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Session	Subject grade	Total scaled moderated mark	The lower grade boundary mark	The upper grade boundary mark	The marks required for grade to increase
MAY 2019	B	25	21	26	2

EE Reflection appended to the end. Make sure you do them properly (worth a lot of marks)

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An Experimental Study of The Aerofoil-Shaped Formula One Rear Wing

A Physics Extended Essay

Research Question: *"To what extent does a change in the angle of attack of an aero-foil shaped rear wing affect the magnitude of downforce produced"*

Word Count: 3694

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1 Introduction

Formula One (Also known as F1 or Formula 1) is a motorsport with teams that push the boundaries of automotive engineering further than any other motorsport. With cars that weight around 700kg and travel at speeds up to 375km/h, a challenge to the F1 racing teams to engineer their vehicles so that they're able to maintain the high speed for as long as possible to outrace their opponents on racetracks with sharp and frequent turns. One of the ways they solve this problem is by further optimizing the aerodynamics of their cars

with efficiency and *downforce* in mind. One of the most important aerodynamic surfaces used on the vehicles are the aerofoil shaped rear wings (See figure 1 and 1.1).

Figure 1 (left) and 1.1 (up)*: Close-up of the rear wing of Ferrari's new SF71H Formula One vehicle (Petrić, 2018)*

They serve the purpose of providing large amounts of downforce, enabling the vehicles to make aggressive turns at relatively high speeds. The scope of this essay is to investigate the optimization of F1 rear wings, with respect to their angle of attack relative to the car and downforce produced. With the research question:

"To what extent does a change in the angle of attack of an aero-foil shaped rear wing affect the magnitude of downforce produced"

This essay seeks to answer this question experimentally, using wood carved wings and a wind tunnel made in-house.

1.1 Personal engagement

I have long had an interest in the aerospace industry and seek to pursue a field of work in that area. This, coupled with an interest in the Formula One motorsport lead to that the field of study for my Extended Essay would be something involving fluid mechanics. The choice of studying rear wings, as opposed to front-wings or bodywork, is that the rear wing is much less complex, making it easier to experimentally test.

2 Background

2.1 The Coefficient of lift

The premise of this paper is to determine the optimal angle of attack relative to the direction of airflow with respect to the dimensionless coefficients of lift. To find it, derivations of the formulas given by Merle C. Potter must be done:

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

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

Where F_L is the force of lift, ρ is the fluid density of the fluid, V is the airspeed, A is the surface area, in this case, since the focus is on aerofoils, A is the distance from the nose to the trailing edge (chord length) times the width (Potter, 2009). However, since the study of fluid dynamics is complex by nature, we must be in possession of in-depth knowledge about the fluid in study. An important reason for this is so that an as accurate model as possible can be deducted from our experiment.

2.2 Reynolds Number

An important characteristic of the fluid in study, in this case, air, is whether the flow of air that hits the wing is laminar, meaning a straight and elegant flow, or turbulent, a chaotic one. The *Reynolds number* (Re) was used, and given by:

$$Re = \frac{U_\infty L_W}{\nu}$$

Where U_∞ is the freestream velocity of the fluid given in ms^{-1}. L_W is the chord line of the wing, which means the distance from the trailing edge to the leading edge, given in m, and ν is given as the kinematic viscosity of the fluid. Viscosity is defined as a fluid's susceptibility to move when subject to stress, kinematic viscosity (v) is the viscosity of the fluid (μ) with respect to its density (ρ).

$$\rho = \frac{p}{RT}$$

$$v = \frac{\mu}{\rho} = \frac{\mu}{\frac{p}{RT}} = \frac{\mu RT}{p}$$

Where R is the specific gas constant for dry air measured in J $Kg^{-1}K^{-1}$ and is given as 287.05 (Universal and Individual Gas Constants, u.d.), T is the temperature of the fluid in Kelvin (K) and p is the pressure measured in Pascals (Pa).

Substituting this into our formula for the Reynolds number, we get a formula with values that are all measure with our equipment described later in section 3.

$$Re = \frac{U_\infty L_W}{\frac{\mu RT}{p}} = \frac{pU_\infty L_W}{\mu RT}$$

Since the air being studied in this experiment is flowing through a wind tunnel, which is a pipe we say that if the Reynolds number is greater than a critical of 1×10^5 (Kianoosh Yousefi, 2018) the airflow is said to be turbulent.

2.3 Why downforce occurs

A common misconception of how lift is generated is that the wings have a longer and shorter side, forcing the air molecules to travel different distances over the wing. The argument is then that the molecules on the long side must travel faster so that they can meet up with its “partner” at the trailing edge of the wing. Causing a higher pressure at the top of the wing. We know that air flows from high-pressure areas to low-pressure areas to even out the differences. And thus, the air is supposed to flow up to top of the wing, causing a force to applied upwards, hence the lift (Hall, Aerodynamic Forces: Incorrect Theory #1, 2018). The same applies to F1 rear wings, though it is flipped since the wings are flipped.

