Name: Ilhan Aziz

Student ID: 200464842

Module Code: EMS514U

Module Title: Subsonic Aerodynamics and Wings

Coursework Name: Pressure Distribution and Lift on a Piercy Aerofoil

Raw Data:

Table 1 - Predetermined Values				
Density of Mercury/ρ_{Hg} (kgm^-3)	Gravitational Constant/g (ms^-2)	Specific gas constant /$R_{specific}$ (J.kg^-1.K^-1)	Reference Temperature/T_{ref} (K)	Sutherland Constant for Air/S (K)
13600	9.807	287.3	288.2	110.4
Reference Viscosity/μ_{ref} (Nsm^-2)	Density of Water/ρwater (kgm^-3)	Chord Length/C (m)	Tunnel Calibration Constant/K (-)	
1.789E-05	1000	0.254	1.03	

Table 2 - Fluid Properities & Wind Tunnel Conditions						
Atmospheric Pressurre/H_{atm} (mmHg)	Atmospheric Temperature /T_{atm} (°C)	Manometer Inclination/ β (°)	Density of Methylated Spirit/ρ_{MS} (kgm^-3)	Stagnation Pressure/L_A (inches)	Static Pressure/L_B (inches)	ΔH_{Betz} (mmH2O)
762	20	40	829.2	9.5	11.7	30

Table 3 - Manometer Readings	Tapping	Ln at i = 3° (inches)	Ln at i = 6° (inches)	Ln at i = 9° (inches)
LE	1	10.6	13.2	12.9
US	2	13.7	15.4	14.0
LS	3	11.0	10.2	9.8
US	4	13.2	13.6	14.0
LS	5	11.3	10.7	10.8
US	6	12.9	13.3	14.0
LS	7	11.5	10.9	10.6
US	8	12.8	13.2	13.9
LS	9	11.6	11.1	10.7
US	10	12.6	13.0	13.7
LS	11	11.6	11.2	10.9
US	12	12.6	12.8	13.5
LS	13	11.7	11.3	11.0
US	14	12.4	12.6	13.1
LS	15	11.7	11.3	11.0
US	16	12.1	12.5	13.0
LS	17	11.7	11.4	11.2
US	18	12.1	12.9	12.8
LS	19	11.7	11.4	11.2
US	20	12.2	12.9	12.4
LS	21	11.7	11.4	11.3
US	22	11.9	12.1	12.4
LS	23	11.6	11.4	11.3
US	24	11.8	11.9	12.0
LS	25	11.6	11.4	11.4
US	26	11.7	11.7	11.8
LS	27	11.5	11.4	11.4
US	28	11.5	11.5	11.6
LS	29	11.4	11.5	11.4
TE	30	11.4	11.3	11.5

LE	Leading Edge
US	Upper Surface
LS	Lower Surface
TE	Trailing Edge

Apparatus and Instrumentation:

A barometer was used to obtain the atmospheric pressure reading of the room in millimetres of mercury and a thermometer was used to obtain the room temperature in degrees Celsius.

An open return wind tunnel with a working section that had a height of 0.77m, length of 2.3m and width of 1m was used. A Betz projection manometer was connected by plastic tubing to the upstream and downstream sections of the wind tunnel.

A Piercy aerofoil with a chord length of 0.254m and symmetrical profile was placed vertically on a turntable inside the wind tunnel so that the chord aligned with the length of the wind tunnel. The aerofoils angle of incidence was adjustable by rotating the turntable. 30 pressure tapings were fitted along the mid-span of the aerofoil with 2 at each position, one on the upper surface (even numbered) and one on the lower surface (odd numbered) except for the leading and trailing edges which each had one, tapings 1 and 30 respectively. These tapings were connected to an inclined, multi-tube manometer which gave readings in inches of methylated spirit. Tapings 1 to 30 were connected to the aerofoil and tapping 33 was connected to the upstream section whilst taping 34 was connected to the downstream section both in the same position within the wind tunnel as the tubes connected to the Betz manometer for their respective positions.

