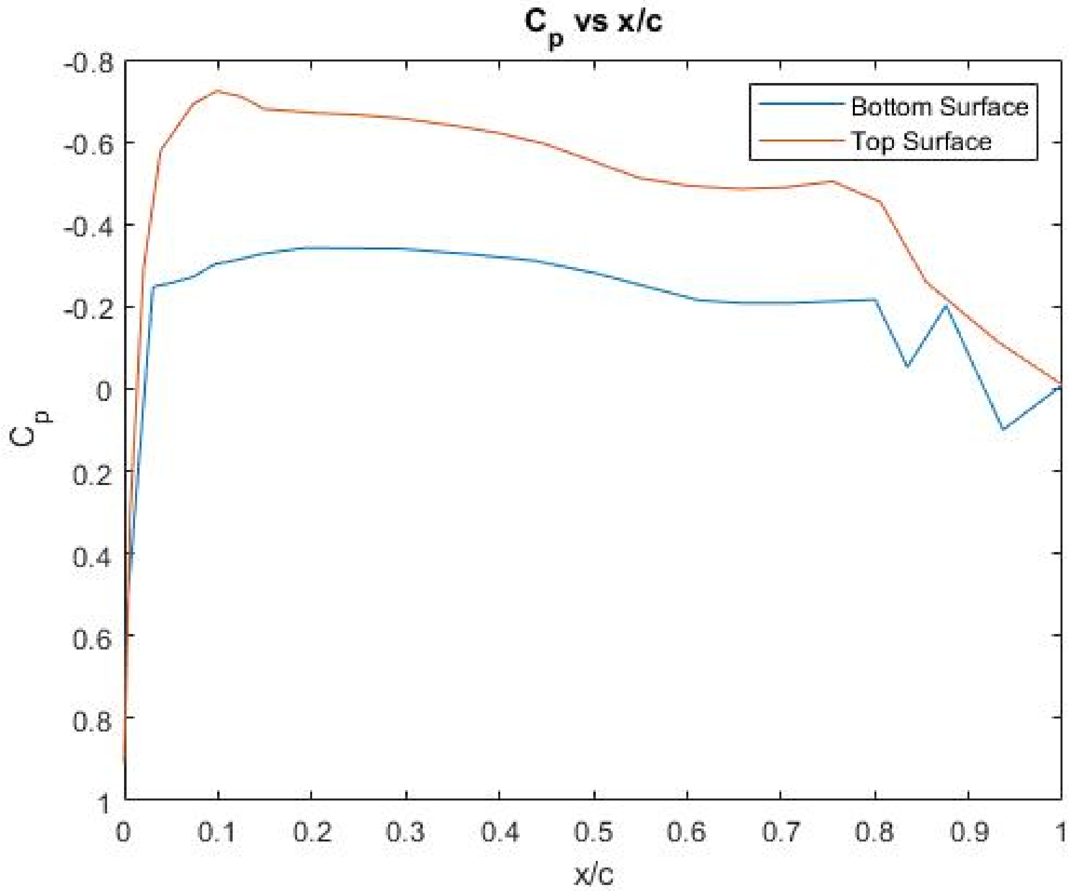

Figure 6: C_P distribution for $\alpha = 0°$

4.3 C_P distribution for $\alpha = 4°$

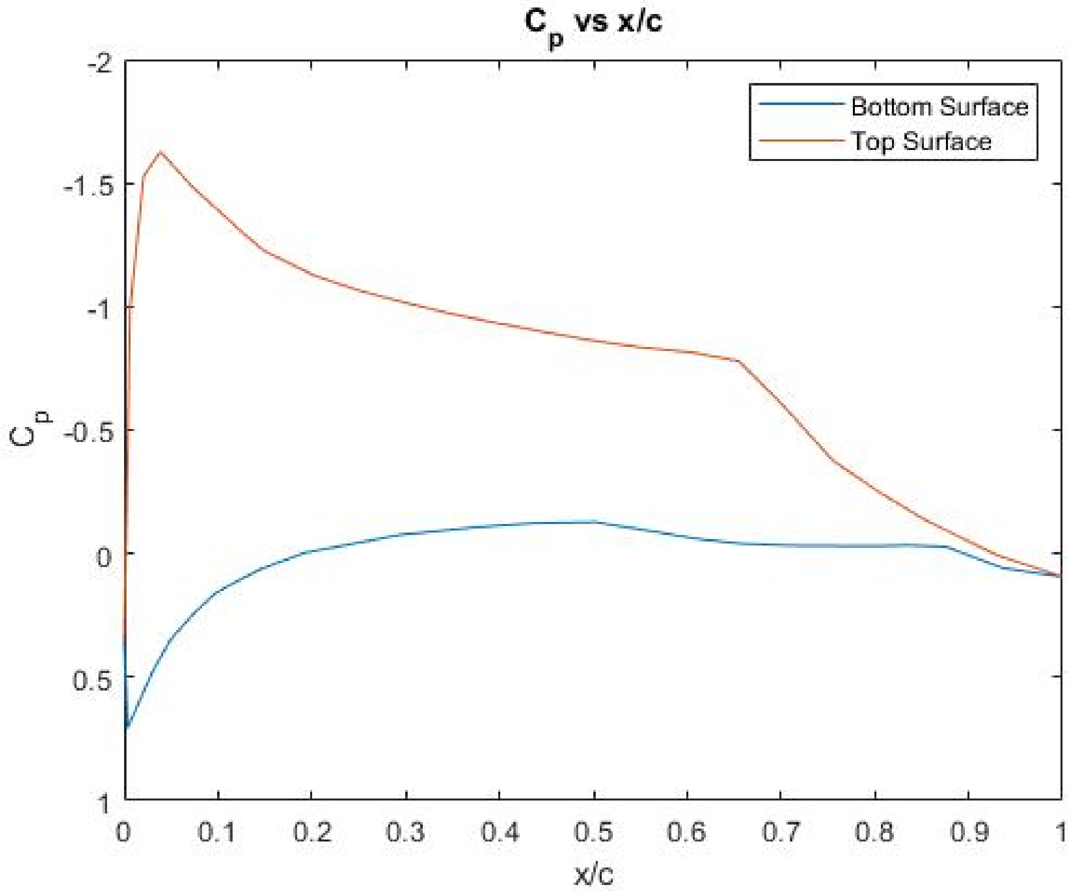

Figure 7: C_P distribution for $\alpha = 4°$

4.4 C_P distribution for $\alpha = 6°$

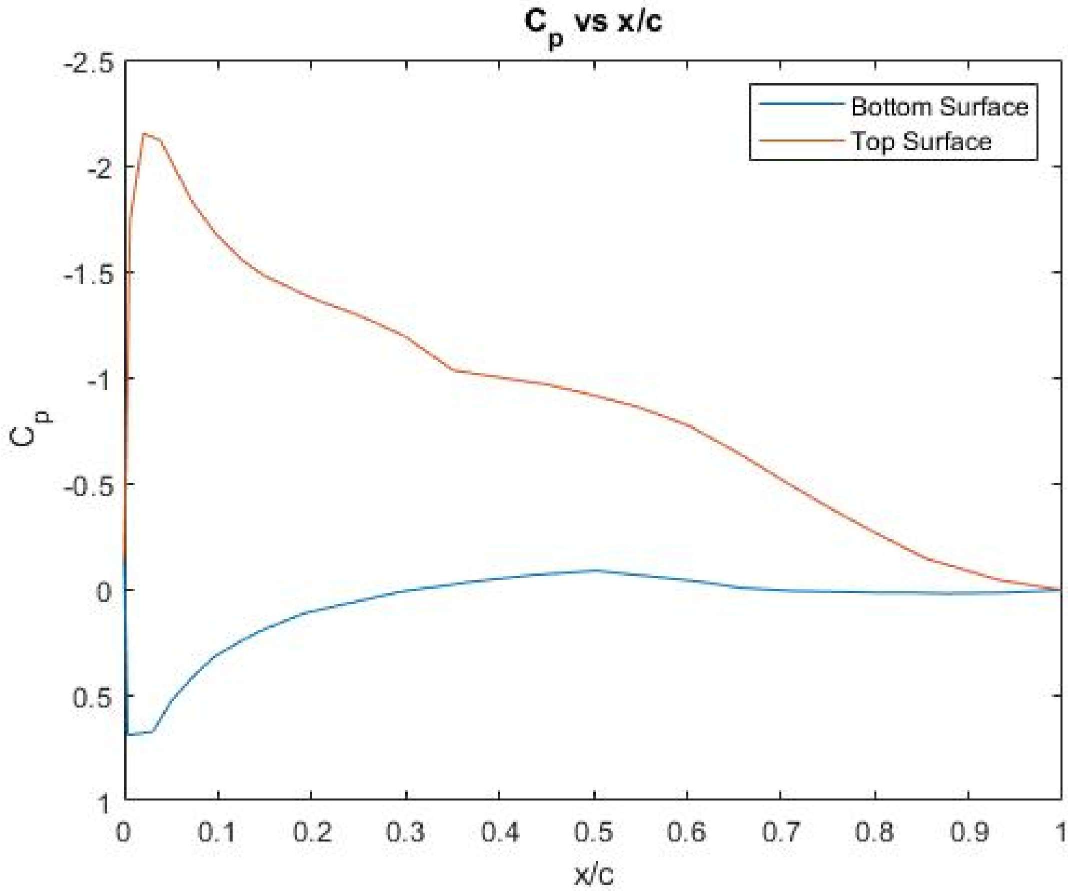

Figure 8: C_P distribution for $\alpha = 6°$

4.5 C_P distribution for $\alpha = 8^\circ$

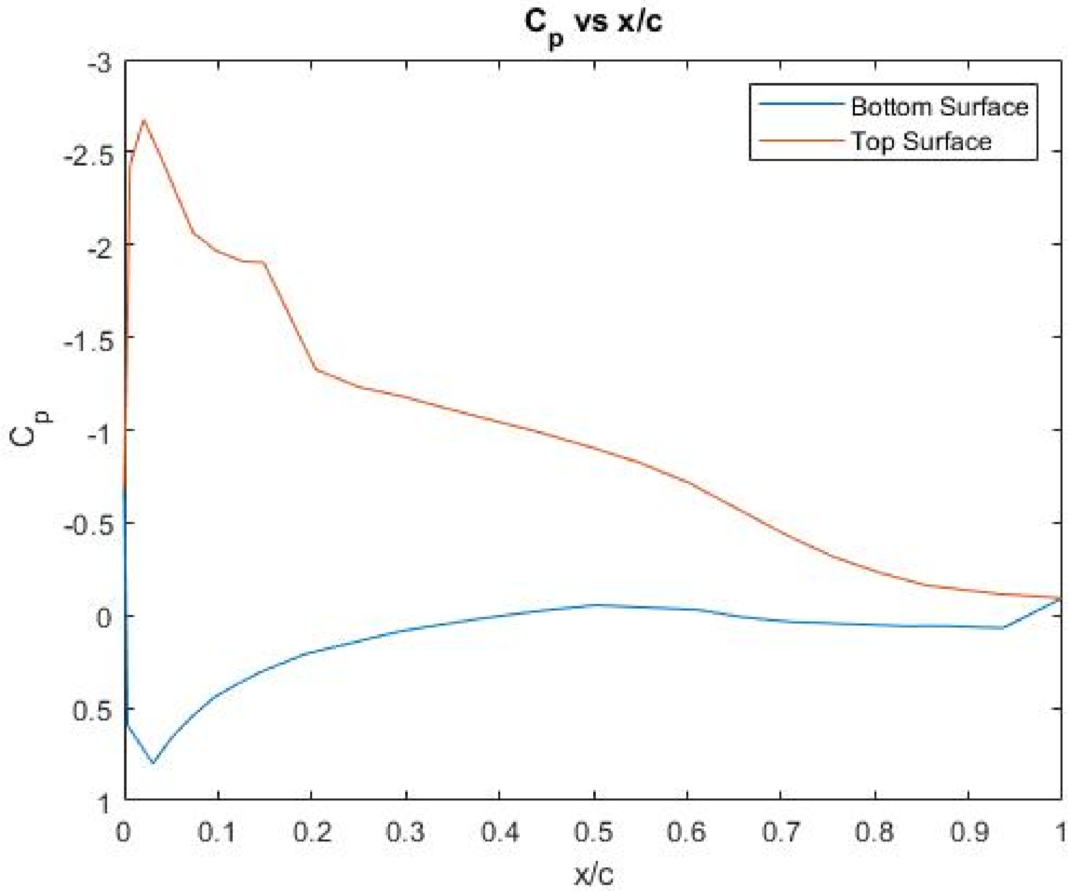

Figure 9: C_P distribution for $\alpha = 8^\circ$

4.6 C_P distribution for $\alpha = 10°$

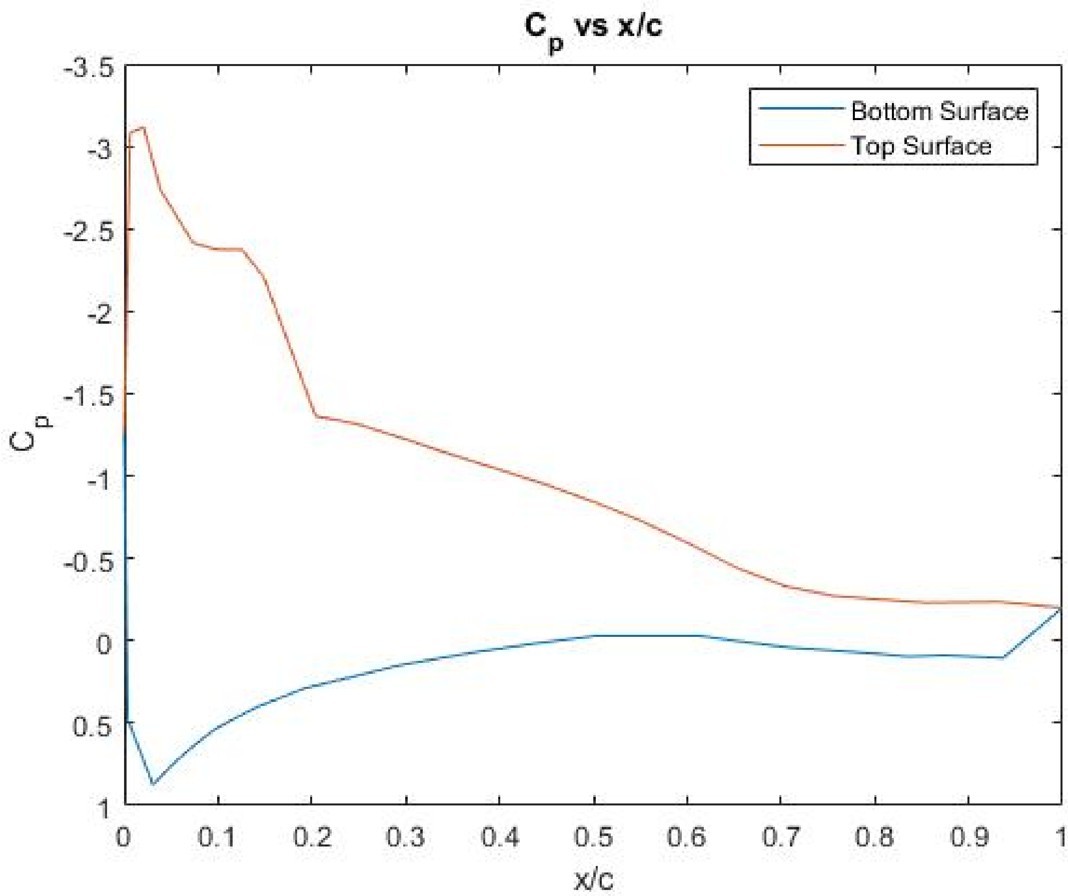

Figure 10: C_P distribution for $\alpha = 10°$

4.7 C_P distribution for $\alpha = 12°$

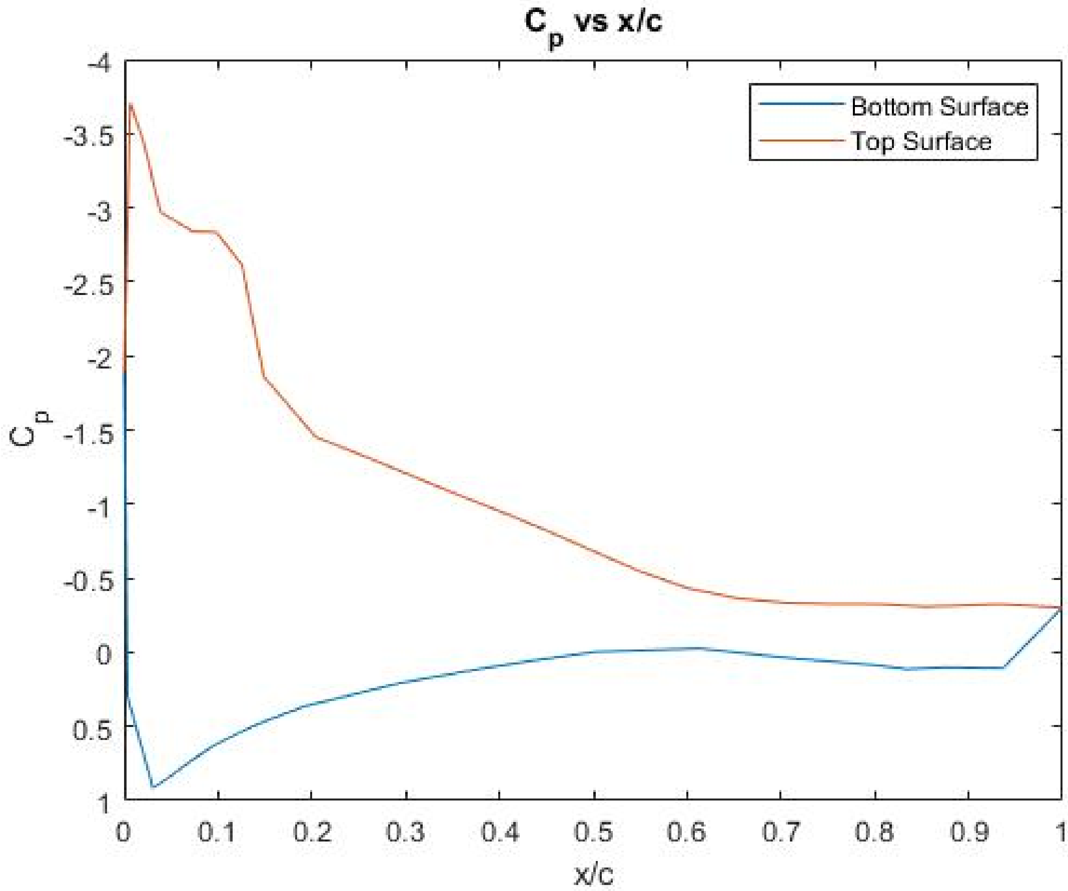

Figure 11: C_P distribution for $\alpha = 12°$

4.8 C_P distribution for $\alpha = 14°$

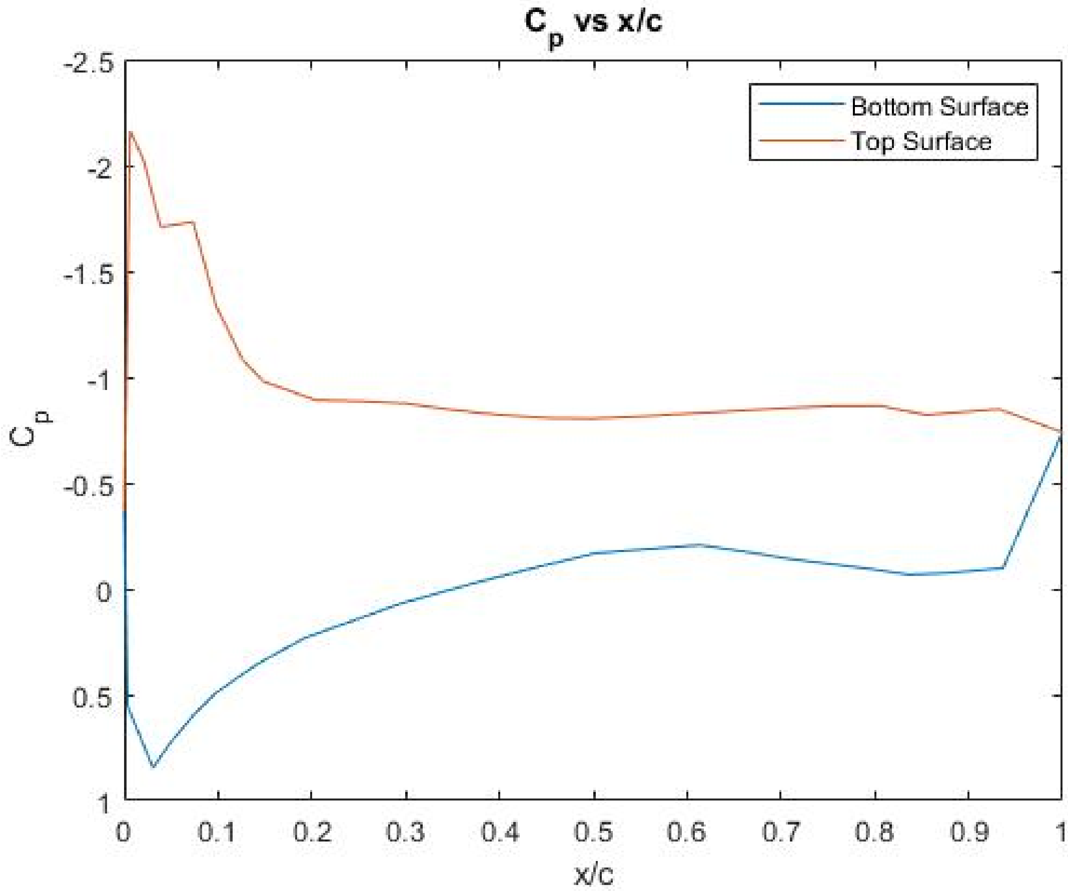

Figure 12: C_P distribution for $\alpha = 14°$

4.9 C_P distribution for $\alpha = 16°$

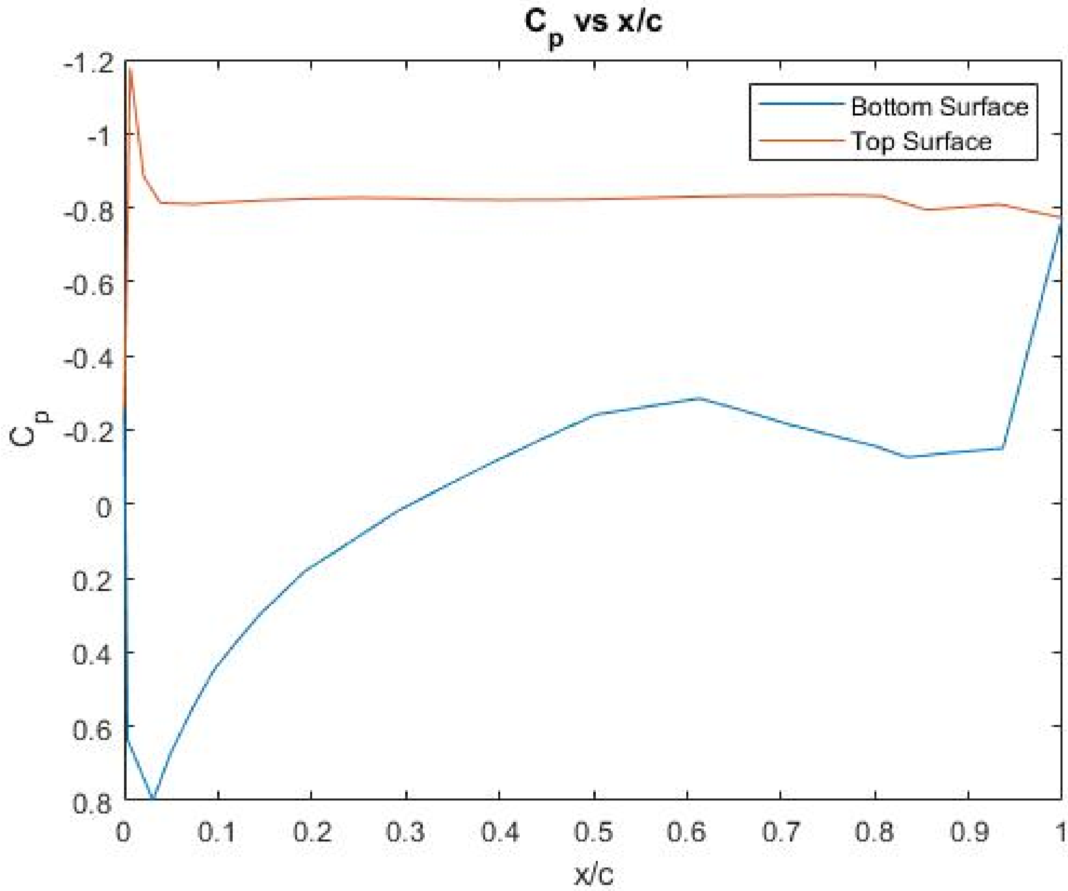

Figure 13: C_P distribution for $\alpha = 16°$

4.10 C_L variation with changes to α

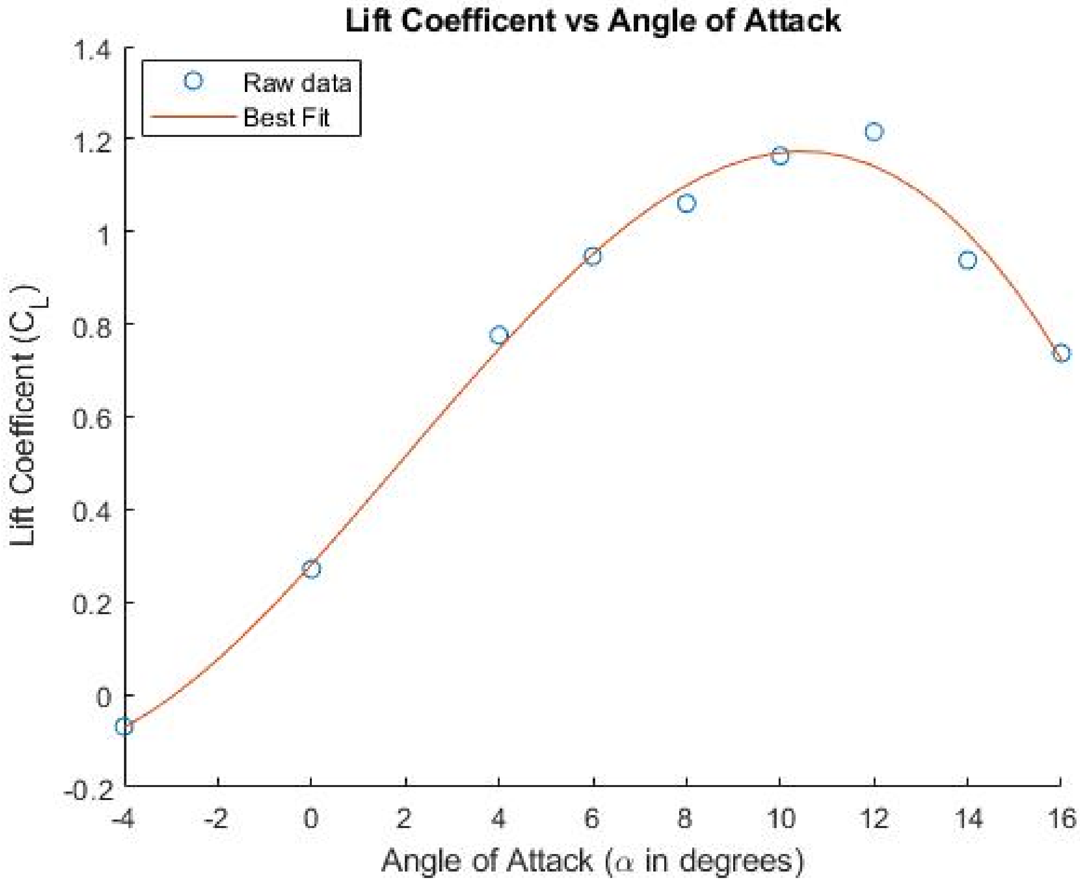

Figure 14: C_L variation with changes to α

4.11 C_D variation with changes to α

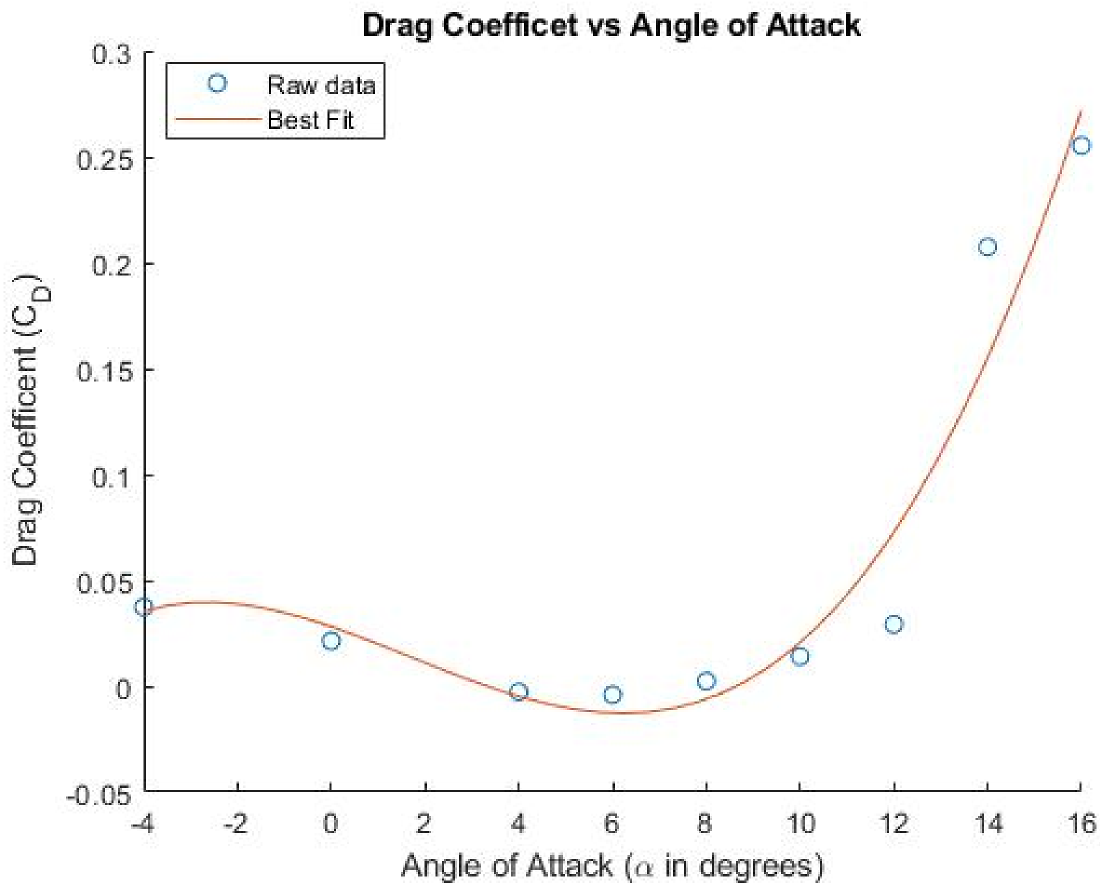

Figure 15: C_D variation with changes to α

4.12 C_M variation with changes to α

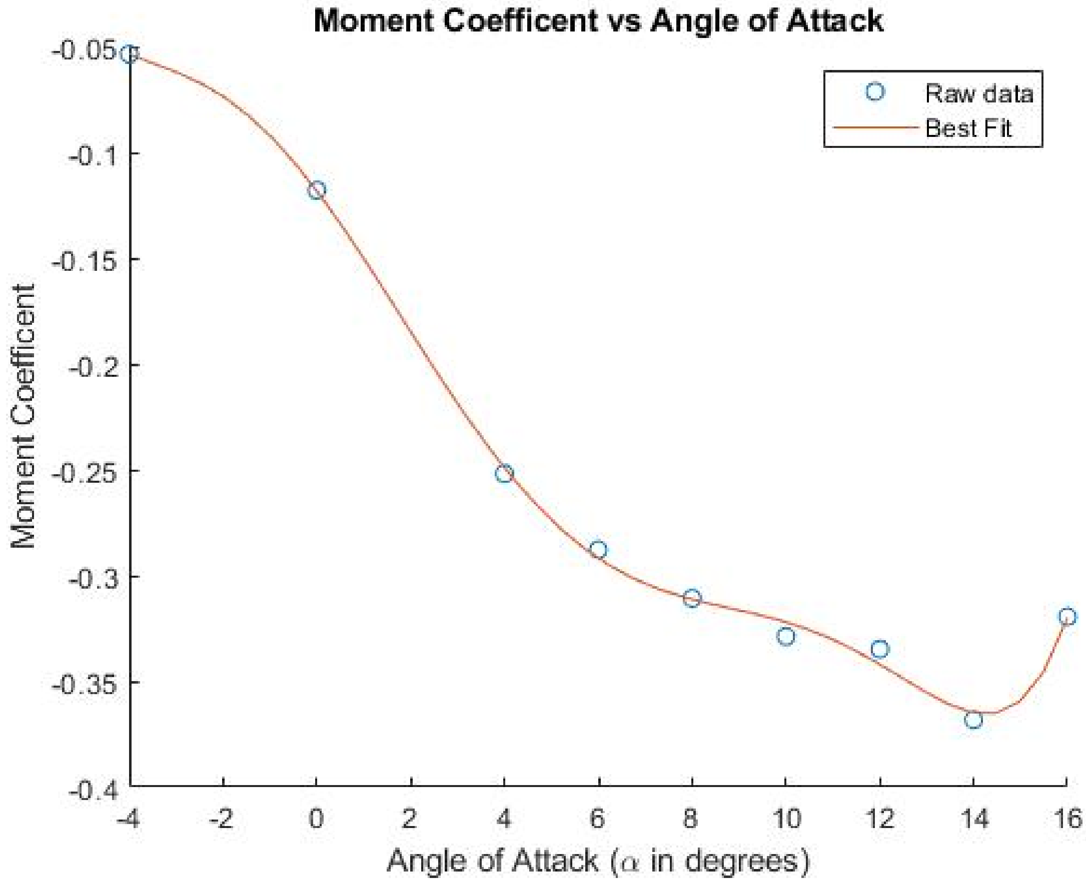

Figure 16: C_M variation with changes to α

4.13 The Calibration Constant and Plot between q_T and Δp

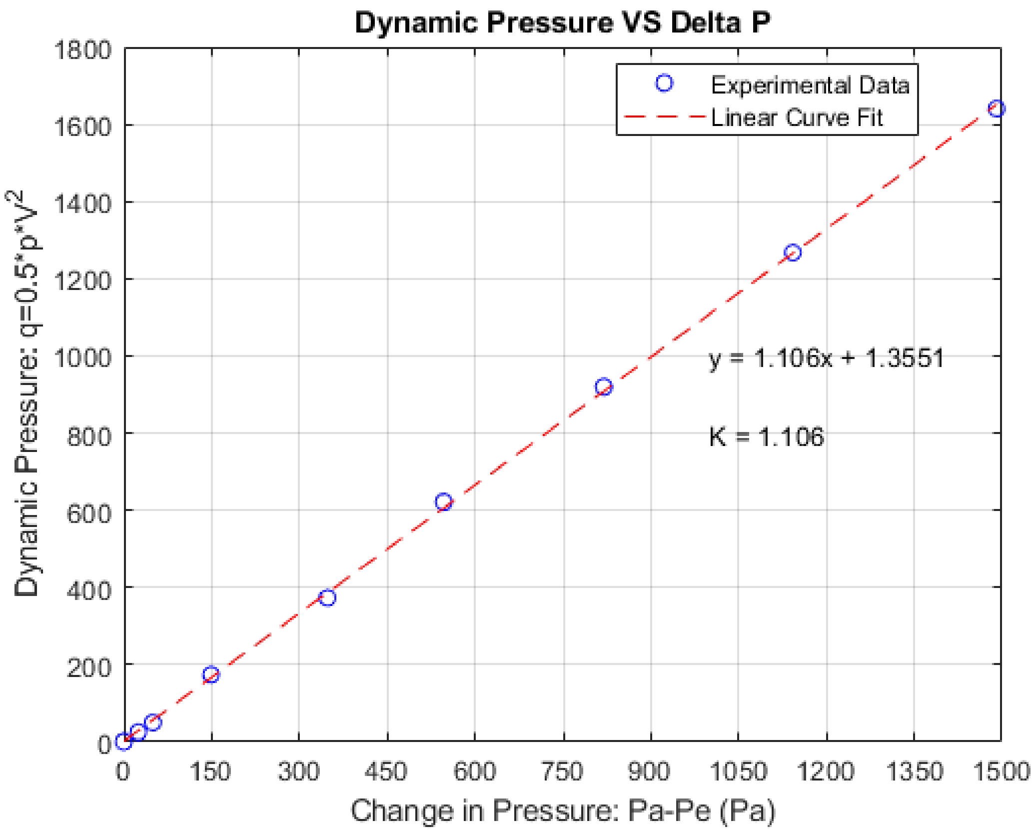

Figure 17: q_T vs. Δp

4.14 Flow Velocity vs. Motor Speed

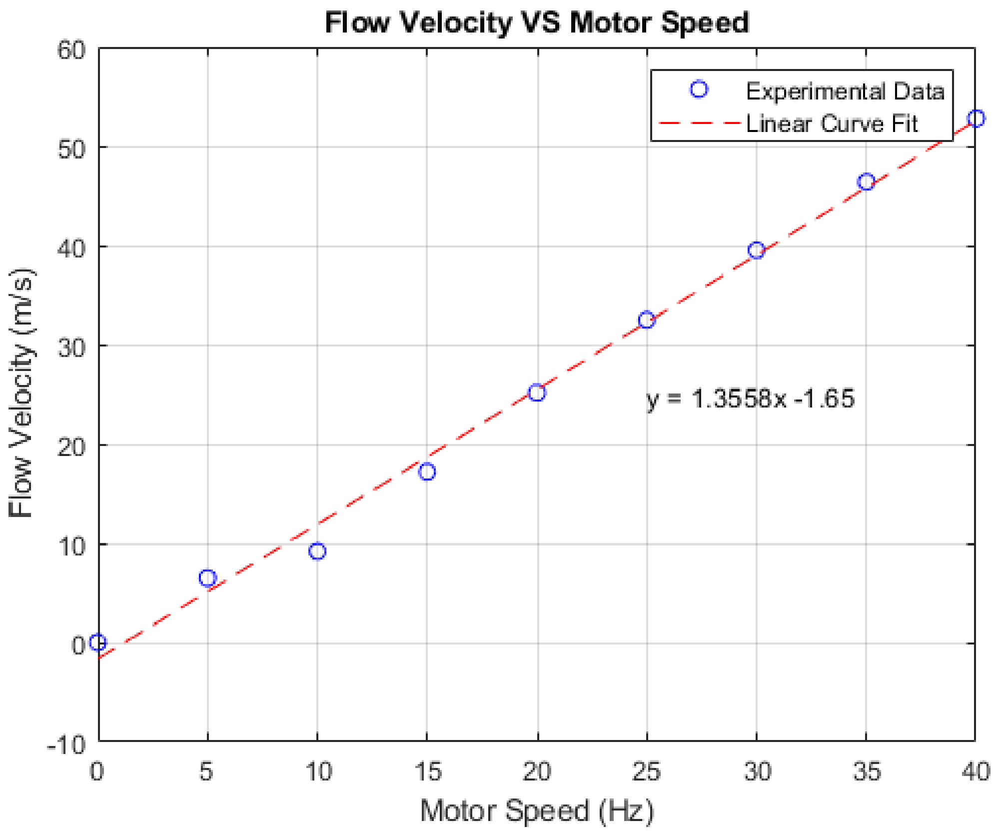

Figure 18: Flow Velocity vs. Motor Speed

4.15 Reynolds Number

The Re value for this experiment is as follows:

$$\text{Re} = \frac{\rho V c}{\mu} = \frac{\left(1.2040\,\frac{\text{kg}}{\text{m}^3}\right)\left(22\,\frac{\text{m}}{\text{s}}\right)(0.101\ \text{m})}{(1.81 * 10^{-5}\ \text{Pa s})} = 147805.97$$