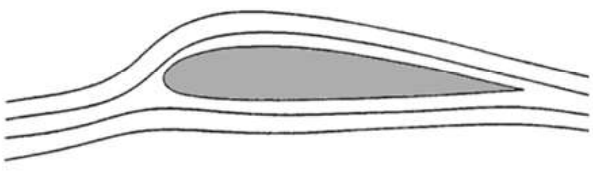
The correct explanation of why lift occurs can be explained through the Coandă effect and what Bernoulli explains in his famous equation.

2.3.1 The Coandă effect

The Coandă effect was first attempted explained during the 1800s, and was described as follows:

“The lateral pressure which urges the flame of a candle towards the stream of air from a blowpipe is probably exactly similar to that pressure which eases the inflection of a current of air near an obstacle. Mark the dimple which a slender stream of air makes on the surface of water. Bring a convex body into contact with the side of the stream and the place of the dimple will immediately show the current is deflected towards the body; and if the body be at liberty to move in every direction it will be urged towards the current...” (Young, 1800, ss. 111-112)

What the Coandă effect describes the phenomenon that an object submerged in a flowing fluid, will have a "boundary layer" where only viscous forces are acting on the body. This layer forms on the surface of the object and can be seen in illustration 3 and 3.1, were air flows around an airfoil.



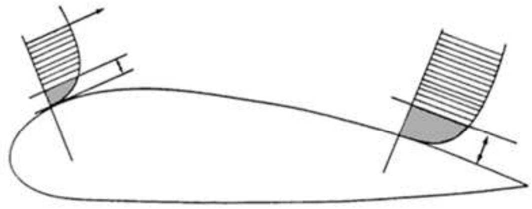


Illustration 2.1 (left) and 2.2 (right): *Illustration of the Boundary layer formed around an airfoil (Heintz, 1987)*

As the angle of attack relative to the freestream flow increases, the boundary layer still sticks to the surface, pushing the air down from its incident angle and the freestream velocity's *direction* changes.

We know from Newton's second law that

$$\sum \vec{F} = m\vec{a}$$

And since

$$\vec{a} = \frac{\Delta\vec{V}}{\Delta T}$$

Velocity is a component of Newton's second law through the acceleration ($\vec{a}$), a change in the velocity's direction also changes the direction of the force. The force will get directed downwards and by Newton's third law; *For every action, there's an equal and opposite reaction.* A force in equal magnitude that is directed downwards will be directed upwards. Hence, a force of lift.

This implies that even a flat wing will generate lift, which is true and was exemplified by the Wright brothers when they first flew during the early 1900s. But the airfoil of study in this paper is of a shape similar to a curved wing shape with a thicker and a narrower side, this is the norm for most commercial airplanes and to understand this particular design choice, one must understand Bernoulli's equation.

2.3.2 Bernoulli's equation

The derived version of Bernoulli's equation is given by:

$$p + \frac{1}{2}\rho U^2 = a\ constant$$

Since the results of the equation is supposed to be a constant, the equations can be set to be equal:

$$p + \frac{1}{2}\rho U^2 = p_2 + \frac{1}{2}\rho_2 U_2^2$$

One can see that there is a direct relationship between the pressure (p) and the velocity (U).

The Department of Engineering at the University of Cambridge, tested the airspeed around an airfoil in a wind tunnel, by using pulses of smoke, were able to clearly visualize that the streamlines under the wing travel significantly faster than the ones above. This is seen in illustration 2.3 and 2.4:

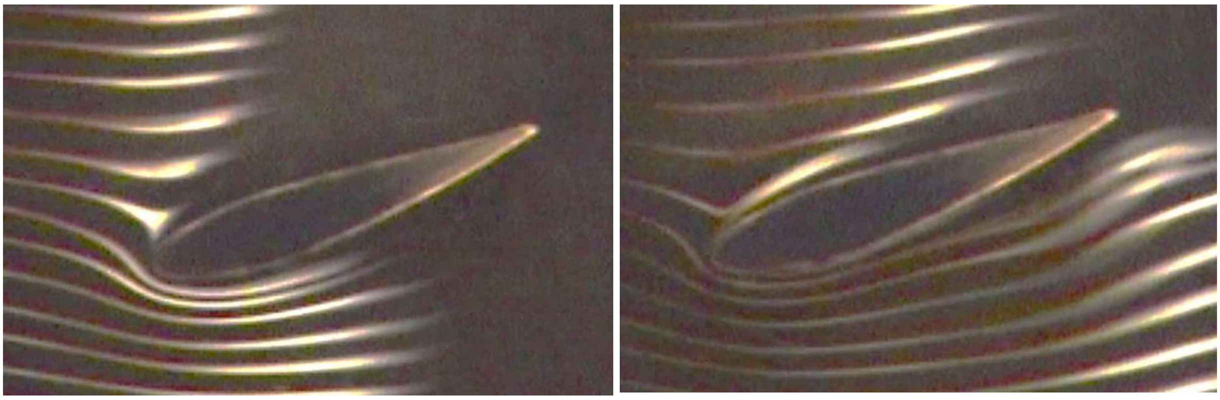


illustration 2.3 and 2.4: *Visual indication of streamlines around an aero-foil. (the images are flipped to better represent F1 rear wings) (Babinsky, 2012)*

This creates a high-pressure area above the wing and a low-pressure area below the wing, this is proven by the Bernoulli's equation, where if the velocity changes, something else must change on both sides to make both sides of the equation equal.