Sample Calculations:

Dynamic pressure -

$$(P_A - P_B) = \rho_{H_2O} \times g \times (\Delta H_{Betz} \times 10^{-3})$$

$$(P_A - P_B) = 1000 \times 9.807 \times (30 \times 10^{-3}) = 294.210Pa$$

Freestream velocity –

$$V_\infty = \sqrt{\frac{2K(P_A - P_B)}{\rho_{air}}} \quad V_\infty = \sqrt{\frac{2 \times 1.03 \times (294.210)}{1.207}} = 22.411ms^{-1}$$

Reynolds number –

$$Re = \frac{\rho_{air} \times V_\infty \times C}{\mu_{air}} \quad Re = \frac{1.207 \times 24.211 \times 0.254}{1.813 \times 10^{-5}} = 378909.308$$

Pressure coefficient calculation for taping 12 at x/C = 0.30 (upper surface) for the 3° inclination test [1] -

$$C_{P_n} = \frac{1}{K} \times \frac{L_n - L_B}{L_A - L_B} \quad C_{P_n} = \frac{1}{1.03} \times \frac{0.320 - 0.298}{0.241 - 0.298} = -0.379$$

This confirms that the even numbered tapings were connected to the upper surface since the inclinations tested in the experiment were positive angles of attack meaning the upper surface became the suction surface at angles greater than 0 which should have resulted in negative values similar to the one obtained in this sample calculation. If the value for the even tapings were positive, they would have been on the lower or pressure surface.

Experimental results, difference in pressure Between the lower & upper surfaces at x/C = 0.30 for the 3° inclination test –

$$\Delta C_P = C_{P_L} - C_{P_U} \quad \Delta C_P = 0.013 - (-0.379) = 0.3919$$

Theoretical results, difference in pressure between the lower & upper surfaces at x/C = 0.30 for the 3° (0.0524Rad) inclination test [1] –

The inclinations (α) were converted to radians before being substituted into this equation

$$\Delta C_P = 4\alpha \times \sqrt{\frac{1-\left(\frac{x}{C}\right)}{\left(\frac{x}{C}\right)}} \quad \Delta C_P = 4 \times 0.0524 \times \sqrt{\frac{1-(0.3)}{(0.3)}} = 0.320$$

Lift Coefficient Perpendicular to the Chord for the experimental results at a 3° inclination[2]–

$$C_L{}' = \int_0^1 \Delta C_P \, d\left(\frac{x}{C}\right)$$

Approximation using the trapezium rule –

$$C_L' = \frac{h}{2}\left(\Delta C_{P_1} + 2(\Delta C_{P_2} + \Delta C_{P_3} + \Delta C_{P_4} + \cdots + \Delta C_{P_{10}}) + \Delta C_{P_{11}}\right)$$

Where ΔC_{P_n} is the n^{th} ΔC_P value with 15 in total, one for each x/C value.

$$C_L' = \frac{0.05}{2}(0.00 + (1.1756 + 0.8273 + 0.6069 + \cdots + 0.1742) + 0.2177) = 0.282$$

The trapezium rule was used twice, once between x/C = 0 & 0.05 with steps (h) of 0.05 with a second integral between x/C = 0.5 & 1 with steps (h) of 0.1.

Lift Coefficient Perpendicular to the Direction of the Freestream Velocity –

$$C_L = C_L{}'\cos(\alpha)$$

Lift Curve Slope –

The range used for this calculation was 6° to 3° since the aerofoil was observed to have stalled between 6° and 9° due to a drop in the lift coefficient.

The inclinations (α) were converted to radians before being substituted into this equation.

$$\frac{dC_L}{d\alpha} = \frac{C_{L6} - C_{L3}}{\alpha_6 - \alpha_3} \quad \frac{dC_L}{d\alpha} = \frac{0.545 - 0.282}{0.105 - 0.0524} = 5.024rad^{-1}$$

The inclinations (α) were converted to radians before being substituted into this equation.

Processed Data:

Table 4 - Processed Data - Single Values Converted						
Atmospheric Pressure/Patm (Pa)	Atmospheric Temperature/Tatm (K)	Density of Air/pair (kgm^-3)	Viscosity of Air/μ (Pa.s)	Stagnation Pressure Height Reading/LA (m)	Static Pressure Height Reading/LB (m)	ΔHBetz (m)
101632	293.16	1.207	1.8128E-05	0.241	0.298	0.030

Table 5 - Processed Data - V∞ & Re Values	
ΔP (Pa)	294.21 ± 0.07
Velocity/V∞ (ms^-1)	22.411 ± 0.012
Reynolds Number/*Re* (-)	378909 ± 18

