Investigating the aerodynamic design of a rear wing aerofoil

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Abstract

This poster will attempt to explain the fundamental physical and mathematical ideas when investigating how to optimize the flow of air over a formula one rear wing aerofoil. The poster will briefly cover the mathematical modelling, construction and physical testing of a rear wing aerofoil. Further information on this project can be found in the report.

1 Introduction

High speed cars maintain contact with the track when travelling between 300-400 kmh^{-1}(185-249 mh^{-1}). In fact, the 2016 Mercedes W07 recorded an acceleration of 0 to 100kmh^{-1} in approximately 2.4 seconds(27.8ms^{-2} or 3g). In addition, Formula One cars display an average breaking force of 5g while braking, 2g when accelerating and up to 6g when cornering. Now I would think that at this rate of acceleration (not to mention changes in gradient over the track) would cause turbulence under the body of the car and cause a reaction force which would contribute to lift. As i'm sure you are aware, F1 cars tend to stay close to the track and lift is rarely observed.

I wish to understand why formula one cars are capable of staying in contact with the track. I also wish to create my own computational and physical model for this problem to help illustrate the effect of aerodynamic design on the fundamental aerodynamics forces (lift, downforce, drag). I will model this with a foam polyethene aerofoil. The aim of my project is to optimize a rear wing aerofoil and to model the effect on lift, drag and downforce using a physical model as well as a Computational Fluid Dynamics software package.

My idea came to me while watching the 2018 Monaco Grand Prix. I drew resemblances between vehicles moving at extremely high speeds and their subsequent interaction with the air around them. I was fascinated to see that despite the velocity of the car, there was little skid when turning, accelerating and decelerating around bends. Also, the car appeared to stick to the track and air resistance appeared to have little noticeable effect on velocity. From this interest, I wanted to find out more and understand how F1 cars move so quickly through air and appear to stick to the track reducing lift and drag.

2 Aerofoils

The forces present when an object is moved through a fluid can be modelled most simply with an aerofoil. An aerofoil is a term used to describe the cross-sectional shape of on object that is moved through a fluid. The following diagram outlines the features of a cambered aerofoil:

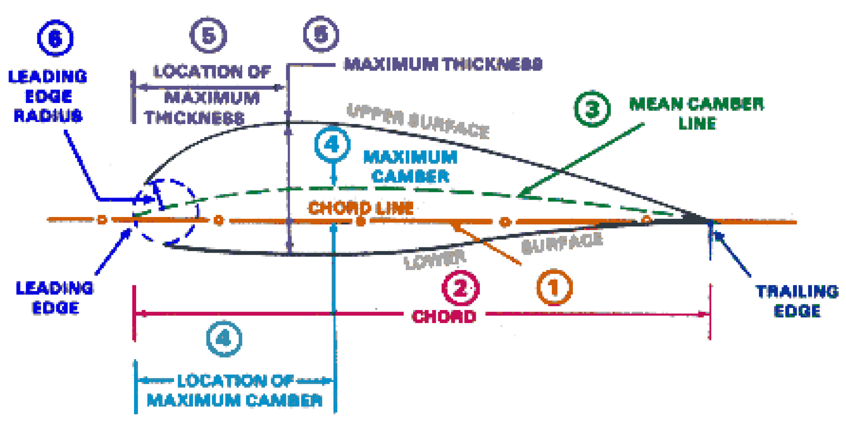


Figure 1: Features of a cambered aerofoil

We can define the features in the diagram:

- Leading edge = Forward edge of the aerofoil
- Trailing Edge = End point/ edge of the aerofoil
- Chord Line = Line drawn from leading and trailing edge. *The chord line cuts the aerofoil into the upper and lower surface of the cross section*
- Mean Camber Line = A line drawn equidistant (equal distance at all points on the line) from the upper and lower surfaces.
- Point of Maximum thickness = Thickest part of the wing (commonly expressed as a percentage of the chord line)
- Boundary Layer = A thin layer of stationary air in contact with the object.

Lift

Lift is a vector quantity. It has a direction opposite to the weight of an object and a magnitude of Force (N). Lift is generated over the entire body however it is modelled as acting through the centre of pressure and is perpendicular to the air flow. Lift is generated by the interaction between a solid and a fluid. This means if there is no fluid there will be no lift. Lift is dependent on the movement of a solid body in a fluid.

