TED ANKARA COLLEGE FOUNDATION HIGH SCHOOL

INTERNATIONAL BACCALAUREATE

PHYSICS EXTENDED ESSAY

May 2015

INVESTIGATING THE RELATION BETWEEN SYMMETRIC PROPERTIES AND LIFT/DRAG COEFFICIENTS FOR AIRFOILS

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Word Count: 3875

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Abstract

The main purpose of this project is to find the relation between symmetric property of an airfoil and lift/drag coefficients. In this essay two airfoils, NACA 0015 and NACA 4412 will be used for comparison and finding the relation. NACA 0015 falls under symmetric airfoil category whereas NACA 4412 is common asymmetric airfoil.

To find the relation NACA 0015 and NACA 4412 airfoils are handcrafted with balsa wood and thin films. Balsa wood is cutted using a laser cutter. With obtained ribs and balsa sheets the model is crafted. In addition to this a thin film is used to cover the crafted airfoils. The crafted airfoils are put into test in AF100 Subsonic Wind Tunnel and datas were taken with AFA3 Three Component Balance System. From obtained datas, mean values are found for each angle of attack and put into coefficient formulas. With calculated coefficient values graphs are plotted to compare two airfoils. At the end of all calculations and plotting it is found that asymmetric airfoil produces much more lift than symmetric one. However, while its asymmetric property helped the airfoil to produce more lift, it also produced more drag than symmetric one. It is understood that while both airfoils show similar drag patterns under same air streams, asymmetric airfoils face lift-induced drag because of their structure. Even though it wasn’t the aim of this experiment it was also seen that asymmetric airfoil had a higher critical angle of attack.

Word Count: 241

INTRODUCTION

In Oxford Dictionary and several others, aerodynamics is defined as "the study of the properties of moving air and the interaction between the air and solid bodies moving through it." In a more scientific way, aerodynamics is a branch of science that uses mathematical equations, quantitative data and designs to improve the performance of a shape that is going through air.

In the case of airplanes it explains how an airplane can fly. There are four forces of flight that act on an airplane that is in air. These are weight, lift, thrust and drag. Weight is simply the force that is caused by gravity. Gravity pulls down on objects and thus creating a force. Thrust is the force or push that moves the airplane forward. While in small airplanes get thrust by a propeller, larger airplanes get their thrust from jet engines. Lift is the opposite of weight. It is the upward push of an airplane. Finally, drag is the force in the opposite direction of the thrust. Drag tries to slow a body down. Different fluids and different shapes all affect drag and change its value.

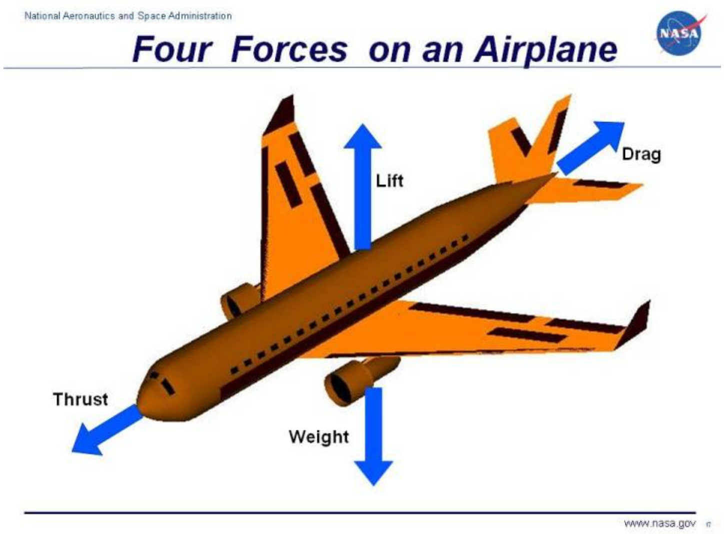

Figure 1 Diagram showing four forces on an airplane[1]

[1] http://www.grc.nasa.gov/WWW/k-12/airplane/Images/forces.jpg

For an airplane to rise, it must have more lift than weight and to move forward it must have more thrust than drag. The way a wing produces lift relies on the Bernoulli equation. In 1738, the Swiss physicist Daniel Bernoulli first derived an expression that relates the pressure to fluid speed and elevation.[2] According to his principle, an increase in the speed of a fluid decreases the pressure it exerts. In wings a situation like in Figure 2 occurs;

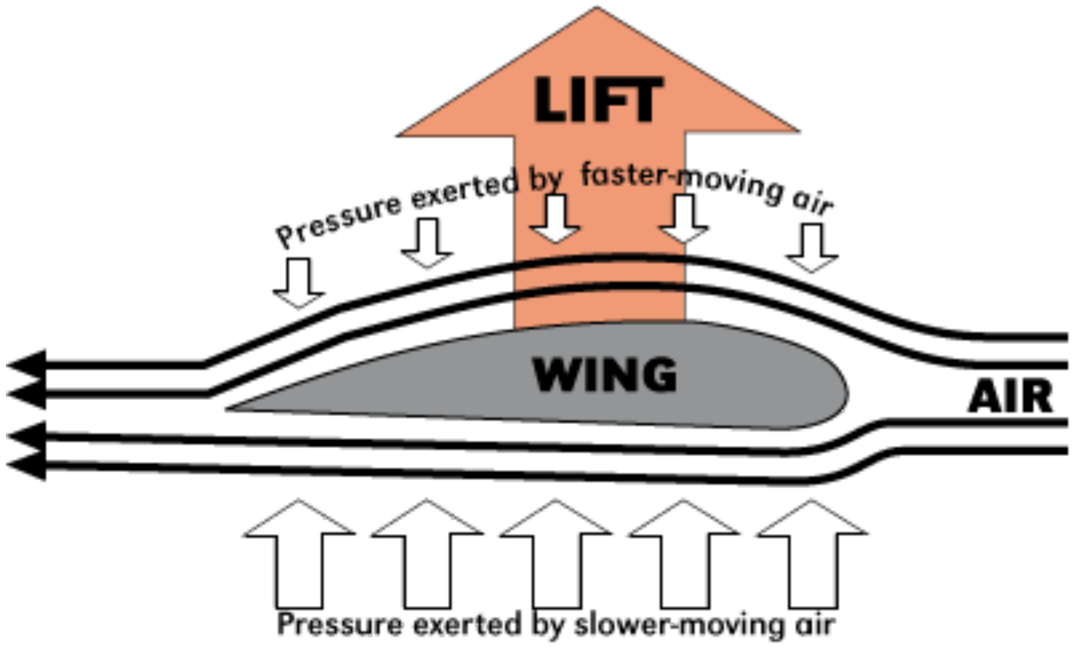

Figure 2 Bernoulli's equation applied on a common wing

Here, because of the curve of the wing, air flows much faster above the wing than below the wing. Faster air produces less pressure and slower air produces much greater pressure. Greater pressure cancels most of the small pressure and net pressure results in an upwards force. This force is simply called the lift. Thus, an airplane gets its lift and drag from its wings. So, to improve an airplanes aerodynamics, its wings should have been redesigned.

Designs for manufacturing better wings has been done for years. In 1899, Wright Brothers manufactured a basic kite-airplane model. Then they experimented with wings and overall plane

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[2] Serway, Raymond A. "Fluid Mechanics." *Physics for Scientists & Engineers, with Modern Physics*. Philadelphia: Saunders College Pub., 1996. N. pag. Print.

shape to improve the thrust and lift. In 1901, they built their own wind tunnel to test replicas of wings to design more efficient wings. With the quantitative and qualitative datas they improved what they have accomplished. Since Wright brothers, wing and plane models have evolved. Nowadays, before the manufacturing of modern wings, airfoils are made. Since experimenting with enourmous wings are difficult, airfoils are needed.

Airfoils are basically replicas of wings that is much more smaller in size. With the drag and lift values that are taken with airfoils, coefficients are calculated and since coefficients does not depend on wing size, larger wings can be produced.