4.16 General Discussion of Results and of Error

The pressure distributions obtained seem realistic and reasonable. Now, there are a few graphs that are particularly interesting. In Figure 2 the pressure on the bottom surface sharply decreases overtaking the pressure on the top surface. This is the only graph in which this happens and it is because the airfoil was at a negative angle of attack thus causing a pressure increase on the top of the airfoil and a decrease in pressure on the bottom surface of the airfoil. Another interesting graph is Figure 9 where there is a large zone on the top surface of the airfoil with constant pressure. The cause of this apparent constant pressure is the flow separating from the airfoil. This separation appears to start at $\alpha = 10°$ (Figure 7) and is exacerbated at $\alpha = 16°$ (Figure 10).

Another interesting result, attained from the pressure distribution graphs, is the movement of the stagnation point on the airfoil as the angle of attack is varied. These estimations can be found under A.4 Figure 17. There it is shown that the stagnation point moves back along the bottom surface of the airfoil as the angle of attack is increased, which makes sense.

As for the graphs for the Lift, Drag, and Moment coefficient, they all seem reasonable and there are no apparent warning signs that indicate there was an error in their calculation. We can also estimate the angle of attack at which stall occurs from our C_L vs α graph (Figure 11). From this graph the angle of attack at which stall occurs at is approximately 12°.

5 Conclusion

Pressure distribution over an airfoil is a function of the angle of attack of that airfoil. However, when flow separation occurs the pressure distribution with flatten out on a constant value. The Lift, Drag, and Moment coefficients are also functions of the angle of attack and the Lift coefficient has an angle off attack at which it drastically drops known as the stall angle. For the GA(W)-1 airfoil this occurs at approximately $\alpha = 12°$. Similarly, flow separation for the GA(W)-1 airfoil begins at $\alpha = 10°$.