Table 6 - Pressure Coefficient Calculations - 3°	Upper Surface			Lower Surface			Leading/Trailing Edge	
x/C	Taping number/ *n*	Fluid Height in Manometer Tube n/*L n* (m)	Pressure Coefficient/ *Cp* (-)	Taping number/ *n*	Fluid Height in Manometer Tube n/*L n* (m)	Pressure Coefficient/ *Cp* (-)	ΔCp	ΔCp Theoretical
0.00	1	0.328	0.492	1	0.328	0.492	0.0000	0
0.05	2	0.356	-0.858	3	0.249	0.318	1.1756	0.91292566
0.10	4	0.356	-0.640	5	0.274	0.187	0.8273	0.62831853
0.15	6	0.356	-0.510	7	0.269	0.100	0.6096	0.49856576
0.20	8	0.353	-0.466	9	0.272	0.057	0.5225	0.41887902
0.25	10	0.348	-0.379	11	0.277	0.057	0.4354	0.36275987
0.30	12	0.343	-0.379	13	0.279	0.013	0.3919	0.31992414
0.35	14	0.333	-0.292	15	0.279	0.013	0.3048	0.28541794
0.40	16	0.330	-0.161	17	0.284	0.013	0.1742	0.25650997
0.45	18	0.325	-0.161	19	0.284	0.013	0.1742	0.23154409
0.50	20	0.315	-0.205	21	0.287	0.013	0.2177	0.20943951
0.60	22	0.315	-0.074	23	0.287	0.057	0.1306	0.17100664
0.70	24	0.305	-0.031	25	0.290	0.057	0.0871	0.13711034
0.80	26	0.300	0.013	27	0.290	0.100	0.0871	0.10471976
0.90	28	0.295	0.100	29	0.290	0.144	0.0435	0.06981317
1.00	30	0.292	0.144	30	0.292	0.144	0.0000	0

Table 7 - Pressure Coefficient Calculations - 6°	Upper Surface			Lower Surface			Leading/Trailing Edge	
x/C	Taping number/ *n*	Fluid Height in Manometer Tube n/*L n* (m)	Pressure Coefficient/ *Cp* (-)	Taping number/ *n*	Fluid Height in Manometer Tube n/*L n* (m)	Pressure Coefficient/ *Cp* (-)	ΔCp	ΔCp Theoretical
0.00	1	0.335	-0.640	1	0.335	-0.640	0.000	0.0000
0.05	2	0.391	-1.598	3	0.259	0.666	2.264	1.8259
0.10	4	0.345	-0.814	5	0.272	0.448	1.263	1.2566
0.15	6	0.338	-0.684	7	0.277	0.361	1.045	0.9971
0.20	8	0.335	-0.640	9	0.282	0.274	0.914	0.8378
0.25	10	0.330	-0.553	11	0.284	0.231	0.784	0.7255
0.30	12	0.325	-0.466	13	0.287	0.187	0.653	0.6398
0.35	14	0.320	-0.379	15	0.287	0.187	0.566	0.5708
0.40	16	0.318	-0.335	17	0.290	0.144	0.479	0.5130
0.45	18	0.328	-0.510	19	0.290	0.144	0.653	0.4631
0.50	20	0.328	-0.510	21	0.290	0.144	0.653	0.4189
0.60	22	0.307	-0.161	23	0.290	0.144	0.305	0.3420
0.70	24	0.302	-0.074	25	0.290	0.144	0.218	0.2742
0.80	26	0.297	0.013	27	0.290	0.144	0.131	0.2094
0.90	28	0.292	0.100	29	0.292	0.100	0.000	0.1396
1.00	30	0.287	0.187	30	0.287	0.187	0.000	0.0000