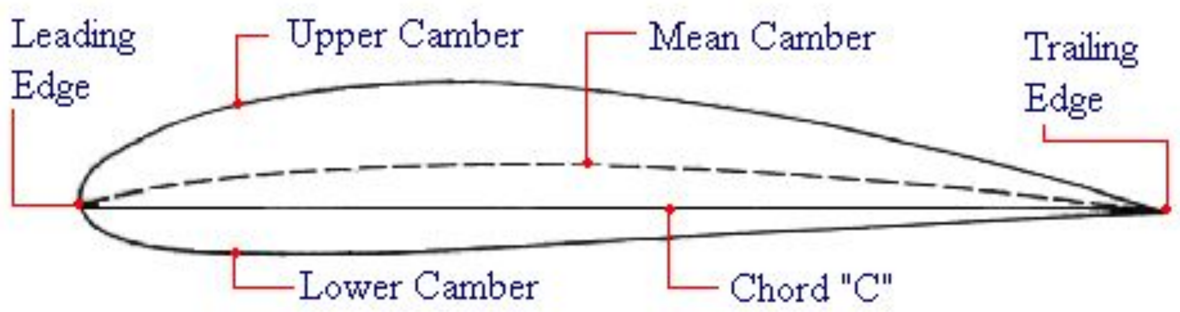

Figure 3 Parts of an basic airfoil[3]

The NACA airfoils are airfoil shapes for aircraft wings developed by the National Advisory Committee for Aeronautics (NACA).[4] Airfoils are described and can be distinguished between each other by the numbers that follow the acronym NACA. There are 6 NACA families which are 4-Digit, 5-Digit, 16-Series, 6-Series, 7-Series and 8-Series. In NACA Four Digit Series, there are four digits that follow the acronym NACA and these 4 digits show 3 different properties of the airfoil. The first digit shows the maximum camber in percentage of the chord. The second digit shows the

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[3] http://www.aerospaceweb.org/question/airfoils/airfoil/airfoil-parts.jpg

[4] E.N. Jacobs, K.E. Ward, & R.M. Pinkerton. NACA Report No. 460, "The characteristics of 78 related airfoil sections from tests in the variable-density wind tunnel". NACA, 1933.

distance of the maximum camber from the leading edge in tenths of chord and the last two numbers describes the maximum thickness of the airfoil in percentage of the chord. For example, the NACA 4412 airfoil has a maximum thickness of %12 with a camber of %4 located %40 back from the airfoil leading edge. NACA 0015 is a symmetric airfoil so the first two digits are zeros while the last two shows us that this airfoil has %15 thickness.

NACA 4-Digit family has both advantages and disadvantages. They have good stall properties and have low roughness effect. However they have low lift coefficients and relatively high drag. These wing are mainly used for general aviations while symmetric ones are used for supersonic jets and helicopter blades.

NACA 4412 differ from NACA 0015 by means of symmetricity. Their lift and drag values differ from each other and vary with changing angle of attack. Thus, their usage in real world changes. However, before wings are used in real world, they must undergo various test in laboratories because of their different aerodynamic characteristics

Every type of structure which is moving in air or influenced by air gets affected by aerodynamic forces. For designing vehicles or crafts it is important to determine these forces and flow behaviour. In wind tunnels these forces and structure air relation can be examined easily and safely.

The basic example of a wind tunnel consists of a tunnel which an uniform air stream passes through.

There are many different wind tunnels. They are divided and categorized according to their speed range and their shape.

According to their speed range;

1. Subsonic Wind Tunnels (max 135 ms^{-1})
2. Transonic Wind Tunnels (up to speed of sound)
3. Supersonic Wind Tunnels
4. Hypersonic Wind Tunnels

According to their shape;

1. Open Circuit Wind Tunnel
2. Closed Circuit Wind Tunnel

AF100 Subsonic Wind Tunnel (Figure 4) is used for this project to test NACA 4412 and NACA 0015 airfoils. This wind tunnel is an open-circuit suction tunnel. Air enters the tunnel through an aerodynamically designed effuser (cone) that accelerates the air linearly. It then enters the working section and passes through a grill before moving through a diffuser and then to a variable-speed axial fan. The grill protects the fan from damage by loose objects. The air leaves the fan, passes through a silencer unit and then back out to atmosphere. [5]

[5] http://www.tecquipment.com/Datasheets/AF100s_0114.pdf

Figure 4 AF100 Subsonic Wind Tunnel used in the experiment

By putting airfoils to test in subsonic wind tunnel, one can gather information about the airfoil. However, wind tunnel on its own is not sufficient. A balance system with sensors must be present for it to take measurements. AFA3 Three Component Balance System is used with AF100 Wind Tunnel. AFA3 Balance System gave out multiple datas including drag and lift. With these values, coefficient can be calculated.

The coefficient of lift is a dimensionless coefficient that is related to the lift. Its formula is[6]

(1) $$C_L = \frac{F_L}{0.5 \times \rho \times V^2 \times S}$$

The coefficient of drag is a dimensionless coefficient that is related to the drag. Its formula is[6]

(2) $$C_D = \frac{F_D}{0.5 \times \rho \times V^2 \times S}$$

CL: Lift Coefficient CD: Drag Coefficient

FL: Lift Force FD: Drag Force

ρ (rho): Fluid Density

V: Airspeed

S: Wing (planform) area

Coefficients are important in manufacturing wings. Small replicas turn into large wings by these values. Coefficients differ from airfoil to airfoil. They represent airfoils' characteristics. Coefficients also vary with changing angle of attack. This is because at every angle of attack, the aerofoil produce different drags and lifts.

Angle of attack (AOA) is the angle between the incoming air stream and a reference line on the wing. This reference line is generally the line connecting the leading edge and trailing edge.

Critical angle of attack refers to the angle at which the lift coefficient is maximum. Critical angle of attack is also mentioned as stall angle of attack. As the angle of attack increases, lift coefficient also

[6] Abbott, Ira H., and Von Doenhoff, Albert E.: *Theory of Wing Sections*. Section 1.2

increases up to the critical angle of attack. Above the critical angle, the airfoil is said to be in stall. Stall is the reduction in lift coefficient as the angle of attack increases above the critical angle of attack. The critical angle of attack for most airfoils is between 15° and 20°.

In symmetric airfoils like NACA 0015, when the angle of attack is 0° the airfoil does not produce any lift. While in asymmetric airfoils, even in 0° there is a little lift produced because of the camber of the airfoil.

Research Question

How does the lift and drag coefficients differ between two different airfoils [NACA 0015 (symmetric), NACA 4412 (asymmetric)] as the angle of attack is gradually increased whilst other environmental conditions (air properties) are kept the same?

The aim of this experiment is to find the relation between lift/drag coefficients with the symmetric properties of two airfoils, NACA 0015 and NACA 4412. So, in this experiment airfoil type based on their symmetric characteristics is the first independent variable. Coefficients are dependent on if the airfoils are independent or not. Also, airfoils are exposed to airstream at different angles. By increasing the degree gradually, the difference in coefficients between airfoils would be observed much more easily. So, angles of attack is another independent variable. It can be deduced that because of its symmetric structure NACA 0015 airfoil will produce lower lift and will have a lower critical angle of attack. However, compared to NACA 4412, NACA 0015 will produce less drag.

For the accuracy of the results, some factors are kept constant. During the manufacture of airfoils, same balsa wood is used. The wood is sanded to reduce the rough surface and each rib and stick is cut with great precision with the laser cutter.

The most important controlled varible is air properties. Since it is directly related to the calculations of coefficients it must be kept constant. To keep it constant, a Reynolds Number was calculated. A Reynolds Number (Re) is a dimensionless quantity that is used to predict similar flow patterns. Reynolds Number can also show the type of flow. One of these flows is turbulent flow. They occur at high Reynolds Numbers and tend to produce complex flow patterns, mostly causing vertices. Laminar flow, which is observed in low Reynolds numbers are mostly steady, smooth and constant. In this experiment a steady flow, a flow that the velocity of the fluid remains constant. To achieve this a small Reynolds Number should have been considered.