6 Work Cited

Department of Aerospace Engineering. ”Lab 5 Instructions”. Lab handbook. Iowa State University. Ames, Iowa. 2020. Print.

A Appendix of Data Tables

A.1 Average Pressure Measurements

#	-4 degrees	0 degrees	4 degrees	6 degrees	8 degrees	10 degrees	12 degrees	14 degrees	16 degrees
1	69.1027143	79.38073878	-25.6661525	-129.286086	-228.945094	-350.5473422	-480.822674	-172.7186254	-149.1717589
2	-114.8714385	-1.25661104	43.88418774	37.73136501	22.16378662	-5.599807119	-41.40218557	11.3177419	27.20766642
3	-319.2109162	-160.312368	-2.06391481	34.62362942	62.905134	74.53301923	82.13210698	69.89649287	59.76725438
4	-286.7156562	-162.206076	-27.0041064	6.453444193	36.42144218	51.74426985	65.97561302	45.56682827	34.40612998
5	-264.7391887	-165.276014	-47.3179604	-17.8179127	11.69343005	27.43677589	43.46519377	20.50691945	9.635667305
6	-255.3110982	-171.646772	-63.8011443	-36.6617755	-7.99507199	7.099544381	23.85098295	0.071836459	-10.75816189
7	-247.596483	-173.880565	-73.7749026	-49.1076203	-21.6305078	-7.422853865	8.724044395	-15.10409291	-25.620243
8	-241.7824456	-176.820169	-83.460699	-61.0406004	-34.7223411	-21.56371396	-5.926918132	-30.0529542	-40.43360236
9	-232.5608516	-179.894176	-96.631556	-77.846727	-53.6379365	-42.48484295	-28.29684009	-52.73077363	-63.12216463
10	-216.4582289	-179.509274	-111.10358	-98.1574218	-78.0780081	-70.73243621	-59.9493013	-85.28121352	-96.55382503
11	-205.3321585	-176.526069	-117.113161	-107.989044	-90.8627782	-86.33209367	-78.1000082	-104.9510995	-117.3016554
12	-197.448788	-173.482824	-120.362318	-113.960875	-99.0544209	-96.55959117	-90.28051036	-118.9309525	-132.2709427