Fluids like air tend to flow from high-pressure areas to low-pressure areas and will thus try to flow from above the foil and down. Hence, a lifting force.

2.4 The hypothesis

As put forward by A. Buljac in his study *"Automobile Aerodynamics Influenced by Airfoil-shaped Rear Wing"* and J. Katz's *"Experimental Study of the Aerodynamic Interaction Between an Enclosed-Wheel Racing-Car and Its Rear Wing".* The force of lift excreted by the wing will reach a critical point where the Force peaks, promptly followed by a decrease. This is what is known as the "stall angle" in aviation.

As explained in section 2.2.1, a boundary layer is formed when an object is submerged in a fluid flow, and this is one of the main reasons how a wing achieves a force of lift. However, as the wing approaches and reaches a stalling angle, the boundary layers eventually separate from the body; the point at which this happens is called a separation point.

Once the separation point occurs close to the nose of the wing, total lift excreted by the wing drops dramatically and is called a *stall*.

In A. Buljac's study, a computational fluid dynamics (CFD) simulation of an airfoil with a one-part setup, similar to what is being studied in this paper, took place. The study focused on the optimal angle of attack with respect to lift and drag and concluded with that *"the lift coefficient reached its maximum at around* 20°*"* (Buljac, Džijan, I. Korade, & Kozmar, 2016).

It is therefore reasonable that to an extent, similar results are to be expected in this study. The key differing factor is that Buljac's study is done using CFD simulations, while this study is experimental. Experimental studies are often found to be subject to random inaccuracies and inconsistencies, whilst CFD simulations can subject to inaccuracies, they are to an arguably lesser extent; as it's purely based on the mathematical computation of models describing the way air-molecules behave, which may not be a 100% realistic interpretation if how fluids move.

3 Experimental setup

The design of the experiment was centered around the usage of a wind-tunnel, the home-made wing will be placed inside the wind tunnel and taped onto a scale. The scale was tared once the wing was placed on it. This was done so that the scale would display the downforce only.

3.1 The wind tunnel

The design of the wind tunnel was centered around an open return type, meaning that the air would flow through and out of the tunnel. The tunnel separated into three sections; the intake section with a settling chamber, the main chamber and the exhaust chamber.

The dimensions and an illustration of the tunnel can be seen in illustration 3.1

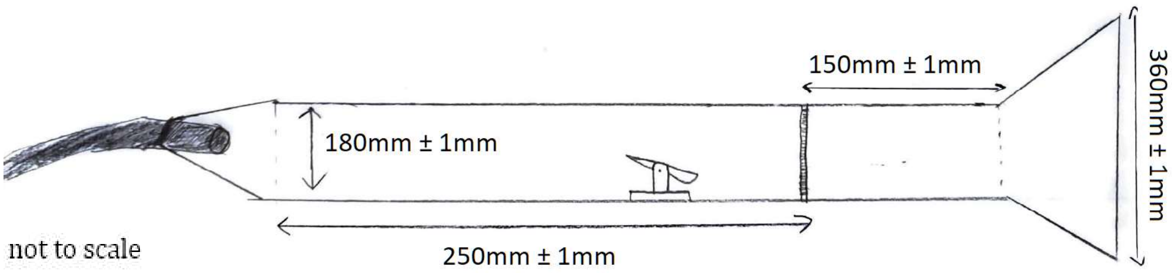


Illustration 3.1: *An overview of the dimensions of the wind tunnel*

3.1.1 The Intake Section and Settling Chamber

The settling chamber is used to increase the uniformity of the air, decreasing the amount of random vortexes and inequalities. A vacuum cleaner was used to produce a flow of air, as the fans available were not strong enough. The vacuum cleaner produced high-pressure air in the back of the tunnel and as derived from Bernoulli's equation in section 2, air tries to flow into the high-pressure areas, hence a flow of air through the tunnel.

A wall of cut straws was placed in front of the wing, as it would aid in the achievement of better flow uniformity (Hernández, 2013, p. 12). Although this might have worked against its purpose, this will be discussed in section 5.

3.1.2 The Main Chamber

The airspeed inside the tunnel was measured using an anemometer and determined to be 1.2 ms^{-1} with an uncertainty of $\pm$ 0.1. This was determined by placing two identical models of the same tool inside the wind tunnel at the same time, then comparing the results they gave, and their value difference was given as the uncertainty.

The weight used to measure the force exerted by the wings is found to be one of the most inaccuracy prone part of the experiment. 3 scales of the same kind were used to measure the weight of the same object and all three of them showed different results. The greatest gap was used as the uncertainty, which was found to be $\pm 0.6g$. although some anomalies in the scale itself were observed, which would result in an even greater uncertainty.