Reynolds Number is also needed for the stall characteristics of the airfoils. Angles of attack that are used in this experiment based on the Reynolds Number that was chosen. For this investigation, Re 160.00 was used. The flow of the airstream was 15 ms^{-1}, the air density was 1.19 kgm^{-3} and the temperature was 25°C. The relative humidity of that day was nearly %70. The rooms temperature was however kept constant with an air conditioner just in case the temperature would change. The experiment is held in METU Department of Aerospace Engineering in Ankara,Turkey. So its elevation was known beforehand as 938 m above sea level.

Material and Equipment

- Balsa wood
- Laser cutter
- Carbon spar
- Thin films (for covering wings)
- AF100 Subsonic Wind Tunnel
- AFA3 Three Component Balance System
- Air Conditioner
- Computer

Manufacturing

Manufacturing of the wings is the essential part of this experiment. The wings which will be investigated should be manufactured with great precision. The wings have to have smooth surfaces, equally balanced weight and good shape geometry. The trailing and leading edges should meet the calculated geometries as the angle of attack depends on their reference line. AF100 Subsonic Wind Tunnel and AFA3 Three Component Balance System are chosen for this particular experiment and the airfoils should fit in the wind tunnel and meet the required properties. The wind tunnel has an 30 cmx30 cm test section so the wingspan is determined to be 30 cm and the chord is chosen to be 15 cm.

The wings are manufactured from balsa wood. First a scheme is designed for laser cutting. These schemes as seen in Figure 4 are for the ribs of the wings. Then, from a 3 mm balsa sheet, the ribs are cut with the laser cutter. Every piece of balsa is sanded out to gain smooth surfaces. 10 ribs are prepared for each wing. Ribs are placed 30 mm apart from each other and fixed with three 300 mm balsa stick from three points. (1, 2, 3 in Figure 5) A carbon spar with 12mm inner and 14mm outer diameter is placed in the 14 mm hole. After that, the profile is covered with 1mm balsa sheets. After sanding the outer balsa sheet, the wing is covered with a thin film to minimize the friction. The process is done one more time for NACA4412 airfoil.

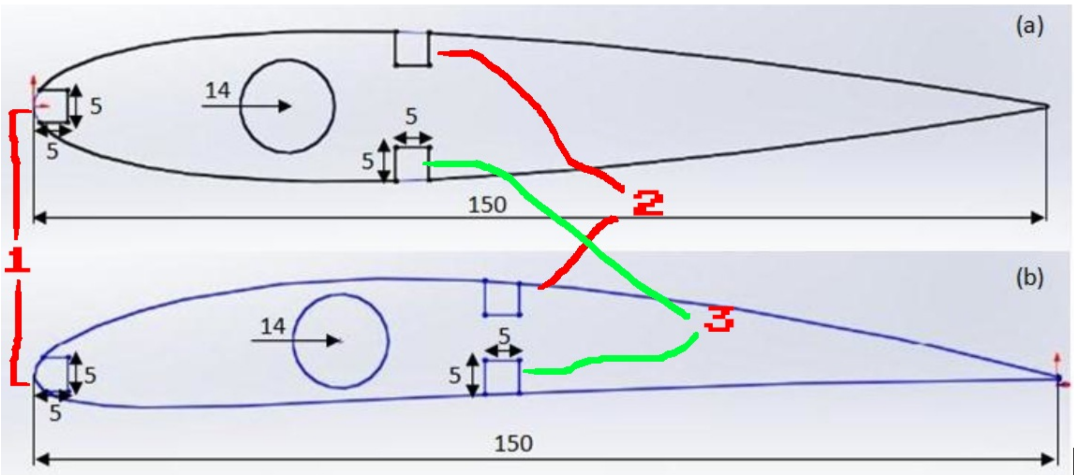


Figure 5 Rib geometries for NACA0015 (a) and NACA4412 (b) respectively. (Dimensions in mm)

Figure 6 Manufacturing of the wing step by step

Experimentation

Crafted airfoils are tested with AF100 Subsonic Wind Tunnel and AFA3 Three Component Balance System in METU Aerospace Engineering Hangar. Airfoils are fitted inside the test section of the wind tunnel with help of a shaft. The airfoil had 30 cm wing span so it fittted perfectly. AFA3

Balance System's instruction manual mentions that airfoils must be placed on the shaft upside down. Since NACA 0015 is symmetric it did not make any difference but in NACA 4412 it is important to turn it upside down since it is asymmetric.

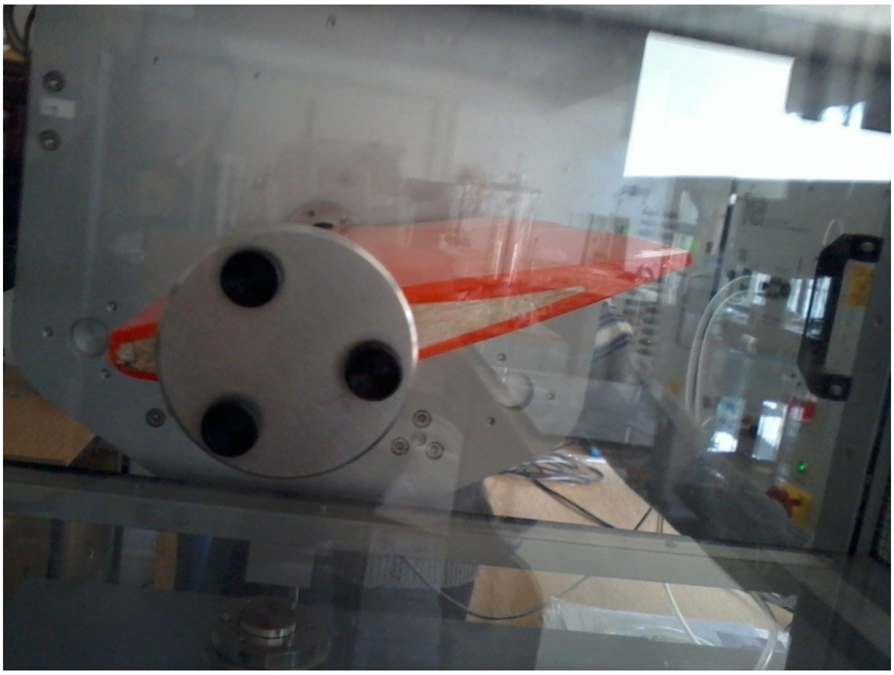


Figure 7 Upside down placement of NACA 4412 on AFA3 Balance System inside AF100 Subsonic Wind Tunnel (14 degrees)

The velocity of air inside the wing tunnel is determined by the Reynolds Number. Reynolds Number is kept constant in order for fluid flow characteristics to stay the same. 15 ms^{-1} is used for experimentation. When the air density at Ankara is put into equation Reynolds Number of 160.00 was found. To change the angle of attack, tuning knob on the AFA3 Balance System is used. Stall angles are found to be 16-18 degrees for NACA 4412 and 12-14 degrees for NACA 0015 for Reynolds Number of 160.00