13	-187.9387266	-167.15174	-121.182753	-118.068184	-105.924792	-105.9460466	-101.9005635	-132.9281122	-147.4261118
14	-178.5914042	-153.477926	-107.624953	-107.729203	-100.764119	-106.0263947	-106.448199	-140.568849	-156.0860243
15	-179.3848332	-152.200901	-103.969359	-101.780543	-93.364337	-99.05449786	-100.6478653	-134.9163507	-150.0413113
16	-151.5205452	-152.120582	-102.518054	-98.9809229	-88.1586301	-91.81557064	-93.5340546	-127.5622279	-142.0322175
17	-89.33463975	-153.912634	-102.061669	-97.3166723	-84.7019694	-84.5929579	-84.05522422	-117.3027568	-130.4775986
18	-77.30165615	-119.889328	-102.743684	-97.3065566	-83.3738701	-80.94245782	-78.68216392	-112.5932738	-124.4514573
19	-82.37277869	-150.996381	-101.525323	-96.5511011	-83.4432952	-82.48474211	-81.06093358	-114.0019269	-126.6845888
20	-78.26553792	-88.5102903	-84.2948456	-97.2369021	-81.4908334	-79.12257228	-79.93741587	-118.6686886	-129.2944811
21	-119.9094628	-110.935865	-77.3225162	-99.6833648	-113.402042	-139.9775054	-161.9729159	-246.9942043	-253.0919769
22	-159.7852844	-132.311005	-94.1536416	-109.227084	-117.762214	-147.2535209	-166.5060391	-268.7871495	-260.3518027
23	-165.514321	-162.559195	-122.389785	-129.542286	-126.831876	-146.0615388	-163.1219561	-263.3408386	-257.3391139
24	-169.0750281	-203.03563	-144.698532	-151.441295	-140.088596	-150.0479159	-166.4613255	-271.8876336	-264.9564866
25	-167.2896213	-213.355161	-170.663768	-175.79206	-157.555392	-154.3736635	-166.6565688	-271.6423039	-265.4643746
26	-167.1202599	-210.340605	-213.236353	-202.585046	-181.234333	-166.2069233	-168.2821747	-269.7517806	-265.1260664
27	-168.4145754	-209.582672	-250.612979	-229.306659	-207.619697	-187.1443475	-174.0576235	-267.2306551	-265.0091453
28	-172.6126984	-211.15157	-257.80712	-255.823598	-236.34377	-218.0405473	-187.7037154	-264.5063221	-264.4411236
29	-182.4373333	-215.019867	-261.548836	-272.839319	-257.371053	-245.7435397	-210.7822296	-261.8920308	-263.7403974