As the plexiglass that was used as a window were closed after the scale was put in place, the wing put on top, and the scale tared; the scale showed fluctuating values between $0.1g$ and $0.9g$. This could be because of a faulty scale, but as the scale was replaced the problem persisted through the trails.

The cause of these fluctuations was determined to be due to the climate control systems at our school and that we had an open window to the room. As the tunnel was sealed when the plexiglass was closed, the only place for the air to escape the would be at the back of the tunnel, meaning that a miniscule flow through the tunnel was present when the anomalies were observed. The cause for this could be that the air-conditioning system design at the school, that follows the norm of industrial design, makes sure that the inside has a positive air pressure. Which causes air to flow *out* of the room if a window is opened. Hence, an airflow through the tunnel. It was therefore determined that no additional uncertainty should be added due to this.

3.2 The wing

The construction of the wing used in the experiment was carved out of wood and then trimmed down using sandpaper. The shape of the wing was aimed towards a NACA 4112, designed by the National Advisory Committee for Aeronautics (NACA). It is to be noted, however, that Formula One engineering teams take another approach into consideration when constructing their rear wings. They usually adopt a two-part setup, consisting of two trailing aerofoils with varying Angles of attack., this is done to achieve a greater magnitude of downforce (J. Katz, 1989). However, the wing tested has adopted a one-part structure since a two-part structure was relatively complex to manufacture.

Figure 3.1: *A profile of the wing used in the experiment*

The wing used had a width of $930mm$ and a cord length (L_w) of $1150mm$. The uncertainties of these measurements were determined to be $\pm$ $1mm$. As the dimensions was measured using ruler, any smaller uncertainties would be unrealistic due to the nature of its construction, where the accuracy measures down to the nearest millimeter.

An inaccuracy to consider is that the wing was not constructed by laser accurate machinery, but by rather inaccurate humans. This causes an irregularity in the dimensions of the wing and therefore a small added uncertainty, an estimate $\pm 0.1mm$ was determined to be the added due to this. Adding up to a total of $\pm$ $1.1mm$. However, it was later decided that this uncertainty was small enough to be *negligible* in the final calculations

An attempt was made to make the surface of the wing as smooth-surfaced as possible, in order to minimize the potential anomalies discussed in section 5**.** This was done using sand-paper, although methods such as; adding a plastic film (tape) or paint could have been done in order to further optimized the accuracy of this experiment.

The wing was screwed in place into a mounting brace, angles were marked with reference for the previously drawn chord line on the wing. An uncertainty in the angle measurement was figured to be $\pm 0.5°$, this was due to how the degrees were imprinted on the brace, and inaccuracies in measurements as the wing was put in place; The wing was angled and the screws holding the wing in place firmly tightened prior to it being placed into the wind tunnel. However, the wing could've collided with the roof of the tunnel and therefore gotten out of place, hence an attritionary $\pm 0.5°$ of uncertainty, resulting in a total of $\pm 1°$. However, this might be an overestimate.

4 Results

The data was collected a total of 4 times, with the angle of attack being the independent variable and Force of lift being the dependent one.

A representation of the average data across all 4 trails can be seen in table 4.1:

Angle of attack $(\Delta^\circ \pm 1)$	**Downforce** $(\Delta g \pm 0.06)$	**Freestream flow speed** $(\Delta m s^{-1} \pm 0.1)$	**Pressure** $(\Delta kpa \pm 0.1)$	**Temperature** $(\Delta ^\circ C \pm 1)$
5	0.22	1.2	102.1	25
10	0.36	1.3	102.1	25
15	0.71	1.3	102.1	25
20	0.90	1.2	102.1	25
25	1.18	1.3	102.1	25
30	1.18	1.2	102.1	25
35	1.07	1.2	102.1	25
40	0.94	1.2	102.1	25

Table 4.1: *Raw average experiment data (the full data can be found in the appetencies at the end of the document)*

By using the formula for the Reynolds number derived in section 3 and substitution the values needed from the table above, we find that the flow inside the tunnel is:

$$Re = \frac{pU_{\infty}L_W}{\mu RT}$$

$$Re = \frac{(102.1 \times 10^3\ pa)(1.3\ ms^{-1})(1150 \times 10^{-3}m)}{(18.37 \times 10^{-6}\ Nsm^{-2})(287.05\ \ J\ Kg^{-1}K^{-1})(25 + 273.15K)}$$

$$Re = 9.7 \times 10^3 \pm 5.9 \times 10^2$$

This since the Reynolds Number (Re) is *smaller* than the critical, the flow inside the test chamber prior to hitting the wing is said to be *turbulent.* the consequences of this will be discussed in section 5. It is reasonable to assume that since the temperature and pressure stayed largely the same across all trails, it is reasonable to assume that the airflow stayed the same for all trails.