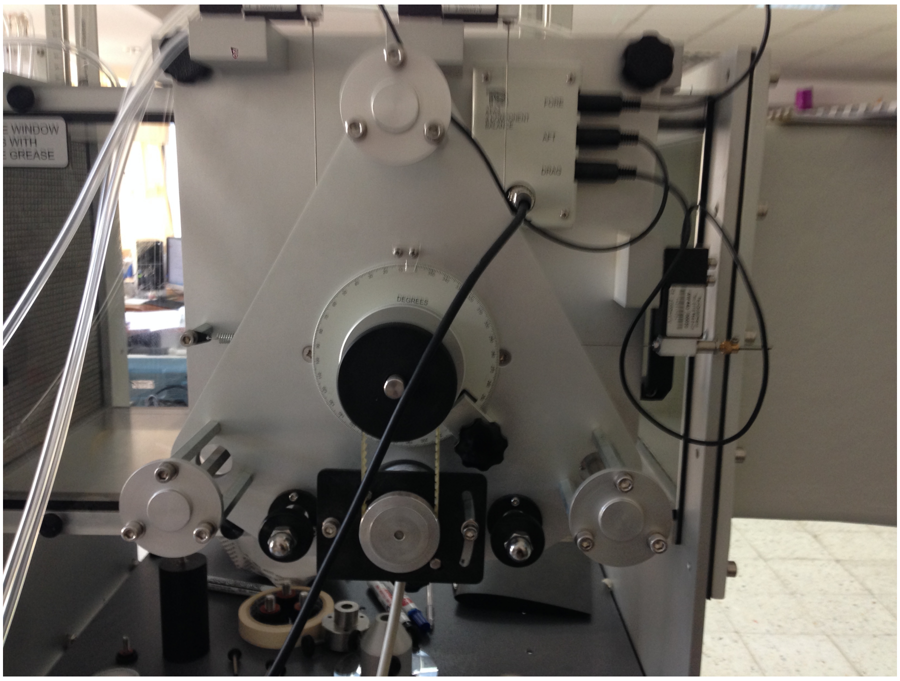


Figure 8 AFA3 Balance System with tuning knob for degree at center

Since the machine complex takes instantenous measurements, 20 datas were taken for each angle of attack. Meanvalues are used for processing and comparison. With averaged drag and lift datas, coefficients are calculated for each angle of attack. Then graphs are plotted to observe the difference between these two airfoils.

For processing, firstly, obtained datas for lift and drag forces for each angle of attack for each wing is averaged. An example is shown below for the mean lift forces for NACA 0015 airfoil with an angle of attack of 0 degrees.

$$\frac{1.22+1.25+1.28+1.33+1.34+1.30+1.32+1.38+1.39+1.38+1.37+1.33+1.30+1.26+1.25+1.23+1.21+1.23+1.23+1.22}{20}$$

$$F_L = 1.29N$$

Then mean values for forces are put into equation to calculate the coefficient. For air density (rho) 1.19 $kg.m^{-3}$ is used. This was determined by the elevation of the METU Campus, temperature and the relative moisture. As mentioned earlier by this air density Reynolds Number is calculated to determine the velocity of the air stream which was determined as 15 ms^{-1}.

The wings has a span of 30 cm and chord lengths of 15 and 12 cm (for NACA 0015 and NACA 4412 respectively) Their area are then converted to m^2 and put into equation.

With the mean lift forces that were already found, coefficient of lift of the NACA 0015 airfoil at 0 degrees angle of attack is calculated by;

$$C_L = \frac{1.29}{0.5 \times 1.19 \times 225 \times 0.0045}$$

$$C_L = 0.214$$

Same calculations are applied for different angle of attacks and also for the other airfoil. Since NACA 4412 has a higher stall angle 16 and 18 degrees are too taken into consideration.

Uncertainty Calculations

In the formula (1) every parameter has an uncertainty.

For velocity the value had an uncertainty of 0.1 $m\ s^{-1}$

$\frac{0.1}{15} \times 100\% = 0.67\%$; since velocity is squared;

$$0.67\% + 0.67\% = 1.34\%$$

For air density the value had an uncertainty of 0.01 kg m^{-3}

$$\frac{0.01}{1.19} \times 100\% = 0.84\%$$

For wing area both width and length had uncertainties of 0.001 m

$\frac{0.001}{0.3} \times 100\% = 0.34\%$ (length)

$\frac{0.001}{0.015} \times 100\% = 6.67\%$ (width)

$6.67\% + 0.34\% = 7.01\%$ (total area)

An example is shown below for the uncertainty of the coefficient of lift for NACA 0015 airfoil with an angle of attack of 0 degrees.

For mean of lift values;

Each force data has an uncertainty of 0.01 N

$$\frac{0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01}{20}$$

$$= 0.01$$

The mean lift value had an uncertainty of;

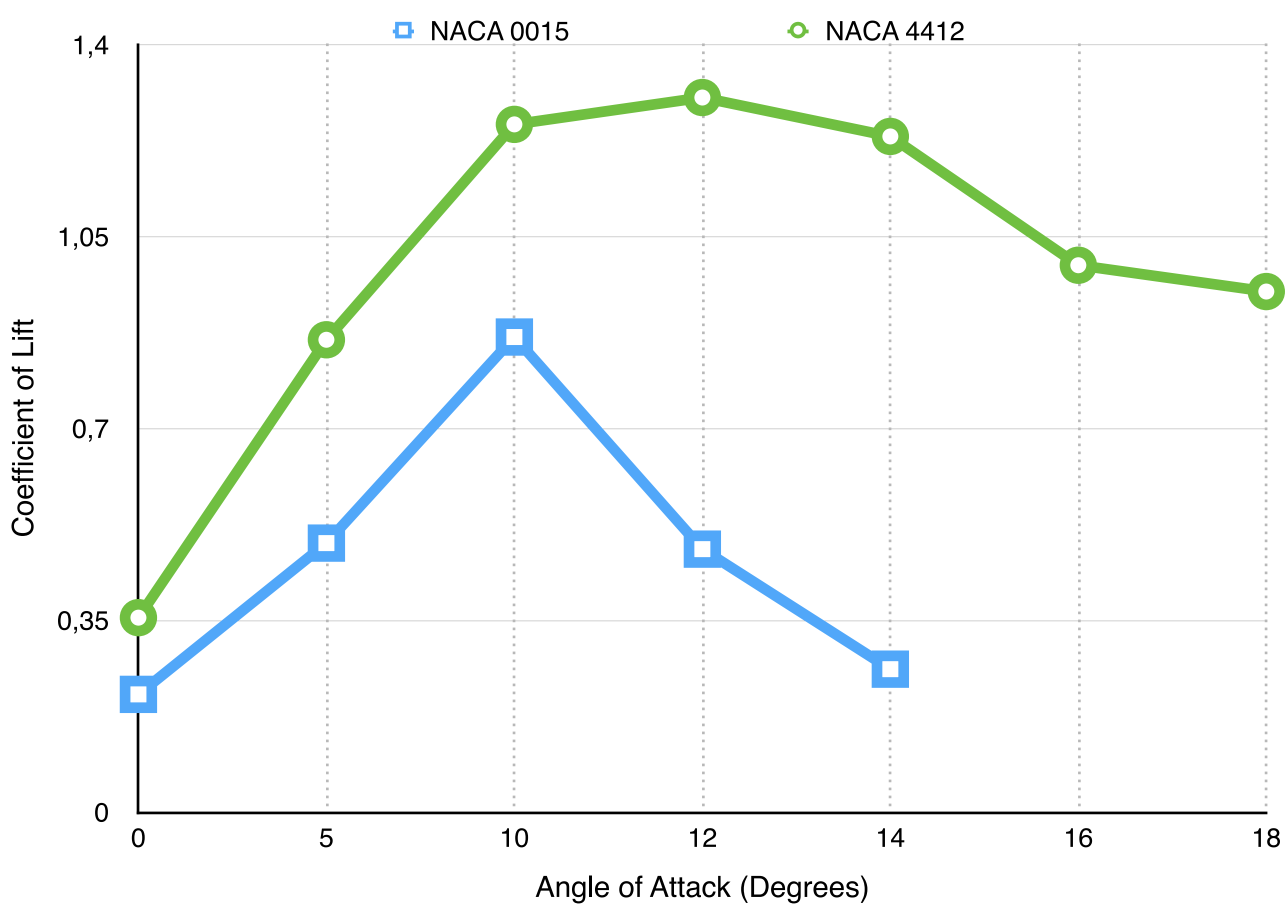
$$\frac{0.01}{1.29} \times 100\% = 0.78\%$$