30	-189.6281008	-223.324769	-266.811059	-284.370773	-273.10797	-268.17644	-238.0039077	-259.9778168	-263.1758773
31	-192.5579325	-232.028307	-273.526621	-294.933789	-288.109846	-289.1611352	-266.450547	-260.4639026	-262.8700757
32	-191.8987779	-237.831705	-280.816492	-301.636136	-301.250116	-307.715015	-293.0816087	-263.5287189	-262.8131103
33	-189.5471848	-241.490271	-288.167076	-308.242544	-313.404895	-324.664577	-317.020067	-267.9712474	-263.0146988
34	-186.0342109	-244.840696	-297.344735	-340.235222	-327.442651	-344.1302945	-343.6543935	-274.1700275	-263.6396771
35	-180.7356541	-246.864089	-307.335477	-360.674404	-338.186091	-362.0029729	-369.700604	-276.2801857	-263.9295685
36	-173.3414514	-247.76402	-318.616316	-375.128323	-357.020937	-371.981535	-392.3637232	-277.2369787	-263.5476587
37	-161.7362883	-249.778002	-339.142877	-398.017364	-470.523773	-539.8339363	-474.0481151	-294.8109276	-262.5715209
38	-160.1476858	-255.870149	-353.924474	-412.561916	-472.178437	-573.1762675	-624.7832859	-316.1553794	-261.9162949
39	-151.1682004	-258.709029	-372.949077	-437.132136	-483.207815	-573.595903	-669.1863784	-365.6499403	-261.1616496
40	-131.1870667	-252.251771	-389.664466	-466.441854	-502.319637	-581.4624123	-669.9734178	-445.2089004	-260.440594
41	-80.45237941	-228.647584	-418.547057	-526.195646	-584.018257	-645.5163609	-696.1412575	-440.777049	-261.1353867
42	-14.96450481	-169.680046	-398.843153	-532.930391	-623.097119	-721.4271172	-790.6307309	-503.3163684	-275.2928375
43	71.76617903	-45.4222329	-292.684532	-450.23941	-574.756593	-715.0423966	-843.8332527	-531.4920483	-333.5003336
44	-100.4022197	-108.992246	-96.0216162	-100.873245	-95.0386076	-100.089928	-101.2772273	-99.20047075	-99.35946286
45	84.4132505	79.31449752	84.2276551	81.72027537	84.30384715	81.17051335	80.81576493	82.44348799	81.58035715