Table 8 - Pressure Coefficient Calculations - 9°	Upper Surface			Lower Surface			Leading/Trailing Edge	
x/C	Taping number/ *n*	Fluid Height in Manometer Tube n/*L n* (m)	Pressure Coefficient/ *Cp* (-)	Taping number/ *n*	Fluid Height in Manometer Tube n/*L n* (m)	Pressure Coefficient/ *Cp* (-)	ΔCp	ΔCp Theoretical
0.00	1	0.328	-0.510	1	0.328	-0.510	0.0000	0.0000
0.05	2	0.356	-0.988	3	0.249	0.840	1.8287	2.7388
0.10	4	0.356	-0.988	5	0.274	0.405	1.3933	1.8850
0.15	6	0.356	-0.988	7	0.269	0.492	1.4804	1.4957
0.20	8	0.353	-0.945	9	0.272	0.448	1.3933	1.2566
0.25	10	0.348	-0.858	11	0.277	0.361	1.2191	1.0883
0.30	12	0.343	-0.771	13	0.279	0.318	1.0885	0.9598
0.35	14	0.333	-0.597	15	0.279	0.318	0.9144	0.8563
0.40	16	0.330	-0.553	17	0.284	0.231	0.7837	0.7695
0.45	18	0.325	-0.466	19	0.284	0.231	0.6967	0.6946
0.50	20	0.315	-0.292	21	0.287	0.187	0.4790	0.6283
0.60	22	0.315	-0.292	23	0.287	0.187	0.4790	0.5130
0.70	24	0.305	-0.118	25	0.290	0.144	0.2612	0.4113
0.80	26	0.300	-0.031	27	0.290	0.144	0.1742	0.3142
0.90	28	0.295	0.057	29	0.290	0.144	0.0871	0.2094
1.00	30	0.292	0.100	30	0.292	0.100	0.0000	0.0000

Table 9 - Lift Coefficients & Lift Curve Slope			
Angle of inclination/α (°)	3	6	9
Lift Coefficient/C'_L (-)	0.282 ± 0.002	0.545 ± 0.003	0.676 ± 0.005
Lift Coefficient/C_L (-)	0.282 ± 0.004	0.545 ± 0.004	0.675 ± 0.007
Lift Curve Slope	5.024 ± 0.015		

Plots:

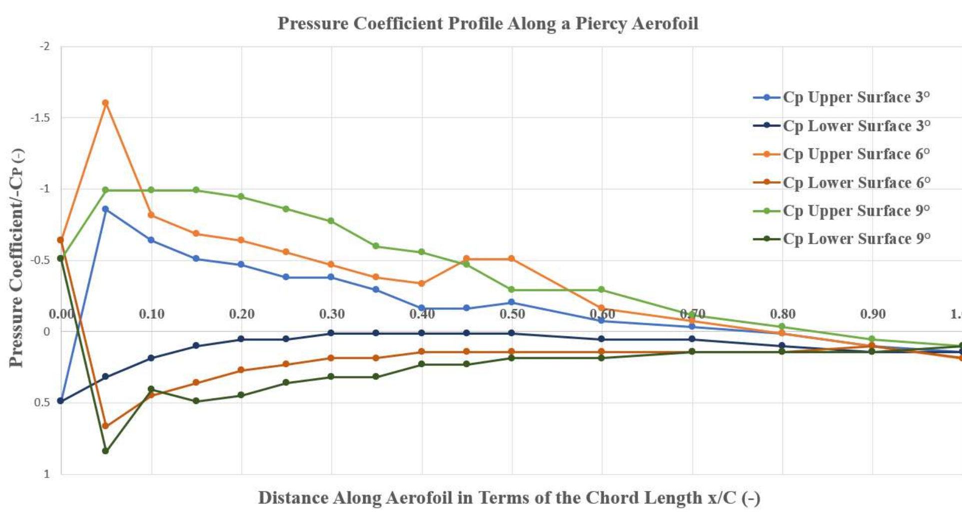

Figure 1: Plot of pressure coefficients for both the upper and lower surfaces of a Piercy Aerofoil against their distance along the chord with the y-axis inversed.