To calculate the coefficient of lift, the data seen in *Table 1* had to be converted into the appropriate units, this can be seen in *Table 2.*

The density (ρ) was calculated using the formula shown in section 2.1. Whilst the Force of lift ($\overrightarrow{F_L}$) was calculated as follows:

$$\overrightarrow{F_L} = -\frac{(Downforce\ measured\ in\ g) \times (9.81ms^{-2})}{1000}$$

Angle ($^\circ \pm 1$)	Force of lift ($\vec{N} \pm 0.006$)	Air-speed ($ms^{-1} \pm 0.1$)	Density ($kg\ m^{-3}$)	Area (m^2)
5	-0.023	1.2	1.2	1.1
10	-0.036	1.2	1.2	1.1
15	-0.072	1.3	1.2	1.1
20	-0.092	1.2	1.2	1.1
25	-0.12	1.3	1.2	1.1
30	-0.12	1.2	1.2	1.1
35	-0.11	1.2	1.2	1.1
40	-0.096	1.2	1.2	1.1

Table 4.2: *Converted Experiment Data*

for the different angles used in the experiment, the following was done (using dataset for 5°):

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

$$C_L(5^\circ) = \frac{2(-0.023N)}{(1.2kg\ m^{-3})(1.1m^2)\left(1.2ms^{-1^2}\right)}$$

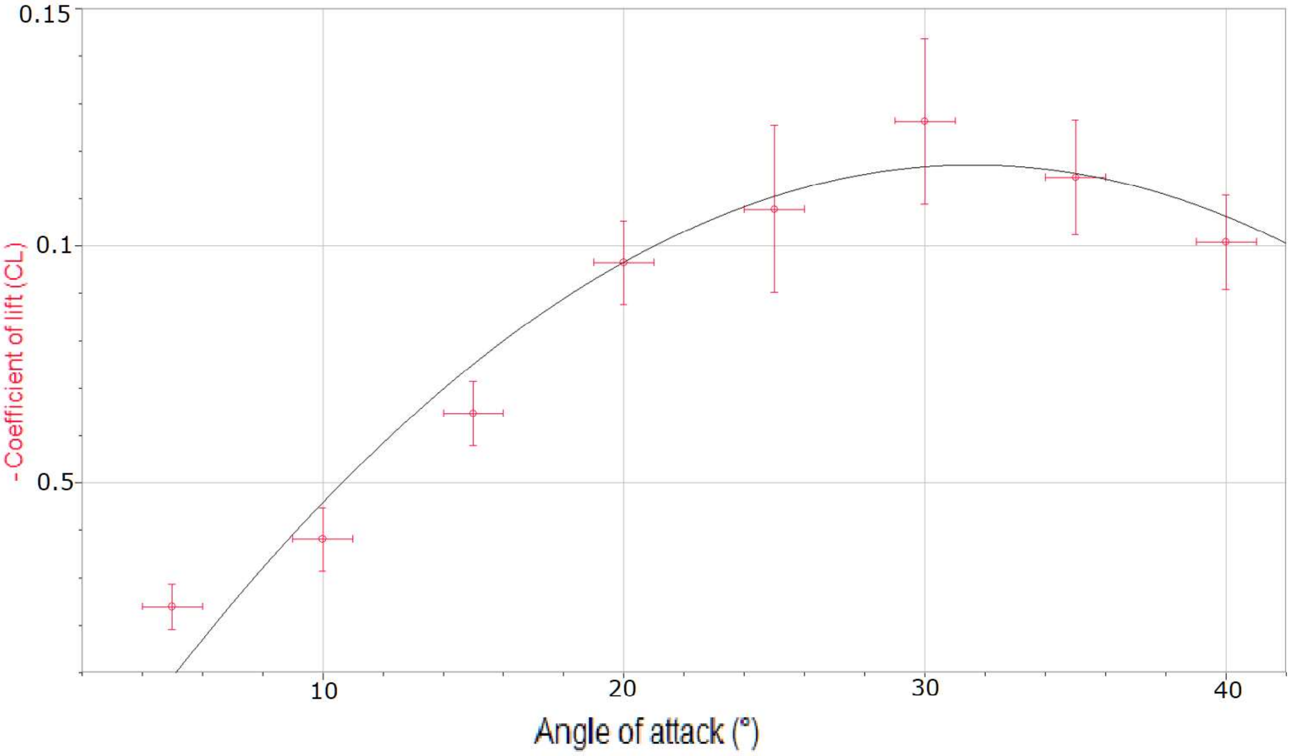
$$C_L(5^\circ) = -0.024 \pm 0.0047$$

In the table below, the calculations seen above were repeated for each data-set. The uncertainties on the graph and table was calculated from the random errors across the trails made.

Angle ($\Delta°\pm 1$)	Lift Coefficient C_L	Random error in lift coefficient $\pm\Delta C_L$
5	-0.024	0.0047
10	-0.038	0.0067
15	-0.065	0.0068
20	-0.098	0.0088
25	-0.11	0.018
30	-0.13	0.018
35	-0.12	0.012
40	-0.10	0.0099

Table 4.3: *Processed data*

The data above was plotted and curve-fitted using Logger Pro (Vernier Software)**.** To yield the following:



As seen in the best-fit curve above, the coefficient of lift reaches a maximum at an angle of attack of $\sim 32°$. This is seen by observing the curve of best fit. However, the experimental data shows that a maximum lift coefficient was reached at 30°.