Figure 19: Pressure Tap Averages in (Pa)

A.2 Values for C_L, C_D, and C_M

Angler of Attack (degrees	C_L	C_D	C_M
-4	-0.069376334	0.037331094	-0.053634
0	0.270752884	0.021328288	-0.11794271
4	0.776297605	-0.00267382	-0.25185547
6	0.946686839	-0.00401741	-0.28780164
8	1.060914246	0.002378045	-0.31077283
10	1.163664754	0.014041192	-0.32886592
12	1.215523363	0.02917855	-0.33478178
14	0.937911889	0.207437566	-0.36815363
16	0.737426437	0.255280848	-0.31944442

Figure 20: Values for C_L, C_D, and C_M

A.3 C_P Data

tap #	-4 degree	0 degree	4 degree	6 degree	8 degree	10 degree	12 degree	14 degree	16 degree
1	0.833779739	0.909410703	0.354839229	-0.14146096	-0.67877497	-1.256140373	-1.894863229	-0.367943346	-0.250270535
2	-0.071172804	0.520116723	0.705617801	0.690080298	0.594101554	0.47390434	0.298923399	0.553121079	0.63590771
3	-1.076300575	-0.24775882	0.4738776	0.674607601	0.800620354	0.87580132	0.915662686	0.846295761	0.799495943
4	-0.916459272	-0.25690109	0.348091231	0.534354764	0.666373929	0.761506967	0.835002132	0.72453076	0.672074751
5	-0.808358978	-0.27172187	0.24563789	0.413513292	0.541027083	0.639595525	0.722619896	0.599111035	0.547621203
6	-0.761983036	-0.30247807	0.162504613	0.319694057	0.441225626	0.537596478	0.624696849	0.496837619	0.445157054
7	-0.724035528	-0.31326218	0.112201757	0.257729074	0.372107298	0.464761059	0.549176302	0.420885193	0.370485913
8	-0.695436794	-0.32745374	0.063351244	0.198317526	0.305744502	0.393839201	0.476032044	0.346069196	0.296059563
9	-0.650076591	-0.34229417	-0.00307624	0.114643709	0.209860926	0.288911683	0.364351235	0.232571342	0.18206605
10	-0.570869218	-0.34043597	-0.0760662	0.013521457	0.085973658	0.147239126	0.206327774	0.069663039	0.014096288
11	-0.516141064	-0.32603391	-0.10637564	-0.03542792	0.021167373	0.069000837	0.115711203	-0.028780722	-0.090146459
12	-0.477363464	-0.311342	-0.12276283	-0.06516028	-0.02035625	0.017705999	0.054900605	-0.098747031	-0.165356234
13	-0.430584315	-0.28077734	-0.12690071	-0.08560962	-0.05518231	-0.02937069	-0.003111977	-0.168799956	-0.241499928
14	-0.384605665	-0.21476409	-0.05852167	-0.03413423	-0.02902275	-0.029773667	-0.025815839	-0.207040283	-0.285009686
15	-0.388508472	-0.20859898	-0.0400846	-0.00451723	0.008486915	0.005193081	0.003142061	-0.178750683	-0.254639403
16	-0.25144651	-0.20821123	-0.03276492	0.009421435	0.03487476	0.041499088	0.038657434	-0.141944801	-0.214399535
17	0.054440444	-0.21686274	-0.03046313	0.017707354	0.05239665	0.077723272	0.08598006	-0.090598244	-0.156345985
18	0.113629624	-0.05260798	-0.03390289	0.017757718	0.059128815	0.096031936	0.112804817	-0.067028244	-0.12606901
19	0.088685222	-0.20278391	-0.02775806	0.021518956	0.058776898	0.088296786	0.100928919	-0.074078265	-0.137288871
20	0.108888375	0.098881004	0.059144209	0.018104511	0.06867397	0.105159363	0.10653803	-0.097434454	-0.15040168
21	-0.095954399	-0.00938323	0.094309296	0.005924139	-0.09308466	-0.20005156	-0.30302044	-0.739677447	-0.772393998
22	-0.292100029	-0.11257627	0.009421168	-0.04159183	-0.11518647	-0.236543579	-0.32565185	-0.848746686	-0.808869339
23	-0.320280652	-0.25860585	-0.1329884	-0.14273652	-0.16116079	-0.23056533	-0.308756971	-0.821489012	-0.79373277
24	-0.337795455	-0.45401447	-0.24550303	-0.25176662	-0.2283594	-0.250558546	-0.325428619	-0.864263975	-0.832004524
25	-0.329013197	-0.5038342	-0.37645923	-0.37300345	-0.31689898	-0.272253836	-0.326403363	-0.86303615	-0.834556292
26	-0.328180123	-0.48928079	-0.59117494	-0.50639953	-0.43692806	-0.33160219	-0.334519126	-0.853574467	-0.832856539
27	-0.334546747	-0.4856217	-0.77968472	-0.63944026	-0.57067606	-0.436611435	-0.363352789	-0.840956749	-0.832269096
28	-0.355196941	-0.49319589	-0.81596852	-0.77146197	-0.71627902	-0.591567774	-0.431480276	-0.827322019	-0.8294152
29	-0.403523449	-0.51187092	-0.83483994	-0.85617931	-0.82286679	-0.730508948	-0.5466987	-0.814238025	-0.825894561
30	-0.438894197	-0.5519646	-0.86138007	-0.91359175	-0.90263758	-0.843018581	-0.682601679	-0.804657775	-0.823058258
31	-0.453305779	-0.59398279	-0.89525015	-0.96618257	-0.97868242	-0.948264907	-0.82462022	-0.807090535	-0.821521828
32	-0.450063456	-0.62199993	-0.93201676	-0.999552	-1.04529074	-1.041319759	-0.957574574	-0.822429315	-0.821235618
33	-0.438496178	-0.63966243	-0.96908958	-1.03244378	-1.10690359	-1.126328339	-1.077086229	-0.844663262	-0.822248454
34	-0.421216171	-0.65583732	-1.0153773	-1.19172792	-1.17806129	-1.223956408	-1.210056882	-0.875686891	-0.825388515
35	-0.39515304	-0.66560568	-1.06576581	-1.29348988	-1.23252002	-1.313594772	-1.340091393	-0.886247801	-0.826845008
36	-0.358781613	-0.66995029	-1.12266095	-1.3654526	-1.32799428	-1.363641103	-1.453235975	-0.891036355	-0.824926189
37	-0.301696844	-0.67967322	-1.22618708	-1.47941185	-1.90334269	-2.205485528	-1.861041554	-0.978990379	-0.820021807
38	-0.29388265	-0.70908436	-1.30073837	-1.55182581	-1.91173022	-2.372710158	-2.613579978	-1.085815	-0.816729774
39	-0.249713357	-0.72278965	-1.39668935	-1.67415525	-1.96763838	-2.374814792	-2.83526038	-1.333525167	-0.81293823
40	-0.151427932	-0.69161587	-1.48099376	-1.82008156	-2.06451664	-2.414268365	-2.839189638	-1.731701511	-0.809315451
41	0.098131495	-0.57766163	-1.6266637	-2.11758187	-2.47864877	-2.735523582	-2.969831378	-1.709521	-0.812806278
42	0.420260543	-0.29298328	-1.52728665	-2.1511126	-2.67674039	-3.116245254	-3.441565738	-2.022517519	-0.883937165
43	0.846881086	0.306897778	-0.99187346	-1.73941333	-2.43170118	-3.084223422	-3.707176887	-2.163531041	-1.17638747

