



School of Engineering

Designing the structural support for a front automotive wing for a new race series

Stress Analysis and Dynamics (ACMA5010)

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1 Introduction

A wing of a race car was initially designed by Michael May, in the 1950's to provide vertical downforce in an effort to mitigate the risk of the small, lightweight and aerodynamically flawed car of that period, from lifting off the ground during high speeds. The concept was rejected by the governing body of the time, following complaints from other drivers that the mid-chassis mounted wing obstructed their view (Fuller, 1996).

The full potential of an inverted wing's effect on shortening a race cars lap time wasn't realised until the mid-1960's, when Jim Hall engineered the 'Chaparral-Chevrolet 2E', a race car with a high rear wing which created downforce. It was recognised that the fixed wing of the '2E' when setup to minimise drag on a straight, insufficient downforce was present to corner effectively, Hall's 'Chaparral-Chevrolet 2F' removed this problem by engineering the wing to adjust it's attack angle to coincide with adjustment the driver made to the throttle pedal (David, 2009).

Recognising the advantages the rear wing gave the 'Chaparral-Chevrolet 2F', Colin Chapman of Lotus introduced a simple fixed rear wing to his Lotus 49, knowing that downforce needed to be distributed, he also introduced winglets to the nose of the car. The Lotus 49B with its rear and front wing's won the 1968 Monaco Grand Prix by six-tenths of a second (Fagnan, 2018).

Colin Chapman's design of the Lotus 49B single element wing created downforce over the front axle of the car which increased traction and improved handling while cornering. However, the evolution of front wing since the 1960's has seen it become one of the most important aerodynamic elements of a modern race car (Giuliana, 2020). The modern front wing is responsible for redistributing downforce over the front and rear tyres; Direct the airflow to the underfloor and rear diffuser; re-direct the flow of air away from the front wheels, avoiding downstream turbulence (TOTALSIM, 2022). This has been achieved through the evolution of a multi-element design that incorporates; turning vanes; endplates; flaps which require a material with a high strength-weight ratio which is why carbon fibre is used for their construction (McLaren, 2022).

This report will calculate the maximum aerodynamic force (to be known further more as downforce), applied to a race cars front wing – specified in the design brief as a single element with endplate design - during its maximum level of speed. An understanding of 'Bernoulli's principle' will be sought to further analyse downforce and its required variables such as; air density; wing surface; surface dimensions.

During maximum velocity a front wing of a race car will be expected to bear the load applied by the downforce. Analysis of the distribution of the load across the front wing's surface and the points at which the load will be supported, will determine the dimensions of its supporting structure. Bending

beam theory will be used to calculate the minimum diameter of the support structure required to prevent the hollow circular cross-section of the support from deflecting more than 10 mm.

2 Methodology

Downforce applied to the front wing of a race car will be subject to the air pressure differential between the top and bottom side of its surfaces (Rastogi, et al., 2017). The differential is created by the front wings profile; its ‘angle of attack’; its mounted height from the ground (Porcar, et al., 2021). A front wings profile is design in such a way that it’s upper side is relatively flat in comparison with the curved underside, this allows for the air to flow close to its surface, as illustrated by the blue arrows in Figure 1. The curved underside of the wing creates a low pressure region, this draws the air faster around the surface and is illustrated by the green arrows in Figure 1.