Lift is generated by two effects:

- Newton's Third Law
- Bernoilli Principle

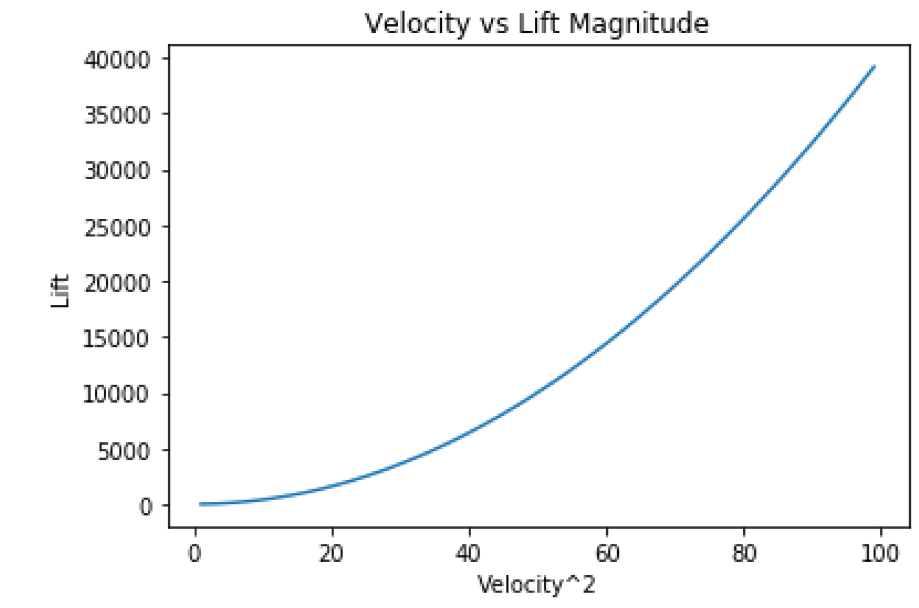
The equation for lift can be expressed as:

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

From this equation we can deduce that:

$$L \infty V^2$$
$$L = kV^2$$

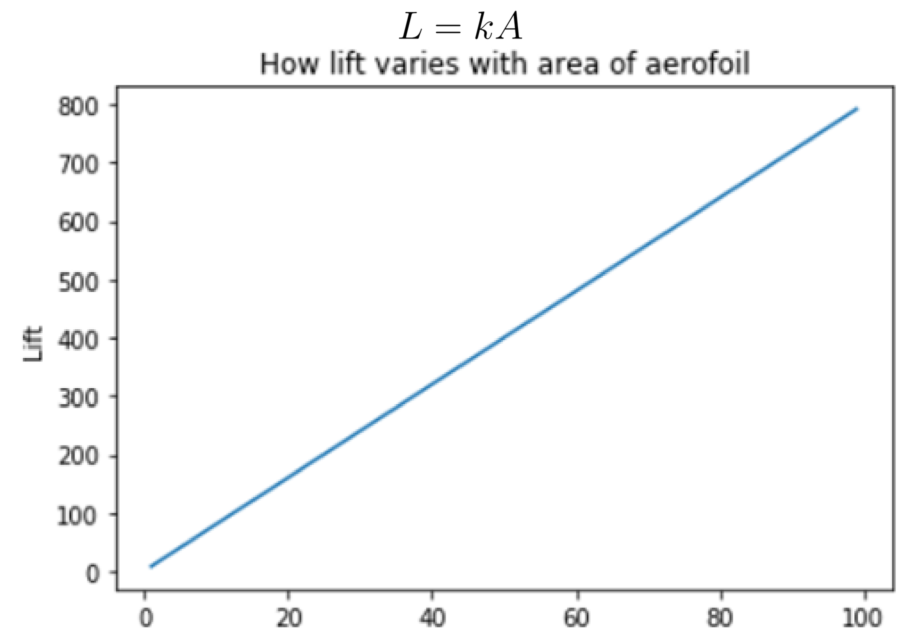
We are able to model this relationship as a simple quadratic to predict values of lift based on the velocity of the object.



We should note that lift is also proportional to the area, and density of the fluid the aerofoil is moving through. I have specifically chosen to investigate the relationship between area and lift.