5 Discussion

The results of this experiment showed that when the aerofoil reached its stall angle at around 32° at a speed of around $1.3ms^{-1}$. Though as the error bars for the results were rather large, one can argue that the maximum coefficient of lift could lie anywhere between 25° and 40°. Which further complicates our ability to draw an accurate conclusion, since no data beyond 40° was recorded. The reasons for why these errors where of such magnitude and their origin will be suggested and discussed in this section.

5.1 Inconsistencies in wing and wind tunnel construction

Formula 1 cars have two main elements attributing to the generation of downforce, the rear wing (studied in this paper) and the front wing. A typical front wing has a multitude of tiny plates shaped in precise and delicate manners, layer on top of it, these plates are called vortex generators and can be seen in Illustration *(5).*

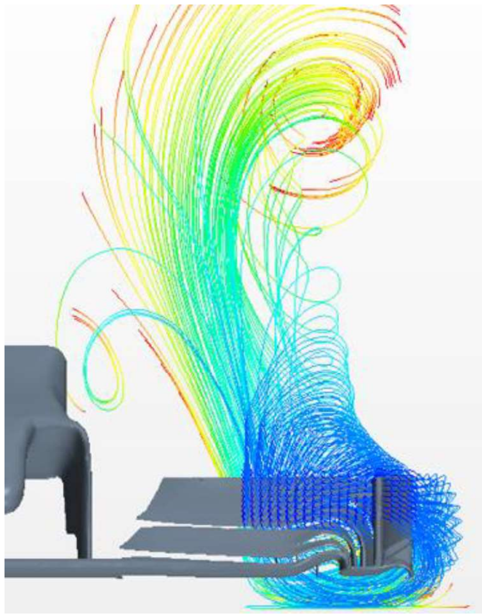


Illustration* 5.1: A simulation of the vortex generation caused by a typical F1 front wing. (Xin Zhang, 2015)*

It has been found that if the flow hitting a wing is of a vortex-laden characteristic, the separation point for the boundary layer tends to be further along the wing as opposed to a laminar flow. Therefore, a further increase of the coefficient at all angles of attack and at all speeds and an increase in the stall angle. This is pivotal in F1 racing as cars need to slow down in sharp turns to avoid losing traction. As the car slows down the downforce generated is also dropping, forcing the driver to slow down even more. However, when vortex generators in use, the driver don't need to slow down as much and can therefore increase his average speed across the racing track.

The vortexes occur when a stream of air hits a surface perpendicular to the flow direction of the boundary layer. The boundary layer will then break up into a high pressure and low-pressure area, parted by the surface. Since the flow wants to keep flowing, and since it wants to flow from high-pressure to low-pressure areas, the air tries to move up and around the surface, only to be cut off right before it gets to flow over, the wake of this phenomenon is a vortex.

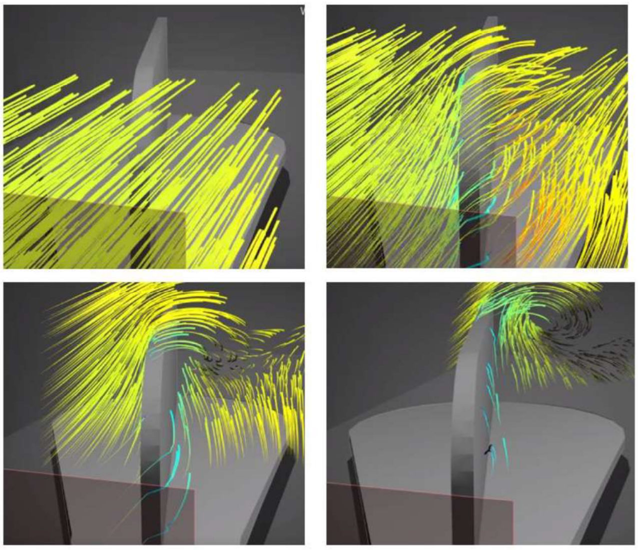


Figure 5.2: *A strip showing the air flowing around a vortex generator in an "Autodesk Flow Design" Simulation (Sheperd, 2015)*

5.1.1 The Honey-comb filter

The reason for outlining the effect of vortexes on the Coefficient of lift, is that a flaw in the design of the wind-tunnel might have caused a vortex-laden airflow.

Figure 5.3 (up) and 5.4 (right): *Images of the honeycomb patter made of cut straws. 5.4 is a close-up shot*

In the illustration above; pictures of the cut straws resembling a honey-comb pattern is shown.

There was a noticeable difference between the length of the straws sticking out of the pattern (*Figure 5.4*). The fact that the straws were sticking out could mean that vortexes were able to form, as the airstream flow out of the tubes. This would result in the air, which through calculations involving reynold's number was determined to be a laminar stream, could in fact not be and would therefore cause inconsistent results. This may also be a cause of a more turbulent and unpredictable airflow than what the calculated reynold's number predicted. A turbulet airflow would result in messy and inconistent data, causing the large errors observed

These potential votex generators could have been avoivded by making sure that all the straws were cut to the same lenght, and glued together in such a way that a perfect line-up would be achieved.