Adding it all up for the coefficient uncertainty yields;

$$0.84\% + 1.34\% + 7.01\% + 0.78\% = 9.97\%$$

	NACA 0015		NACA 4412	
a.o.a	**Experiment**	**Literature**	**Experiment**	**Literature**
0	0.214 ± 9.97%	0.000	0.354 ± 5.49%	0.340
5	0.490 ± 8.01%	0.550	0.861 ± 6.01%	0.865
10	0.866 ± 7.86%	0.832	1.254 ± 6.17%	1.267
12	0.479 ± 7.98%	0.594	1.303 ± 6.05%	1.300
14	0.260 ± 8.43%	0.237	1.232 ± 5.78%	1.238
16	-	-	0.997 ± 5.96%	0.990
18	-	-	0.949 ± 6.13%	0.950

Table 1 Processed data table showing calculated lift coefficients for NACA 0015 and 4412 with data obtained and uncertainties and literature coefficient values for comparison

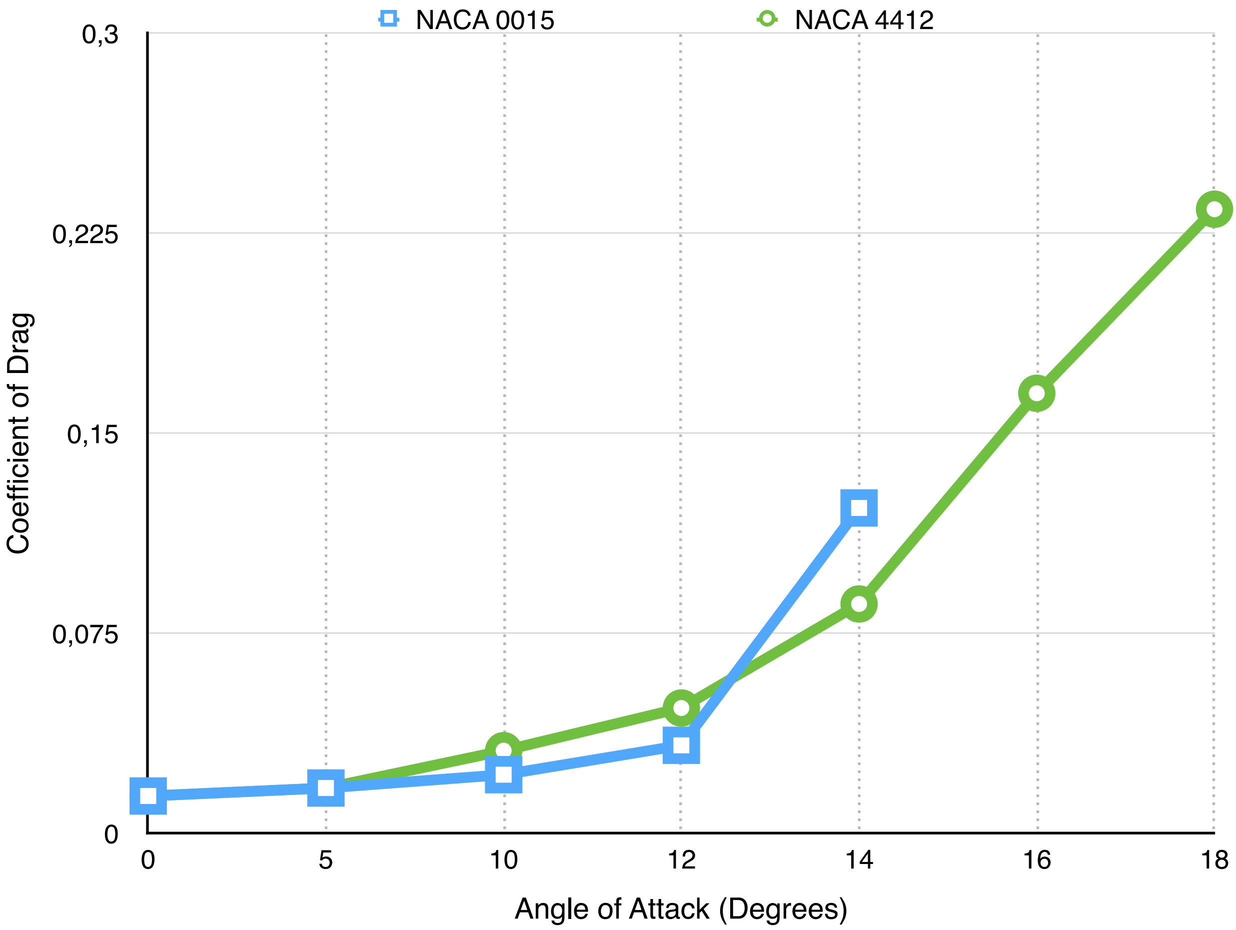


Graph 1 Graph showing the difference in coefficients of lift for NACA 0015 (square) and NACA 4412 (circle). Notice that NACA 0015 does not have any coefficient values for angles of attack 16 and 18 since NACA 0015 has small stall angle.

Coefficient of drag differs from coefficient of lift from only the type of force. Drag coefficient depends on drag force where lift depended on lift force. The equations are similar for drag so examples given above are sufficient to have an understanding of the calculations. The usage of (2) yielded Table 2 below.

	NACA 0015		NACA 4412	
a.o.a	**Experiment**	**Literature**	**Experiment**	**Literature**
0	0.014 ± 7.46%	0.012	0.014 ± 3.21%	0.015
5	0.017 ± 7.84%	0.014	0.017 ± 3.54%	0.018
10	0.022 ± 8.03%	0.023	0.031 ± 3.47%	0.033
12	0.033 ± 8.01%	0.028	0.047 ± 3.61%	0.050
14	0.122 ± 10.23%	0.104	0.086 ± 3.29%	0.085
16	-	-	0.165 ± 3.12%	0.163
18	-	-	0.234 ± 3.69%	0.237

Table 2 Processed data table showing calculated drag coefficients for NACA 0015 and 4412 with data obtained and literature coefficient values for comparison



Graph 2 Graph showing the difference in coefficients of drag for NACA 0015 (square) and NACA 4412 (circle). Notice that NACA 0015 does not have any coefficient values for angles of attack 16 and 18 since NACA 0015 has small stall angle.

Percentage error for drag and lift coefficients

$$\text{percent error} = \frac{|\text{measured - actual}|}{\text{actual}} \times 100\%$$

Lift coefficient for NACA 0015 for angle 5 degrees;

$$\frac{|0.490 - 0.550|}{0.550} \times 100\%$$

$$= 10.90\%$$

	NACA 0015		NACA 4412	
a.o.a	**Lift (%)**	**Drag (%)**	**Lift (%)**	**Drag (%)**
0	-	16.67	4.11	6.67
5	10.90	21.42	0.46	5.56
10	4.08	4.34	1.03	6.06
12	19.30	17.86	0.23	6.00
14	9.70	17.30	0.48	1.18
16	-	-	0.71	1.23
18	-	-	0.11	1.27

Table 3 Percentage errors for lift and drag coefficients for airfoils NACA 0015 and NACA 4412. For NACA 0015, at 0 degrees percentage error for coefficient for lift value could not be calculated because the literature value for it would make the formula unidentified.