From the equation, we can also investigate the relationship between lift and the area of the aerofoil.

$$L \infty A$$
$$L = kA$$



3 Explaining Downforce

In the application of a Formula One rear wing, the most important aerodynamic force is downforce. From the research I have conducted I believe downforce is essentially lift in the opposite direction and can be modelled with the same equation as lift. The most recent application of the rear wing is it's involvement in the Drag Reduction System (DRS).

Bernoilli Effect

The Bernoulli Effect is a principle that explains downforce. Due to shape of an aerofoil the velocity of air on the top is greater than the velocity on the bottom of the wing. This means that the pressure on the top side of the wing is greater than the standard atmospheric pressure on the down side of the wing. This means more particles of air are exerting a force up on the wing than down on the wing, thus causing the wing to lift. The pressure difference produces lift, however there are other factors which provide a greater contribution to the total lift such as the angle of attack.

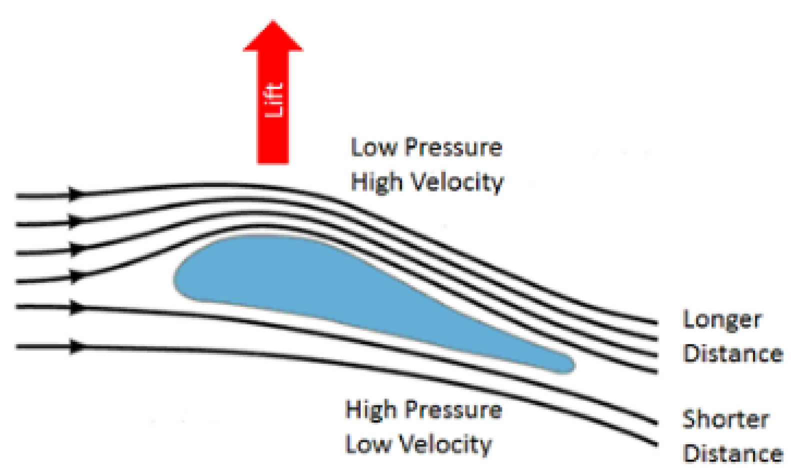


Figure 2: Aerodynamic lift explained by Bernoulli's effect

Newton's Third Law

For the reaction force to occur there must be a difference in velocity before and after the fluid impacts the aerofoil.

$$\delta V \equiv \text{u-v}$$
$$I = mv - mu$$
$$u \neq v$$
$$Hence, mv - mu \neq 0$$
$$I = \frac{F}{t}$$

$\therefore$ Impulse $\neq 0$ so force occurs

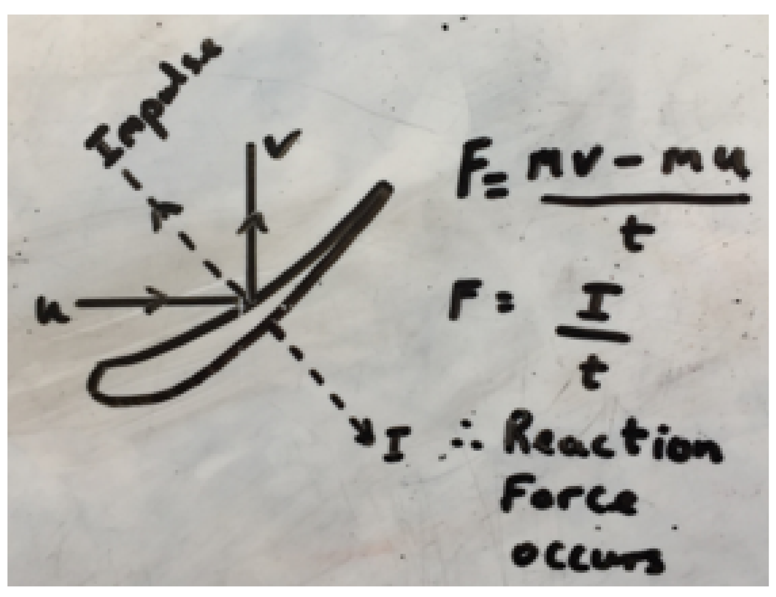


Figure 3: Explanation of Newton's Third Law and lift

As explained above, the two concepts which explain downforce are the Bernoulli effect and Newton's Third Law. However it is understood that the pressure difference resulting in the Bernoulli effect only contributes to approximately 1% of the total lift. Newton's third law and the concept of Impulse is by far the greatest cause of downforce. This is the main reason why the angle of attack of the aerofoil is so important in generating downforce. The angle of attack is the 'the angle between the line of the chord of an aerofoil and the relative airflow'. It is accepted that the angle of attack is the single greatest factor which affects downforce.