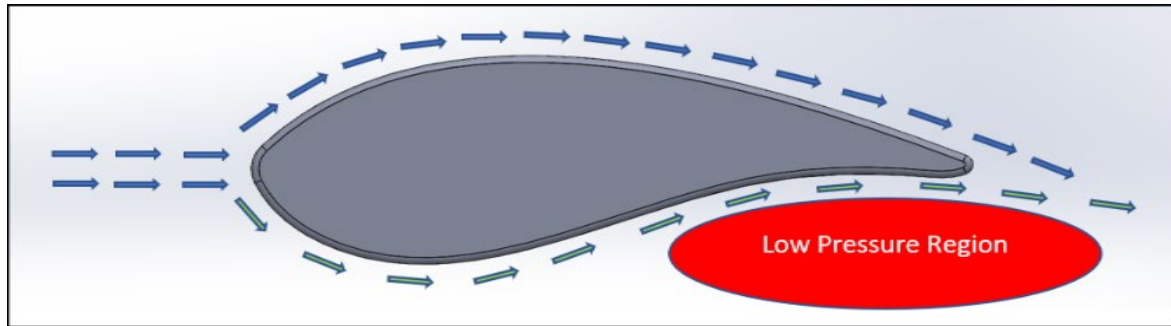


Figure 1 Air flow across the profile of an aerofoil (Walden, 2021)

The increased air flow beneath the wing causes the air pressure to decrease, Hewitt (2014), writes that this phenomenon is in accordance with ‘Bernoulli’s principal’ which describes the pressure characteristics of a fluid as low when, it’s velocity is low and high when it’s velocity is high. Therefore, the difference between the airflow velocity on the upper and lower surfaces of the wing will create a pressure differential, the net resultant pressure will determine the direction of the force applied.

Bernoulli’s fluid flow equation can be manipulated and used to quantify the downforce (F_d) applied with known variables that include; Air density (ρ); surface area (A); Velocity of airflow on the upper surface of the aerofoil (V_1); Velocity of airflow on the surface beneath the aerofoil (V_2) (Tutor, 2017).

$$F_d = \frac{1}{2} \rho A [V_2^2 - V_1^2]$$

Equation 1

However, for this study model it would be difficult to determine the velocity above and below the front wing because of unknown geometrical parameters such as; the curvature of both surfaces; the leading edge radius; the trailing edge exit angle (Molinari, et al., 2011).

In contrast to Tutor (2017), Fricke & Hogg (2010) state that the force imposed on the front of a race car can be calculate with the formula below with tabulated values hence, this method shall be used to calculate downforce as oppose to the former.

$$\text{Front Lift Force (L}_f\text{)} = \text{Dynamic Air Pressure}(q) \times \text{Front Area}(A) \times \text{Lift Coefficient}(C_{L_f})$$

Equation 2

Dynamic air pressure (q) will be calculated with the formula used by Hall (2021), which is stated below.

$$q = \frac{1}{2} \rho u^2$$

Equation 3

It will be assumed that air density (ρ) will be “a worst case scenario” and taken from an adverse racing condition that has a temperature of 5°C which will equate to a value of 1.268 Kg/m³ (Toolbox, 2022). The wind speed (u), will be the combination of an ambient wind speed of 12m/s (Bitesize, 2022) and 110 m/s which is the maximum speed of a formula 1 race car (Duxbury, 2020).

The front area (A) of the wing shall be determined in accordance with the design of a single element wing specified in the report brief, and will 0.225 m². The lift Coefficient used for this report is a tabulated value that corresponds to the surface area of the wing specified in this report and shall be - 0.204 (Agrewale, et al., 2019).

Bending beam theory will be used to calculate the deflection of the front wing at the end of the ‘X’ axis . Figure 2 shows the front and side view of the wing. Each front wing will be fixed to the nose of the race car by securing the tubular section that protrudes from its profile. It can be assumed that the tubular section extends the full width of the aerofoil therefore, Jones (1990), would describe it as a ‘cantilever beam’ which, for this report will support the downforce applied to the surface of the wing.