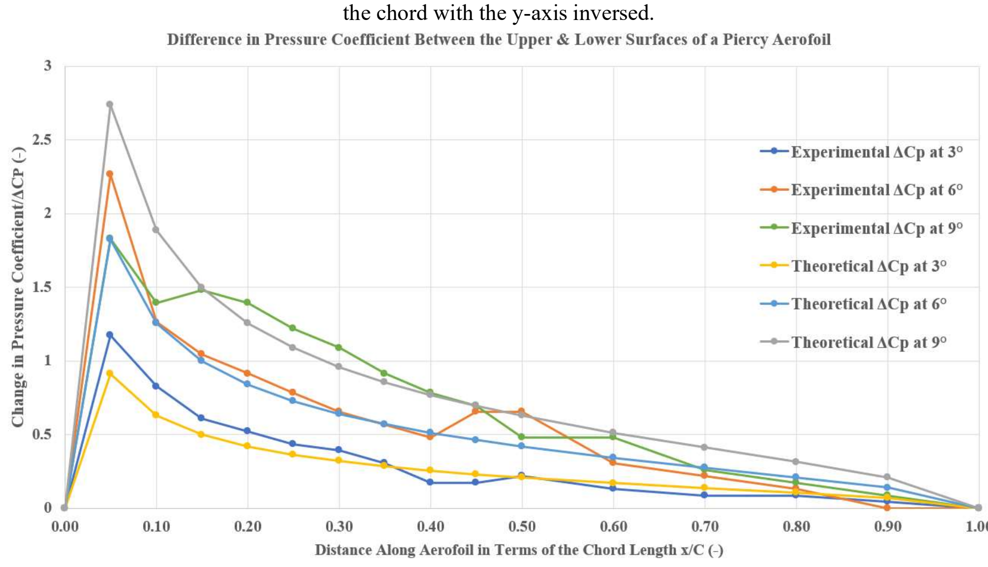

Figure 2: Plot of both the experimental and theoretical differences in pressure coefficient against their position along the aerofoil.

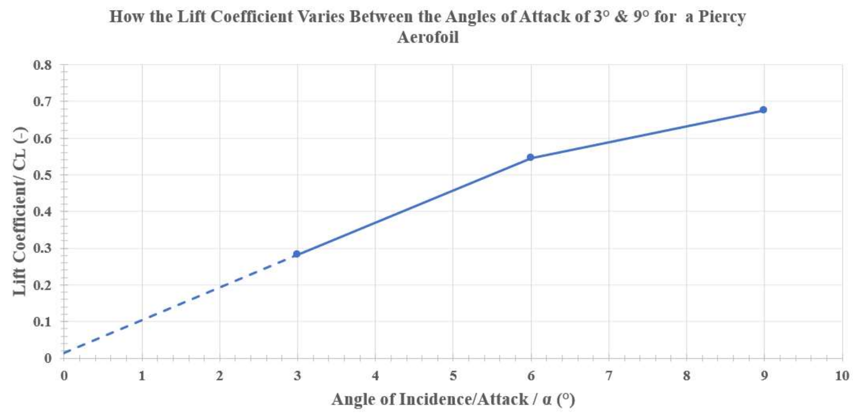

Figure 3: Plot of lift coefficient against angles of incidence of 3°, 6° & 9°.

Learning Outcomes:

To investigate the static pressure profile along a Piercy Aerofoil using experimental and theoretical results for small angles of incidence and to compare plus explain any differences. Using numerical integration, the lift coefficient was to be obtained and the stall angle found by comparing these results along with the inviscid flow theory.

Perceived Difficulties:

The inclined manometer readings were easily influenced by parallax errors since a small change in the height at which readings were taken from resulted in a significant difference between readings for the same value which was a problem as several colleagues of different heights took the readings. The manometer height reading fluctuated for each inclination meaning an average value was required, this introduced further error to these readings. Taping 30's pressure readings were treated as the readings for the trailing edge. However, taping 30 was not located at the trailing edge due to this region being too thin to house a taping as a result our results for this region were inaccurate.

General Trends:

Both the pressure coefficients and change in pressure coefficients are greatest towards the trailing edge for all inclinations as shown in figures 1, 2 & 3. This results in the majority of the lift force acting near to the leading edge due to the difference in pressure between the upper and lower surfaces being the greatest in this region. This agrees with the theoretical results and the theory for a symmetrical aerofoil [3].

The 6° inclination experiences a spike in pressure half way along the aerofoil which disagrees with the other inclinations and theoretical results. Since the same aerofoil was used for all tests this anomaly was mostly likely caused by an error in the observation of the fluid height levels, either due to a parallax error or an inaccuracy in the average value reading.

The lift coefficient is directly proportional to the angle of attack for all angles but drops off between 6° and 9° which indicates that stall occurred at angle within this range. The stall angle is the angle of attack at which lift continues to increase but not linearly [3]. Since the lift force is related to the lift coefficient by the density of the fluid, the freestream velocity and the crosssectional area of the aerofoil [4] and all of these variables were the same for all tests any observation for the lift coefficient would have been the same for the lift force. Meaning the two terms are interchangeable for this experiment.