Figure 21: C_P Data

A.4 Estimated Location of Stagnation Point

Angle of Attack	x/c position	y/c position
-4	0.0063	0.0227
0	0	0
4	0.0036	-0.0126
6	0.0036	-0.0126
8	0.0306	-0.0293
10	0.0306	-0.0293
12	0.0306	-0.0293
14	0.0306	-0.0293
16	0.0306	-0.0293

Figure 22: Estimated Location of Stagnation Point

A.5 Location of Pressure Taps on GA(W)-1 airfoil

Lower Surface		
tap	x/c	y/c
1	0.0000	0.0000
2	0.0036	-0.0126
3	0.0306	-0.0293
4	0.0494	-0.0355
5	0.0735	-0.0418
6	0.0962	-0.0462
7	0.1201	-0.0502
8	0.1452	-0.0539
9	0.1921	-0.0585
10	0.2944	-0.0641
11	0.3746	-0.0653
12	0.4365	-0.0640
13	0.5023	-0.0609
14	0.6130	-0.0486
15	0.6569	-0.0415
16	0.7093	-0.0322
17	0.8004	-0.0158
18	0.8348	-0.0105
19	0.8759	-0.0056
20	0.9367	-0.0023
21	1.0000	0.0000

Upper Surface		
tap	x/c	y/c
22	0.9321	0.0177
23	0.8549	0.0386
24	0.8059	0.0514
25	0.7552	0.0639
26	0.7042	0.0755
27	0.6551	0.0851
28	0.6013	0.0935
29	0.5496	0.0992
30	0.5003	0.1027
31	0.4492	0.1045
32	0.3982	0.1047
33	0.3503	0.1036
34	0.2992	0.1015
35	0.2493	0.0979
36	0.2040	0.0930
37	0.1487	0.0838
38	0.1256	0.0792
39	0.0980	0.0725
40	0.0734	0.0651
41	0.0385	0.0503
42	0.0207	0.0383
43	0.0063	0.0227