4 Designing an aerofoil

Material

It is common for carbon fibre to be used to produce aerofoils and other structures in motorsport. Carbon fibres hold useful properties such as high stiffness, tensile strength, low weight, and low thermal expansion. In addition carbon fibre sheets can be moulded to complex structures and can be set in an autoclave to create a rigid carbon fibre structure. The moulding and setting of the carbon fibre allows manufacturers in the motorsport industry to produce a structure with a very high tensile strength with a low density and at a relatively low cost.

For the creation of my rear car wing, I aim to buy materials on a minimum budget. The car wing was moulded with a laminate surface material. The wing is formed from a mixture of isocyanate and polyol resin which react to form a type of expanding foam that forms a solid material that can be sanded and cut. I also used a wooden pallet to compress the wing shape and a wooden brace to maintain the maximum line of camber.

I have analysed different materials which I may use for my wing. My rear car wing material must have the following properties.

- Low Density
- High Tensile strength
- High Young Modulus

Material	Density Kg/m^3	Young Modulus GPa	Tensile Strength MPa
Graphene	2267	1034	13000
Carbon Fibre (0 degrees rotation)	1800	228	600
Steel	8050	200	370
Portland Concrete	2400	17	2.8

Figure 4: Properties of possible aerofoil materials

Manufacturing

For my project I have designed and manufactured a symmetrical, cambered and flat-bottomed aerofoil.The aerofoil is made from a polyurethane foam. Useful properties of Polyurethane include: high rigidity, low density (lightweight), high tensile and compressive strength. Due to a lack of rigidity in the mould the aerofoil took a symmetrical shape. The intended shape for the aerofoil was a cambered aerofoil, as documented in figure 1. I struggled to achieve the intended shape for the aerofoils due to the expanding nature of the foam.

The manufacturing process for making the aerofoil was a costly and time consuming process. The process includes cutting and shaping the mould, filling the mould with the Polyurethane spray and cutting/sanding the foam wing. I was able to produce a cambered, symmetrical and flat-bottomed aerofoil.

Figure 5: Manufacturing the aerofoil

5 Results

Figure 6: Symmetrical aerofoil

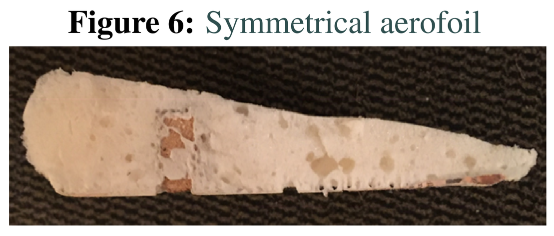


Figure 7: Flat-bottomed aerofoil

Figure 8: Cambered aerofoil

My project culminated in successfully manufacturing three aerofoils. Unfortunately due to time constraints I have not been able to test the aerofoils for their respective components of downforce and drag. Despite exploring the Computational Fluid Dynamics software package Simflow, I have been unsuccessful in modelling my aerofoils due to the complexity of the software.

6 Conclusions

In conclusion, I have gained a thorough and in depth understanding of aerofoils and the concepts explaining downforce. I have been able to model the lift equation and explain the key principles which contribute to downforce. Also I have successfully designed and manufactured an aeofoil . If I could repeat this project I would test my aerofoils in a wind tunnel, to see if my results match the model equation. In addition, I would use a CFD to model my aerofoils and CAD software such as SolidWorks so I could record the exact geometric properties of the aerofoil(camber, chord length, total area). I believe I have learned valuable skills such as organization and programming. Most importantly, I have been able to further my understanding in an area of physics and engineering.

References

- Figure 1-http://aviationknowledge .wikidom /aviation:aerofoil
- Figure 2-https://www.mpoweruk.com/flight$_{t}heory.htm$
- https://www.grc.nasa.gov/www/k-12/airplane/drag1.html
- *Please see report for full reference list*