The lift curve slope obtained was 5.024 which is similar to the theoretical result of 6.28 obtained using the thin aerofoil theory [4] and other experiments [5] at similar Reynolds numbers (table 5). Although the calculated uncertainty (figure 3) does not account for this error there were significant sources of error which could not be accounted for in these calculations such as fluctuations in the manometer readings. Since the aerofoil tested was symmetrical, an inclination of 0° should have resulted in 0 [6] lift but extending the line for the linear section of the data does not result in a y-intercept of 0 as shown by the dashed line in figure 3. Uncertainties within the results have reduced the accuracy of the data points and so the line. Instead of taking these data points as precise a better method of obtaining the lift curve slope would have been to use lines of best fit. One with a maximum and the other with a minimum slope, both based on the uncertainty of the data points. An average of these slopes would have resulted in a more accurate lift curve slope. Bernoulli's equation was used to derive the pressure coefficient equation. An alternative method would have been to use streamlines around the aerofoil and Euler's equation [7].

Errors & Uncertainties:

Table 10 - Resolution of Measuring Equiptment/Uncertainty in Raw Data Readings

Barometer Pressure Reading/H_{at} (mmHg)	Thermometer Room Temperature Reading/T_{at} (°C)	Betz Manometer Dynamic Pressure Reading/ΔH_{Betz} (mmH_2O)	Inclined Manometer Height Readings/L_n (inch)	Turntable Angle Reading/i (°)
0.1	0.1	0.1	0.1	0.1

$$Z = f(A,B,C) \rightarrow (\Delta Z) = \sqrt{\left(\frac{\partial f}{\partial A}\Delta A\right)^2 + \left(\frac{\partial f}{\partial B}\Delta B\right)^2 + \left(\frac{\partial f}{\partial C}\Delta C\right)^2}$$

$$\Delta(C_P) = \sqrt{(L_n)^2 + (L_A)^2 + (L_B)^2} \quad \Delta(C_P) = \sqrt{(0.003)^2 + (0.003)^2 + (0.003)^2} = 0.005$$

Table 11 - Percentage Uncertainty in Lift Coefficients & Lift Curve Slope

Lift Coefficient/ C_L (-)	Percentage Uncertainty (%)
3	1.4
6	0.7
9	1.0
Lift Curve Slope	0.3

Improvements:

Since the manometer height readings fluctuated for each test a more accurate approach for taking readings would have been to take several readings and obtain an average value for each taping rather than using the value closest to the mid-point of the fluctuating fluid level. This resulted in a large discrepancy between the calculated uncertainties and the total uncertainty, as shown in table 11. This would have reduced the uncertainty in the data range, increasing the accuracy and precision of the final results and plots.

A greater number of inclinations could have been tested to identify the exact stall angle. Based on the results of this experiment the stall angle is known to be between 6° and 9°. Further tests in this range would not only allow for the identification of the stall angle but also a better analysis of the relationship between the lift force and the angle of attack such as the percentage decrease in lift production at the stall angle.

Conclusion:

The outcomes of this experiment were a successful investigation into the lift vs angle of attack relationship through the use of experimental and theoretical results since the stall region of a symmetrical aerofoil was identified using the data collected. This data closely matched the theoretical results with a stall angle between 6° and 9° as well an accompanying sudden drop in lift and pressure coefficient within this range. More tests are required to identify the exact stall angle and fully meet the objectives.

References:

[1] **-** John D Anderson Jr (2016) *Free download! introduction to flight by full book PDF EPUB -DizBooks GoogleSites:Sign-in*. Available at: https://sites.google.com/site/dizbooke/0078027675, Chapters: 5.6 & 5.7 (Pages 316 - 322)

[2] – John J Bertin (2014) Aerodynamics for Engineers, 4th Edition, Pearson, Chapter 5.4 (Pages 254 -259)

[3] – John D Anders Jr (2017) Fundamentals of Fluid Mechanics, 6th Edition, McGraw Hill, Chapters 4.2 & 4.3 (Pages 326 – 333)

[4] - John D Anderson Jr (2016) *Free download! introduction to flight by full book PDF EPUB -DizBooks GoogleSites:Sign-in*.Available at: https://sites.google.com/site/dizbooke/0078027675, Chapters 5.2, 5.3 & 5.4 (Pages 290 - 315)

[5] – Ali Akbar (2020), Effect of Angle of Attack on Airfoil NACA 0012 Performance, eknik Mesin Universitas Muhammadiyah Sidoarjo

[6] – NASA Langley Research Centre , 2D NACA 0012 Airfoil Validation Case

[7] **-** Nakamura, M., How an aerofoil works. Available at:

https://web.mit.edu/2.972/www/reports/airfoil/airfoil.html