5.1.2 Inconsistencies in the wing

As briefly mentioned in section 3.2, the wing was constructed by carving it out of wood and the wing was neither covered in a smooth plastic nor a coat of paint. An attempt was made to smoothen out the surface of the wing, but the improvements were minuscule.

If there are bumps and ridges along the wing, like that in shape of figure 5.2, they may have served as vortex generating devices and causes a turbulent airflow.

The wing was never placed into the tunnel in the exact same way each trial, suggesting that the airflow would hit the bumps in the wing at different angles, meaning that they might serve as vortex generators for a random number trials, resulting in inconsistent data.

It's worth noting that predicting the transition of a fluid is a difficult part of fluid mechanics, and other sources of error not accounted for in this section could have been present.

6 Concluding remarks

Downforce is a crucial part of the competitive performance of a Formula 1 vehicle, and one of the largest contributors to a production of downforce is the rear wing.

An experiment carried through using a wind tunnel and a wood-carved wing found that the angle of attack influences the downforce exerted by the wing. It was found that at a critical angle of around 32°, the magnitude of the wing will stall. However, the data collected proved to be too inconsistent and the author has therefore chosen that it is not possible to draw a valid and accurate conclusion from this experiment.

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8 Appendix with Raw Data

Angle (± 1)	Force in g (± 0.06)	Air-speed (m/s ± 0.1)	Pressure (kpa ± 0.1)	Temperature (°C ± 1)
5	0.03	1.1	102.1	25
10	0.38	1.1	102.1	25
15	0.49	1.2	102.1	25
20	0.77	1.2	102.1	24
25	1.06	1.2	102.1	25
30	1.01	1.2	102.1	25

35	0.97	1.3	102.1	25
40	0.96	1.2	102.1	24

Trail 2

Angle (± 1)	Force in g (± 0.06)	Air-speed (m/s ± 0.1)	Pressure (kpa ± 0.1)	Temperature (°C ± 1)
5	0.25	1.2	102.1	24
10	0.34	1.3	102.1	24
15	0.67	1.2	102.1	24
20	0.92	1.2	102.1	24
25	1.25	1.2	102.1	24
30	1.24	1.3	102.1	24
35	1.11	1.2	102.1	25
40	0.96	1.2	102.1	25

Trail 3

Angle (± 1)	Force in g (± 0.06)	Air-speed (m/s ± 0.1)	Pressure (kpa ± 0.1)	Temperature (°C ± 1)
5	0.2	1.2	102.1	24
10	0.39	1.2	102.1	24
15	0.72	1.3	102.1	25
20	0.92	1.2	102.1	25
25	1.18	1.3	102.1	26
30	1.17	1.2	102.1	26
35	1.09	1.2	102.1	25
40	0.93	1.2	102.1	25

Trail 4

Angle (± 1)	Force in g (± 0.06)	Air-speed (m/s ± 0.1)	Pressure (kpa ± 0.1)	Temperature (°C ± 1)
5	0.21	1.2	102.1	26
10	0.31	1.2	102.1	25
15	0.73	1.3	102.1	25
20	0.89	1.2	102.1	24
25	1.13	1.3	102.1	24
30	1.19	1.2	102.1	24
35	1.05	1.2	102.1	25
40	0.93	1.2	102.1	26

Average

Angle of attack (± 1)	Force in g (± 0.06)	Air-speed (m/s ± 0.1)	Pressure (kpa ± 0.1)	Temperature (°C ± 1)
5	0.1725	1.175	102.1	24.75
10	0.355	1.2	102.1	24.5
15	0.6525	1.25	102.1	24.75
20	0.875	1.2	102.1	24.25
25	1.155	1.25	102.1	24.75
30	1.1525	1.225	102.1	24.75
35	1.055	1.225	102.1	25
40	0.945	1.2	102.1	25

Calculations

Angle (deg)	Force (N)	Air-speed (m/s)	Density (kg/m^3)	Area (m^2)	Lift Coeff.
5	-0.0227	1.20	1.194	1.0695	0.024669602
10	-0.0362	1.20	1.195	1.0695	0.039327457
15	-0.0721	1.25	1.194	1.0695	0.072293797
20	-0.0917	1.20	1.196	1.0695	0.099619669
25	-0.1203	1.25	1.194	1.0695	0.120574813
30	-0.1200	1.23	1.194	1.0695	0.125280464
35	-0.1088	1.23	1.193	1.0695	0.113672296
40	-0.0958	1.20	1.193	1.0695	0.104309602

Uncertainty in avg data (relative)