Conclusion and Evaluation

The purpose of this particular study was to find the relation between lift/drag coefficients and the symmetric properties of two airfoils, NACA 0015 and NACA 4412. For lift coefficients the literature suggested that asymmetric airfoil NACA 4412 will produce more lift force compared to NACA 0015 in angles of attack from 0 degrees to 10 degrees. This results in higher coefficients of lift for airfoil NACA 4412. For drag coefficients literature shows that difference between two airfoils are not majestic and they both show a similar exponential pattern with NACA 0015 producing less drag force than NACA 4412. However, literature values are determined with computer programming. Airfoils are modelled in softwares and put into virtual wind tunnels and results are obtained. Computational fluid dynamics (usually abbreviated as CFD) deals with these things. It is a branch of fluid dynamics and they use numerical methods to find these kind of values. However, since everything is virtual, values the software provide could be questionable. To prove the values reliability, an experiment was conducted with airfoils NACA 4412 and NACA 0015. Firstly, the airfoils are manufactured. These are done according to their NACA values. NACA 4 digit system is universal so that airfoils' length properties are not chosen randomly. Then, crafted airfoils are put into wind tunnel testing. The literature values helped me with this stage. With calculated Reynolds Number, angles of attacks are determined with literature values. However these values are not based on CFD but they are all compiled with years of research and experimentation so they were reliable. With AFA3 Three Component Balance System, drag and lift values are recorded with chosen angles of attack. AFA3 took 20 instantenous datas for each angle of attack. Putting each data into the equation would be useless so mean values for each force is calculated. Then, mean value of force is put into equation along with the air density, cross-sectional area and velocity of the free stream air. These yielded coefficient values for lift and drag. Graph 1 and 2 is sketched in order to see the relation between airfoils for both lift coefficients and drag coefficients.

My hypothesis states that because of it being symmetric, NACA 0015 will produce much less lift force and thus have low coefficient value. The pressure exerted by faster moving air and slower moving air mostly evens each other out. Thats why wings without cambers can't produce lift at 0 degrees. Net pressure on the wing would be zero. When Table 1 and Graph 1 is considered, it can be seen that the hypothesis is proven to be correct except for the NACA 0015's lift value for the 0° angle of attack. Even though it is not expected, NACA 0015 airfoil produced lift. This error would be explained more briefly in the upcoming part of this report. On the other hand, when we cancel out that error everything seems to favor the hypothesis. For drag, fluid (air) resistance would be same for both of the airfoils. However, because of its asymmetric properties NACA 4412 produced vortices which tries to slow down the airfoil. These are called lift-induced drags. Its the reason why NACA 0015 is expected to have less drag forces and thus coefficients. As mentioned earlier both airfoils show similar exponential pattern but NACA 0015 is slightly higher because of the lift-induced lift. This can be seen clearly if Graph 2 is examined.

For both of the graphs, values after the stall angles are not evaluated. This is because after the critical angle of attack, airfoils cause hard-to-track turbulent flows and also it is not the aim of the experiment.

The experiment brought out some values which look promising and reliable. The results also look similar to CFD literature values. However when percentage errors are calculated the real errors come to surface. It can be seen from the Table 3 that NACA 0015 had most of the errors going all the way up to 21.42% while NACA 4412 usually stayed around 1%'s or 5%'s. NACA 0015 also produced lift at zero degrees even though mathematical and physical deductions showed that it shouldn't. These show that there were random errors and limitations with this experiment.

The first and the main error source is the manufacturing of airfoils. I wasn't under possession of wide variety of materials and because of this limitation the airfoils are made out of balsa wood and thin films. Existance of a lot of defect of the wings due to handcrafting and laser cutting were present. The profiles were not too proper and same. Because of handcrafting, leading and trailing edges of the profiles couldn't be produced properly. Also, the structures were bended due to elasticity of the balsa wood. Both airfoils had rough and their surfaces was not smooth. This resulted in NACA 0015 not to be symmetric and so it produced lift at zero degrees.

Additionally the airfoils vibrated too much during the experiment because of their low weight, especially in high angles of attack. There is also doubt that AFA3 balance could measure such lightweight objects accurately. Calibration of the system for these airfoils were out of the question because of their weight.

As a result of experimentation, it was decided that this manufacturing method is not suitable for this kind of work. It would be much better to use heavy materials and most preferably aliminum or carbon fiber. Using heavy materials will also prevent any vibration of the airfoil. Also, a much more precise cutting machine or manufacturing tools may come in handy. This way AFA3 balance system could be calibrated and would take much accurate results. Also the surfaces of the airfoils would be smooth and without rough that may create small turbulances.

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APPENDIX

NACA 0015 DATAS

Time	AFA2 Basic Balance	AFA3 Balance			AFA4 Encoder Input	AFA5 DP Cell 1	AFA5 DP Cell 2
Time	Force	Lift	Drag	Pitching Moment	Angle	Pressure	Pressure
(s)	(N)	(N)	(N)	(Nm)	(Degrees)	(Pa)	(Pa)
0.0	--	1.22	0.65	-0.01	0.1	139	140
1.0	--	1.25	0.66	-0.01	0.1	138	141
2.0	--	1.28	0.67	-0.01	0.1	134	139
3.0	--	1.33	0.69	-0.01	0.1	135	139
4.0	--	1.34	0.69	-0.01	0.1	135	138
5.0	--	1.30	0.69	-0.01	0.1	136	139
6.0	--	1.32	0.69	-0.01	0.1	138	138
7.0	--	1.38	0.70	-0.01	0.1	134	138
8.0	--	1.39	0.72	-0.01	0.1	135	136
9.0	--	1.38	0.72	-0.01	0.1	134	137
10.0	--	1.37	0.71	-0.01	0.1	135	139
11.0	--	1.33	0.71	-0.01	0.1	134	137
12.0	--	1.30	0.69	-0.01	0.1	138	139
13.0	--	1.26	0.69	-0.01	0.1	137	138
14.0	--	1.25	0.67	-0.01	0.1	136	140
15.0	--	1.23	0.67	-0.01	0.1	134	139
16.0	--	1.21	0.66	-0.01	0.1	135	138
17.0	--	1.23	0.67	-0.01	0.1	135	140
18.0	--	1.23	0.67	-0.01	0.1	137	142
19.0	--	1.22	0.67	-0.01	0.1	135	139

Time	Force	Lift	Drag	Pitching Moment	Angle	Pressure	Pressure
(s)	(N)	(N)	(N)	(Nm)	(Degrees)	(Pa)	(Pa)
0.0	--	1.84	0.31	-0.01	5.0	145	143
1.0	--	1.87	0.32	-0.01	5.0	138	142
2.0	--	1.98	0.33	-0.01	5.0	136	144
3.0	--	2.00	0.36	-0.01	5.0	135	143
4.0	--	1.99	0.37	-0.01	5.0	134	143
5.0	--	1.97	0.37	-0.01	5.0	139	145
6.0	--	1.93	0.37	-0.01	5.0	141	147
7.0	--	1.90	0.37	-0.01	5.0	140	148
8.0	--	1.87	0.37	-0.01	5.0	140	148
9.0	--	1.85	0.36	-0.01	5.0	140	148
10.0	--	1.81	0.36	-0.01	5.0	139	146
11.0	--	1.86	0.37	-0.01	5.0	138	146
12.0	--	2.21	0.41	-0.01	5.0	137	145
13.0	--	2.54	0.57	-0.01	5.0	139	147
14.0	--	3.34	0.67	-0.02	5.0	141	147
15.0	--	3.69	0.87	-0.02	5.0	138	146
16.0	--	4.21	0.95	-0.01	5.0	137	148
17.0	--	4.47	1.12	-0.01	5.0	141	150
18.0	--	4.73	1.21	-0.01	5.0	141	147
19.0	--	5.15	1.39	-0.01	5.0	139	146

Time	Force	Lift	Drag	Pitching Moment	Angle	Pressure	Pressure
(s)	(N)	(N)	(N)	(Nm)	(Degrees)	(Pa)	(Pa)
0.0	--	2.54	0.45	-0.01	9.9	135	145
1.0	--	2.55	0.45	-0.01	9.9	137	149
2.0	--	2.55	0.45	-0.01	9.9	134	143
3.0	--	2.55	0.44	-0.01	9.9	139	150
4.0	--	2.54	0.43	-0.01	9.9	137	150
5.0	--	2.54	0.42	-0.01	9.9	134	149
6.0	--	2.54	0.42	-0.01	9.9	133	147
7.0	--	2.54	0.42	-0.01	9.9	133	146
8.0	--	2.52	0.43	-0.01	9.9	136	150
9.0	--	2.54	0.43	-0.01	9.9	140	153
10.0	--	2.55	0.41	-0.01	9.9	132	148
11.0	--	2.61	0.41	-0.01	9.9	134	148
12.0	--	2.66	0.43	-0.01	9.9	132	146
13.0	--	2.74	0.45	-0.01	9.9	131	146
14.0	--	2.76	0.47	-0.01	9.9	129	144
15.0	--	2.77	0.48	-0.01	9.9	133	149
16.0	--	2.77	0.49	-0.01	9.9	142	148
17.0	--	2.77	0.49	-0.01	9.9	136	148
18.0	--	2.75	0.49	-0.01	9.9	138	149
19.0	--	2.74	0.49	-0.01	9.9	136	151