Figure 23: Location of Pressure Taps on GA(W)-1 airfoil

B Appendix of Matlab Code

B.1 Code for Plots and Data Manipulation

```
%344 Lab 4
clear, clc
%Create an array with all the averages
avg = zeros(9,45);
cphold = zeros(1,24);
% -4 degree
f5 = csvread('344Lab5Data\-4.csv');
i = 1; p = 1;
while (i < 44)
    avg(1,p) = mean(f5(:,i));
    i = i+1;
    p = p+1;
end
avg(1,44) = mean(f5(:,44));
avg(1,45) = mean(f5(:,45));

% 0 degree
f5 = csvread('344Lab5Data\0.csv');
i = 1; p = 1;
while (i < 44)
    avg(2,p) = mean(f5(:,i));
    i = i+1;
    p = p+1;
end
avg(2,44) = mean(f5(:,44));
avg(2,45) = mean(f5(:,45));

% 4 degree
f5 = csvread('344Lab5Data\4.csv');
i = 1; p = 1;
while (i < 44)
    avg(3,p) = mean(f5(:,i));
    i = i+1;
    p = p+1;
end
avg(3,44) = mean(f5(:,44));
avg(3,45) = mean(f5(:,45));

% 6 degree
f5 = csvread('344Lab5Data\6.csv');
i = 1; p = 1;
while (i < 44)
    avg(4,p) = mean(f5(:,i));
```

```
    i = i+1;
    p = p+1;
end
avg(4,44) = mean(f5(:,44));
avg(4,45) = mean(f5(:,45));

% 8 degree
f5 = csvread('344Lab5Data\8.csv');
i = 1; p = 1;
while (i < 44)
    avg(5,p) = mean(f5(:,i));
    i = i+1;
    p = p+1;
end
avg(5,44) = mean(f5(:,44));
avg(5,45) = mean(f5(:,45));

% 10 degree
f5 = csvread('344Lab5Data\10.csv');
i = 1; p = 1;
while (i < 44)
    avg(6,p) = mean(f5(:,i));
    i = i+1;
    p = p+1;
end
avg(6,44) = mean(f5(:,44));
avg(6,45) = mean(f5(:,45));

% 12 degree
f5 = csvread('344Lab5Data\12.csv');
i = 1; p = 1;
while (i < 44)
    avg(7,p) = mean(f5(:,i));
    i = i+1;
    p = p+1;
end
avg(7,44) = mean(f5(:,44));
avg(7,45) = mean(f5(:,45));

% 14 degree
f5 = csvread('344Lab5Data\14.csv');
i = 1; p = 1;
while (i < 44)
    avg(8,p) = mean(f5(:,i));
    i = i+1;
    p = p+1;
end
```

```
avg(8,44) = mean(f5(:,44));
avg(8,45) = mean(f5(:,45));

% 16 degree
f5 = csvread('344Lab5Data\16.csv');
i = 1; p = 1;
while (i < 44)
    avg(9,p) = mean(f5(:,i));
    i = i+1;
    p = p+1;
end
avg(9,44) = mean(f5(:,44));
avg(9,45) = mean(f5(:,45));

%-----------------------------------------------------------------------%
%-----------------------------------------------------------------------%
%-----------------------------------------------------------------------%

x = [0 0.0036 0.0306 0.0494 0.0735 0.0962 0.1201 0.1452 0.1921 0.2944 0.3746
    0.4365 0.5023 0.613 0.6569 0.7093 0.8004 0.8348 0.8759 0.9367 1 0.9321 0.8549
    0.8059 0.7552 0.7042 0.6551 0.6013 0.5496 0.5003 0.4492 0.3982 0.3503 0.2992
    0.2493 0.204 0.1487 0.1256 0.098 0.0734 0.0385 0.0207 0.0063 0 ];
y = [0 -0.0126 -0.0293 -0.0355 -0.0418 -0.0462 -0.0502 -0.0539 -0.0585 -0.0641
    -0.0653 -0.064 -0.0609 -0.0486 -0.0415 -0.0322 -0.0158 -0.0105 -0.0056
    -0.0023 0 0.0177 0.0386 0.0514 0.0639 0.0755 0.0851 0.0935 0.0992 0.1027
    0.1045 0.1047 0.1036 0.1015 0.0979 0.093 0.0838 0.0792 0.0725 0.0651 0.0503
    0.0383 0.0227 0];


%-4
cp1 = ((avg(1,1:43)-avg(1,44))./(1.1.*(avg(1,45)-avg(1,44))));
figure(1)
plot(x(1:21), cp1(1:21));
set(gca, 'Ydir', 'reverse')
hold on

cphold(1:23) = cp1(21:43);
cphold(24) = cp1(1);
plot(x(21:44), cphold(1:24))

title("C_p vs x/c");
xlabel("x/c");
ylabel("C_p");
legend("Bottom Surface","Top Surface")
hold off

%0
```

```
cp2 = ((avg(2,1:43)-avg(2,44))./(1.1.*(avg(2,45)-avg(2,44))));
figure(2)

plot(x(1:21), cp2(1:21));
set(gca, 'Ydir', 'reverse')
hold on
cphold(1:23) = cp2(21:43);
cphold(24) = cp2(1);
plot(x(21:44), cphold(1:24))
title("C_p vs x/c");
xlabel("x/c");
ylabel("C_p");
legend("Bottom Surface","Top Surface")
hold off

%4
cp3 = ((avg(3,1:43)-avg(3,44))./(1.1.*(avg(3,45)-avg(3,44))));
figure(3)

plot(x(1:21), cp3(1:21));
set(gca, 'Ydir', 'reverse')
hold on
cphold(1:23) = cp3(21:43);
cphold(24) = cp3(1);
plot(x(21:44), cphold(1:24))
title("C_p vs x/c");
xlabel("x/c");
ylabel("C_p");
legend("Bottom Surface","Top Surface")
hold off

%6
cp4 = ((avg(4,1:43)-avg(4,44))./(1.1.*(avg(4,45)-avg(4,44))));
figure(4)

plot(x(1:21), cp4(1:21));
set(gca, 'Ydir', 'reverse')
hold on
cphold(1:23) = cp4(21:43);
cphold(24) = cp4(1);
plot(x(21:44), cphold(1:24))
title("C_p vs x/c");
xlabel("x/c");
ylabel("C_p");
legend("Bottom Surface","Top Surface")
hold off
```

```
%8
cp5 = ((avg(5,1:43)-avg(5,44))./(1.1.*(avg(5,45)-avg(5,44))));
figure(5)

plot(x(1:21), cp5(1:21));
set(gca, 'Ydir', 'reverse')
hold on
cphold(1:23) = cp5(21:43);
cphold(24) = cp5(1);
plot(x(21:44), cphold(1:24))
title("C_p vs x/c");
xlabel("x/c");
ylabel("C_p");
legend("Bottom Surface","Top Surface")
hold off

%10
cp6 = ((avg(6,1:43)-avg(6,44))./(1.1.*(avg(6,45)-avg(6,44))));
figure(6)

plot(x(1:21), cp6(1:21));
set(gca, 'Ydir', 'reverse')
hold on
cphold(1:23) = cp6(21:43);
cphold(24) = cp6(1);
plot(x(21:44), cphold(1:24))
title("C_p vs x/c");
xlabel("x/c");
ylabel("C_p");
legend("Bottom Surface","Top Surface")
hold off

%12
cp7 = ((avg(7,1:43)-avg(7,44))./(1.1.*(avg(7,45)-avg(7,44))));
figure(7)

plot(x(1:21), cp7(1:21));
set(gca, 'Ydir', 'reverse')
hold on
cphold(1:23) = cp7(21:43);
cphold(24) = cp7(1);
plot(x(21:44), cphold(1:24))
title("C_p vs x/c");
xlabel("x/c");
ylabel("C_p");
legend("Bottom Surface","Top Surface")
hold off
```

```
%14
cp8 = ((avg(8,1:43)-avg(8,44))./(1.1.*(avg(8,45)-avg(8,44))));
figure(8)

plot(x(1:21), cp8(1:21));
set(gca, 'Ydir', 'reverse')
hold on
cphold(1:23) = cp8(21:43);
cphold(24) = cp8(1);
plot(x(21:44), cphold(1:24))
title("C_p vs x/c");
xlabel("x/c");
ylabel("C_p");
legend("Bottom Surface","Top Surface")
hold off

%16
cp9 = ((avg(9,1:43)-avg(9,44))./(1.1.*(avg(9,45)-avg(9,44))));
figure(9)

plot(x(1:21), cp9(1:21));
set(gca, 'Ydir', 'reverse')
hold on
cphold(1:23) = cp9(21:43);
cphold(24) = cp9(1);
plot(x(21:44), cphold(1:24))
title("C_p vs x/c");
xlabel("x/c");
ylabel("C_p");
legend("Bottom Surface","Top Surface")
hold off


%------------------------------------------------------------------------%
%------------------------------------------------------------------------%
%------------------------------------------------------------------------%
deltax = zeros(1,43);
deltay = zeros(1,43);
x2 = [0 0.0036 0.0306 0.0494 0.0735 0.0962 0.1201 0.1452 0.1921 0.2944 0.3746
    0.4365 0.5023 0.613 0.6569 0.7093 0.8004 0.8348 0.8759 0.9367 1 0.9321 0.8549
    0.8059 0.7552 0.7042 0.6551 0.6013 0.5496 0.5003 0.4492 0.3982 0.3503 0.2992
    0.2493 0.204 0.1487 0.1256 0.098 0.0734 0.0385 0.0207 0.0063];
y2 = [0 -0.0126 -0.0293 -0.0355 -0.0418 -0.0462 -0.0502 -0.0539 -0.0585 -0.0641
    -0.0653 -0.064 -0.0609 -0.0486 -0.0415 -0.0322 -0.0158 -0.0105 -0.0056
    -0.0023 0 0.0177 0.0386 0.0514 0.0639 0.0755 0.0851 0.0935 0.0992 0.1027
    0.1045 0.1047 0.1036 0.1015 0.0979 0.093 0.0838 0.0792 0.0725 0.0651 0.0503
```

```
    0.0383 0.0227];
x3 = zeros(1,43);
y3 = zeros(1,43);
p1 = zeros(1,43);
p2 = zeros(1,43);
p3 = zeros(1,43);
p4 = zeros(1,43);
p5 = zeros(1,43);
p6 = zeros(1,43);
p7 = zeros(1,43);
p8 = zeros(1,43);
p9 = zeros(1,43);


i=1;
while(i<43)

    deltax(i) = x2(i+1)-x2(i);
    deltay(i) = y2(i+1)-y2(i);
    x3(i) = 0.5*(x(i)+x(i+1));
    y3(i) = 0.5*(y(i)+y(i+1));
    p1(i) = 0.5*(avg(1,i) + avg(1,i+1));
    p2(i) = 0.5*(avg(2,i) + avg(2,i+1));
    p3(i) = 0.5*(avg(3,i) + avg(3,i+1));
    p4(i) = 0.5*(avg(4,i) + avg(4,i+1));
    p5(i) = 0.5*(avg(5,i) + avg(5,i+1));
    p6(i) = 0.5*(avg(6,i) + avg(6,i+1));
    p7(i) = 0.5*(avg(7,i) + avg(7,i+1));
    p8(i) = 0.5*(avg(8,i) + avg(8,i+1));
    p9(i) = 0.5*(avg(9,i) + avg(9,i+1));
    i = i+1;


end

    deltax(43) = x2(1)-x2(43);
    deltay(43) = y2(1)-y2(43);
    x3(43) = 0.5*(x(43)+x(1));
    y3(43) = 0.5*(y(43)+y(1));
    p1(43) = 0.5*(avg(1,43) + avg(1,1));
    p2(43) = 0.5*(avg(2,43) + avg(2,1));
    p3(43) = 0.5*(avg(3,43) + avg(3,1));
    p4(43) = 0.5*(avg(4,43) + avg(4,1));
    p5(43) = 0.5*(avg(5,43) + avg(5,1));
    p6(43) = 0.5*(avg(6,43) + avg(6,1));
    p7(43) = 0.5*(avg(7,43) + avg(7,1));
    p8(43) = 0.5*(avg(8,43) + avg(8,1));
```

```
p9(43) = 0.5*(avg(9,43) + avg(9,1));

N1 = sum(p1.*deltax);
N2 = sum(p2.*deltax);
N3 = sum(p3.*deltax);
N4 = sum(p4.*deltax);
N5 = sum(p5.*deltax);
N6 = sum(p6.*deltax);
N7 = sum(p7.*deltax);
N8 = sum(p8.*deltax);
N9 = sum(p9.*deltax);
N = [N1 N2 N3 N4 N5 N6 N7 N8 N9];

A1 = -sum(p1.*deltay);
A2 = -sum(p2.*deltay);
A3 = -sum(p3.*deltay);
A4 = -sum(p4.*deltay);
A5 = -sum(p5.*deltay);
A6 = -sum(p6.*deltay);
A7 = -sum(p7.*deltay);
A8 = -sum(p8.*deltay);
A9 = -sum(p9.*deltay);
A = [A1 A2 A3 A4 A5 A6 A7 A8 A9];

M1 = -sum((p1.*deltax).*x3)-sum((p1.*deltay).*y3);
M2 = -sum((p2.*deltax).*x3)-sum((p2.*deltay).*y3);
M3 = -sum((p3.*deltax).*x3)-sum((p3.*deltay).*y3);
M4 = -sum((p4.*deltax).*x3)-sum((p4.*deltay).*y3);
M5 = -sum((p5.*deltax).*x3)-sum((p5.*deltay).*y3);
M6 = -sum((p6.*deltax).*x3)-sum((p6.*deltay).*y3);
M7 = -sum((p7.*deltax).*x3)-sum((p7.*deltay).*y3);
M8 = -sum((p8.*deltax).*x3)-sum((p8.*deltay).*y3);
M9 = -sum((p9.*deltax).*x3)-sum((p9.*deltay).*y3);
M = [M1 M2 M3 M4 M5 M6 M7 M8 M9];

alpha = [-4 0 4 6 8 10 12 14 16];

L = N.*cosd(alpha) - A.*sind(alpha);
D = N.*sind(alpha) + A.*cosd(alpha);

CL = L;
CD = D;
CM = M;
i=1;
while(i<10)
CL(i)=(CL(i))./(1.1.*(avg(i,45)-avg(i,44)));
CD(i)=(CD(i))./(1.1.*(avg(i,45)-avg(i,44)));
```

```
CM(i)=(CM(i))./(1.1.*(avg(i,45)-avg(i,44)));
i= i+1;
end
z2 = linspace(-4,16,40);
%Lift
figure(10)
p1 = polyfit(alpha,CL,5);

hold on
plot(alpha, CL,"o")
plot(z2, polyval(p1,z2))
title("Lift Coefficent vs Angle of Attack");
xlabel("Angle of Attack (\alpha in degrees)");
ylabel("Lift Coefficent (C_L)");
legend("Raw data","Best Fit")
hold off

%Drag
figure(11)
p2 = polyfit(alpha,CD,4);
hold on
plot(alpha, CD,"o")
plot(z2, polyval(p2,z2))
title("Drag Coefficet vs Angle of Attack");
xlabel("Angle of Attack (\alpha in degrees)");
ylabel("Drag Coefficent (C_D)");
legend("Raw data","Best Fit")
hold off

%Moment
figure(12)
p3 = polyfit(alpha,CM,6);
hold on
plot(alpha, CM,"o")
plot(z2, polyval(p3,z2))
title("Moment Coefficent vs Angle of Attack");
xlabel("Angle of Attack (\alpha in degrees)");
ylabel("Moment Coefficent");
legend("Raw data","Best Fit")
hold off
```