Angle of attack (Δdeg ± %)	Force in g (Δw ± %)	Force in N (ΔN ± %)	Air-speed (± %)	Pressure (± %)	Temperatur e (± %)	Area (m^2)
20.00	11.24	11.45	4.17	0.10	4.04	0.00
10.00	11.27	11.49	4.00	0.10	2.04	0.00
6.67	4.24	4.32	4.00	0.10	2.02	0.00
5.00	2.78	2.83	4.17	0.10	2.06	0.00
4.00	8.05	8.21	4.00	0.10	4.04	0.00
3.33	5.52	5.63	4.08	0.10	4.04	0.00
2.86	4.22	4.30	4.08	0.10	2.00	0.00
2.50	1.60	1.63	4.17	0.10	4.00	0.00

Uncertainty in calculations (relative)

Force (N)	Air-speed (m/s)	Area (m^2)	Lift Coeff.	Reynolds Number
11.45	4.17	0	19.76	8.31
11.49	4.00	0	17.62	6.14
4.32	4.00	0	10.44	6.12
2.83	4.17	0	9.16	6.33
8.21	4.00	0	16.35	8.14
5.63	4.08	0	13.85	8.22
4.30	4.08	0	10.48	6.18
1.63	4.17	0	9.89	8.26

EE/RPPF

For use from May/November 2018

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Candidate personal code: 6969

Extended essay - Reflections on planning and progress form

Candidate: *This form is to be completed by the candidate during the course and completion of their EE. This document records reflections on your planning and progress, and the nature of your discussions with your supervisor. You must undertake three formal reflection sessions with your supervisor: The first formal reflection session should focus on your initial ideas and how you plan to undertake your research; the interim reflection session is once a significant amount of your research has been completed, and the final session will be in the form of a viva voce once you have completed and handed in your EE. This document acts as a record in supporting the authenticity of your work. The three reflections combined must amount to no more than 500 words.*

The completion of this form is a mandatory requirement of the EE. It must be submitted together with the completed EE for assessment under Criterion E. As per the 'Protocols for completing and submitting the Reflections on planning and progress form' section of the EE guide, a mark of 0 will be awarded by the examiner for criterion E if the RPPF is blank or the comments are written in a language other than that of the accompanying essay.

Supervisor: *You must have three reflection sessions with each candidate, one early on in the process, an interim meeting and then the final viva voce. Other check-in sessions are permitted but do not need to be recorded on this sheet. After each reflection session candidates must record their reflections and as the supervisor you must sign and date this form.*

First reflection session

Candidate comments:

I've always, even before starting IB, had my mind set on doing my EE on fluid dynamics. My initial idea was to test the shape of nose cones, which was sparked through my interest in rocketry, but after pondering about the idea and did some test experiments, it would be extremely hard to complete an experiment using the testing equipment in our school. I therefore tried to learn about Fluid dynamics simulation software (CFD), but I soon discovered that it was extremely complicated, so I backed out.

I therefore had to think of a new idea, but I was still eager to learn about fluid dynamics and had just discovered that there's a lot of fluid dynamics going on in the motorsport; Formula 1. I then decided that I would focus on the rear-wing dynamics, since wings are something that's reasonably easier to understand (at least at a surface level), compared to nose-cones.

Date:

Supervisor initials:

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Interim reflection

Candidate comments:

A friend of mine was doing his topic on aircraft wings, so we decided to unite together and create a wind-tunnel out of cardboard to use for our experiments. But with it came many complications and ideas that sounded good at first, but later turned out to hinder our experiments. I also had to construct a wing using wood, which was a fun experience. I also research on wind-tunnel design and figured that a honey-comb filter would be needed to ensure a good airflow.
While doing my research, I searched the web for scholarly articles on rear-wing performance, as it was a topic I though would be well documented and tested due to the size of the motorsport. And I found a lot of articles that I read through, most contained theory I did not know, I therefore had to rent a book from the library about the “fundamentals of fluid dynamics”. However, I soon so this was a great challenge for me because it contained a lot of advanced calculus. This calculus was beyond me, so I decided that my EE would not go down the mathematical path and instead focus on written explanations.

Date: 　　　　Supervisor initials:

Final reflection - Viva voce

Candidate comments:

To reflect on the writing of the EE, I’d say that overall, I’m happy with my work, though It could have been a bit better.
For starters, cardboard should have been replaced with wood in the construction of the wind-tunnel, since cardboard was hard to work when conducting my experiments. I’d also design a better system for mounting the wing inside the tunnel to lower my uncertainties. If the uncertainties were lower, I’d most likely get better data and could draw a more accurate conclusion.
I’m happy with the way I worked with the EE and I’m sure that the skills I’ve learned will serve me greatly in university life. I have learned how to conduct an experiment and organize data with uncertainties, and how to visualize it properly, though, I wish I had used LaTeX when writing my EE as it would’ve been easier to format equations, tables and graphs.

Date: 　　　　Supervisor initials:

Supervisor comments:

***Supervisor**: By submitting this candidate work for assessment, you are taking responsibility for its authenticity. No piece of candidate work should be uploaded/submitted to the e-Coursework system if its authenticity is in doubt or if contradictory comments are added to this form. If your text in the box below raises any doubt on the authenticity of the work, this component will not be assessed.*