Time	Force	Lift	Drag	Pitching Moment	Angle	Pressure	Pressure
(s)	(N)	(N)	(N)	(Nm)	(Degrees)	(Pa)	(Pa)
0.0	--	2.69	0.48	-0.02	11.9	135	152
1.0	--	2.66	0.52	-0.02	11.9	133	117
2.0	--	2.55	0.58	-0.02	11.9	129	129
3.0	--	2.58	0.50	-0.02	11.9	129	128
4.0	--	2.52	0.56	-0.02	11.9	125	99
5.0	--	2.50	0.63	-0.02	11.9	126	90
6.0	--	2.62	0.60	-0.02	11.9	130	138
7.0	--	2.69	0.52	-0.01	11.9	139	154
8.0	--	2.77	0.49	-0.01	11.9	138	152
9.0	--	2.80	0.47	-0.01	11.9	140	156
10.0	--	2.77	0.48	-0.01	11.9	142	150
11.0	--	2.75	0.46	-0.01	11.9	142	156
12.0	--	2.86	0.44	-0.01	11.9	139	158
13.0	--	3.14	0.50	-0.01	11.9	139	157
14.0	--	3.93	0.71	-0.01	11.9	136	147
15.0	--	4.33	0.81	-0.01	11.9	137	141
16.0	--	5.08	1.02	-0.01	11.9	138	149
17.0	--	5.38	1.13	-0.01	11.9	140	154
18.0	--	5.83	1.29	-0.01	11.9	138	153
19.0	--	5.96	1.34	-0.01	11.9	138	157

Time	Force	Lift	Drag	Pitching Moment	Angle	Pressure	Pressure
(s)	**(N)**	**(N)**	**(N)**	**(Nm)**	**(Degrees)**	**(Pa)**	**(Pa)**
0.0	--	2.35	0.61	-0.02	13.9	133	139
1.0	--	2.40	0.62	-0.02	13.9	133	128
2.0	--	2.42	0.62	-0.02	13.9	139	90
3.0	--	2.40	0.70	-0.03	13.9	133	71
4.0	--	2.33	0.72	-0.03	13.9	135	116
5.0	--	2.42	0.62	-0.02	13.9	140	152
6.0	--	2.53	0.56	-0.02	13.9	143	153
7.0	--	2.54	0.55	-0.02	13.9	138	145
8.0	--	2.61	0.53	-0.02	13.9	137	161
9.0	--	2.53	0.56	-0.02	13.9	136	100
10.0	--	2.44	0.57	-0.02	13.9	132	103
11.0	--	2.38	0.61	-0.02	13.9	133	116
12.0	--	2.34	0.65	-0.02	13.9	133	81
13.0	--	2.26	0.67	-0.02	13.9	135	121
14.0	--	2.27	0.68	-0.03	13.9	138	105
15.0	--	2.28	0.66	-0.02	13.9	135	118
16.0	--	2.36	0.65	-0.02	13.9	134	105
17.0	--	2.37	0.59	-0.02	13.9	138	119
18.0	--	2.27	0.61	-0.02	13.9	130	91
19.0	--	2.24	0.61	-0.02	13.9	136	123

Time	Force	Lift	Drag	Pitching Moment	Angle	Pressure	Pressure
(s)	(N)	(N)	(N)	(Nm)	(Degrees)	(Pa)	(Pa)
0.0	--	1.93	0.69	-0.03	16.1	138	156
1.0	--	2.05	0.66	-0.03	16.1	132	136
2.0	--	2.07	0.61	-0.03	16.1	133	130
3.0	--	2.01	0.62	-0.03	16.1	132	128
4.0	--	1.97	0.63	-0.03	16.1	134	97
5.0	--	1.97	0.64	-0.03	16.1	130	137
6.0	--	2.14	0.58	-0.02	16.1	139	133
7.0	--	2.25	0.60	-0.03	16.1	143	125
8.0	--	2.28	0.61	-0.03	16.1	142	135
9.0	--	2.29	0.61	-0.03	16.1	136	116
10.0	--	2.22	0.67	-0.03	16.1	137	86
11.0	--	2.17	0.66	-0.03	16.1	135	114
12.0	--	2.10	0.71	-0.03	16.1	138	116
13.0	--	2.12	0.70	-0.03	16.1	137	138
14.0	--	2.08	0.71	-0.03	16.1	136	124
15.0	--	2.06	0.71	-0.03	16.1	138	107
16.0	--	2.04	0.72	-0.03	16.1	140	109
17.0	--	1.98	0.73	-0.03	16.1	140	118
18.0	--	2.01	0.68	-0.03	16.1	134	104
19.0	--	1.95	0.69	-0.03	16.1	132	80

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Time	Force	Lift	Drag	Pitching Moment	Angle	Pressure	Pressure
(s)	(N)	(N)	(N)	(Nm)	(Degrees)	(Pa)	(Pa)
0.0	--	1.83	0.44	-0.01	0.1	130	137
1.0	--	1.84	0.45	-0.01	0.1	134	139
2.0	--	1.83	0.45	-0.01	0.1	131	138
3.0	--	1.82	0.45	-0.01	0.1	130	136
4.0	--	1.80	0.46	-0.01	0.1	126	135
5.0	--	1.79	0.45	-0.01	0.1	130	138
6.0	--	1.79	0.45	-0.01	0.1	131	138
7.0	--	1.78	0.45	-0.01	0.1	133	139
8.0	--	1.76	0.44	-0.01	0.1	131	139
9.0	--	1.75	0.43	-0.01	0.1	130	137
10.0	--	1.71	0.43	-0.01	0.1	130	137
11.0	--	1.69	0.42	-0.01	0.1	127	136
12.0	--	1.63	0.42	-0.01	0.1	130	138
13.0	--	1.62	0.40	-0.01	0.1	128	137
14.0	--	1.56	0.39	-0.01	0.1	128	135
15.0	--	1.54	0.37	-0.01	0.1	130	139
16.0	--	1.52	0.36	-0.01	0.1	129	138
17.0	--	1.52	0.36	-0.01	0.1	130	141
18.0	--	1.54	0.36	-0.01	0.1	131	139
19.0	--	1.54	0.35	-0.01	0.1	128	136

Time	Force	Lift	Drag	Pitching Moment	Angle	Pressure	Pressure
(s)	(N)	(N)	(N)	(Nm)	(Degrees)	(Pa)	(Pa)
0.0	--	2.78	0.39	-0.01	5.1	133	147
1.0	--	2.79	0.41	-0.01	5.1	133	148
2.0	--	2.82	0.41	-0.01	5.1	135	150
3.0	--	2.81	0.41	-0.01	5.1	133	148
4.0	--	2.82	0.40	-0.01	5.1	135	148
5.0	--	2.82	0.41	-0.01	5.1	137	149
6.0	--	2.83	0.41	-0.01	5.1	133	145
7.0	--	2.85	0.42	-0.01	5.1	132	146
8.0	--	2.87	0.43	-0.01	5.1	129	143
9.0	--	2.86	0.44	-0.01	5.1	129	145
10.0	--	2.86	0.44	-0.01	5.1	131	145
11.0	--	2.84	0.43	-0.01	5.1	131	146
12.0	--	2.83	0.43	-0.01	5.1	132	146
13.0	--	2.80	0.41	-0.01	5.1	129	144
14.0	--	2.75	0.41	-0.01	5.1	136	146
15.0	--	2.72	0.39	-0.01	5.1	134	146
16.0	--	2.68	0.38	-0.01	5.1	130	145
17.0	--	2.66	0.37	-0.01	5.1	129	144
18.0	--	2.66	0.36	-0.01	5.1	131	146
19.0	--	2.65	0.36	-0.01	5.1	127	144

Time	Force	Lift	Drag	Pitching Moment	Angle	Pressure	Pressure
(s)	(N)	(N)	(N)	(Nm)	(Degrees)	(Pa)	(Pa)
0.0	--	3.35	0.50	-0.01	10.1	129	152
1.0	--	3.39	0.51	-0.01	10.1	130	153
2.0	--	3.44	0.51	-0.01	10.1	131	151
3.0	--	3.45	0.52	-0.01	10.1	131	155
4.0	--	3.46	0.53	-0.01	10.1	131	155
5.0	--	3.44	0.54	-0.01	10.1	135	153
6.0	--	3.47	0.53	-0.01	10.1	144	160
7.0	--	3.46	0.53	-0.01	10.1	132	151
8.0	--	3.37	0.52	-0.01	10.1	128	153
9.0	--	3.32	0.54	-0.01	10.1	130	154
10.0	--	3.26	0.52	-0.01	10.1	133	157
11.0	--	3.24	0.52	-0.01	10.1	131	154
12.0	--	3.20	0.52	-0.01	10.1	130	153
13.0	--	3.21	0.51	-0.01	10.1	130	151
14.0	--	3.18	0.50	-0.01	10.1	134	153
15.0	--	3.26	0.52	-0.01	10.1	137	155
16.0	--	3.42	0.53	-0.01	10.1	137	158
17.0	--	3.47	0.56	-0.01	10.1	135	153
18.0	--	3.47	0.58	-0.01	10.1	130	145
19.0	--	3.44	0.62	-0.01	10.1	129	149

Time	Force	Lift	Drag	Pitching Moment	Angle	Pressure	Pressure
(s)	(N)	(N)	(N)	(Nm)	(Degrees)	(Pa)	(Pa)
0.0	--	3.51	0.60	-0.01	12.0	130	155
1.0	--	3.35	0.60	-0.01	12.0	129	141
2.0	--	3.32	0.62	-0.01	12.0	128	154
3.0	--	3.31	0.62	-0.01	12.0	135	156
4.0	--	3.32	0.60	-0.01	12.0	128	149
5.0	--	3.36	0.58	-0.01	12.0	128	147
6.0	--	3.37	0.57	-0.01	12.0	128	156
7.0	--	3.34	0.64	-0.02	12.0	128	151
8.0	--	3.35	0.61	-0.01	12.0	131	147
9.0	--	3.39	0.59	-0.01	12.0	129	157
10.0	--	3.42	0.57	-0.01	12.0	129	154
11.0	--	3.45	0.56	-0.01	12.0	129	154
12.0	--	3.38	0.59	-0.01	12.0	126	148
13.0	--	3.36	0.57	-0.01	12.0	128	156
14.0	--	3.36	0.55	-0.01	12.0	131	154
15.0	--	3.37	0.55	-0.01	12.0	126	153
16.0	--	3.39	0.55	-0.01	12.0	128	157
17.0	--	3.43	0.55	-0.01	12.0	130	158
18.0	--	3.43	0.55	-0.01	12.0	131	158
19.0	--	3.30	0.61	-0.01	12.0	124	134

(s)	(N)	(N)	(N)	(Nm)	(Degrees)	(Pa)	(Pa)
0.0	--	3.30	0.81	-0.02	14.0	130	156
1.0	--	3.28	0.81	-0.02	14.0	139	144
2.0	--	3.32	0.78	-0.02	14.0	141	160
3.0	--	3.34	0.74	-0.02	14.0	136	166
4.0	--	3.34	0.64	-0.02	14.0	142	165
5.0	--	3.39	0.62	-0.02	14.0	141	171
6.0	--	3.45	0.62	-0.02	14.0	150	171
7.0	--	3.53	0.62	-0.02	14.0	138	170
8.0	--	3.59	0.67	-0.02	14.0	140	170
9.0	--	3.74	0.69	-0.02	14.0	133	168
10.0	--	3.73	0.74	-0.02	14.0	129	154
11.0	--	3.68	0.76	-0.02	14.0	132	133
12.0	--	3.63	0.87	-0.02	14.0	134	127
13.0	--	3.58	0.90	-0.02	14.0	133	126
14.0	--	3.55	0.95	-0.02	14.0	135	131
15.0	--	3.64	0.91	-0.02	14.0	138	153
16.0	--	3.58	0.93	-0.02	14.0	133	116
17.0	--	3.55	0.94	-0.02	14.0	132	143
18.0	--	3.52	0.94	-0.03	14.0	134	140
19.0	--	3.74	0.88	-0.02	14.0	137	137

(s)	(N)	(N)	(N)	(Nm)	(Degrees)	(Pa)	(Pa)
0.0	--	3.79	1.21	-0.03	16.0	137	106
1.0	--	3.72	1.22	-0.03	16.0	133	111
2.0	--	3.62	1.26	-0.03	16.0	136	71
3.0	--	3.67	1.27	-0.03	16.0	133	86
4.0	--	3.81	1.25	-0.03	16.0	133	122
5.0	--	3.84	1.26	-0.03	16.0	130	94
6.0	--	3.74	1.27	-0.03	16.0	135	140
7.0	--	3.76	1.24	-0.02	16.0	134	120
8.0	--	3.76	1.21	-0.03	16.0	136	156
9.0	--	3.85	1.16	-0.02	16.0	138	173
10.0	--	3.82	1.15	-0.02	16.0	139	125

11.0	--	3.77	1.15	-0.02	16.0	133	123
12.0	--	3.68	1.17	-0.02	16.0	133	136
13.0	--	3.73	1.17	-0.02	16.0	134	156
14.0	--	3.77	1.17	-0.02	16.0	132	163
15.0	--	3.78	1.16	-0.02	16.0	133	149
16.0	--	3.63	1.18	-0.03	16.0	135	87
17.0	--	3.65	1.16	-0.02	16.0	135	148
18.0	--	3.68	1.10	-0.02	16.0	136	163
19.0	--	3.67	1.10	-0.02	16.0	133	116

(s)	**(N)**	**(N)**	**(N)**	**(Nm)**	**(Degrees)**	**(Pa)**	**(Pa)**
0.0	--	3.78	1.30	-0.03	18.0	134	175
1.0	--	3.91	1.28	-0.03	18.0	132	160
2.0	--	3.86	1.32	-0.03	18.0	139	147
3.0	--	3.92	1.36	-0.03	18.0	135	137
4.0	--	3.97	1.35	-0.03	18.0	132	150
5.0	--	3.96	1.36	-0.03	18.0	136	127
6.0	--	3.99	1.37	-0.03	18.0	129	169
7.0	--	3.95	1.36	-0.03	18.0	132	131
8.0	--	3.87	1.35	-0.03	18.0	138	160
9.0	--	3.88	1.29	-0.03	18.0	137	171
10.0	--	3.86	1.30	-0.03	18.0	142	158
11.0	--	3.78	1.32	-0.03	18.0	139	152
12.0	--	3.82	1.30	-0.03	18.0	131	149
13.0	--	3.83	1.34	-0.03	18.0	133	102
14.0	--	3.66	1.37	-0.03	18.0	129	70
15.0	--	3.63	1.36	-0.03	18.0	132	109
16.0	--	3.63	1.37	-0.03	18.0	130	141
17.0	--	3.68	1.33	-0.03	18.0	131	145
18.0	--	3.80	1.30	-0.03	18.0	132	162
19.0	--	3.78	1.29	-0.03	18.0	130	122