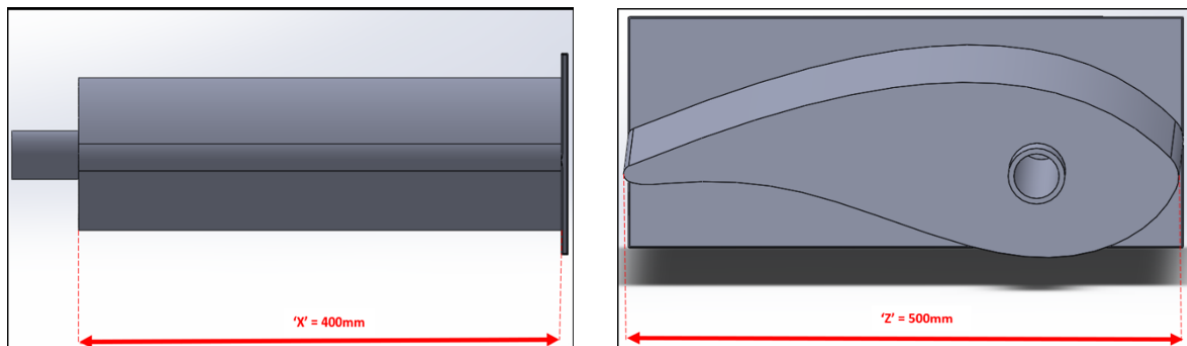


Figure 2 Dimension of aerofoil in 'X' and 'Z' direction

As suggested by Mokhtar & Lane (2008), an aerodynamic force shall be assumed to be consistent across a rectangular surface area of a single element aerofoil. The deflection formula (below), which

has been taken from Gere (2001), can be used for a ‘cantilever beam’ with consideration to an applied uniformly distributed load. To calculate the deflection at the free end of a cantilever beam (δ_B), variables such as; force applied (q); length of beam (L); Young’s Modulus (E); second moment of area (I) will need to be determined.

$$\delta_B = \frac{qL^4}{8EI}$$

Equation 4

The formula below shows a transposition of the deflection formula so that the ‘second moment of area’ (I) can be solved.

$$I = \frac{qL^4}{8E\delta_B}$$

Equation 5

The second moment of area (I) will be used to determine the diameter of the tube required to construct the cantilever beam that will need to support the force applied to the aerofoil without it deflecting >10 mm.

The second moment of area (I) will be evaluated in regard to the standard formula for the second moment of inertia for a circle.

$$I = \frac{\pi D^4}{64}$$

Equation 6

The principal of superposition will then be used to calculate ‘ I ’ for a hollow tube. The principal will consider the second moment of area (I) of a second circle that has a small diameter of which, shall then be subtracted from the larger circle.

$$I = \frac{\pi}{64} (D^4 - d^4)$$

Equation 7

An excel spreadsheet shall be produced to calculate the second moment of area (I), when the outer diameter of the hollow beam varies in increments of 1mm between 5 mm – 20 mm. If an incremental change in diameter results in the second moment of area (I) surpassing the calculated minimum value in Equation 5 then, the associated outer diameter will be sufficient to avoid a deflection of >10 mm to the wing.

3 Results

The lift force of each race car front wing, which have the previously stated assumed values can be determined as follows.

$$\text{Front Lift Force (Lf)} = \text{Dynamic Air Pressure}(q) \times \text{Front Area}(A) \times \text{Lift Coefficient}(CL_f)$$

Therefore,

$$L_f = \left(\frac{1}{2}\rho U^2\right) A C L_f$$

$$L_f = \left(\frac{1}{2} \times 1.268 \times 122^2\right) \times 0.225 \times -0.204$$

$$L_f = -433.13 \text{ Newtons}$$

The minimum second moment of inertia (I) that will prevent the cantilever support from deflecting >10 mm is determined as follows.

$$I = \frac{qL^4}{8E\delta_B}$$

$$I = \frac{-433.13 \times 0.4^4}{8 \times (210 \times 10^9) \times 0.01}$$

$$I = -6.60 \times 10^{-10}$$

The Cross-sectional area of the cantilever beam supporting the force of which, would be applied to the front wing of the race car will be circular. The outer diameter of the beam can be calculated as below.

$$I = \frac{\pi}{64} (D^4 - d^4)$$

$$I = \frac{\pi}{64} (0.005^4 - 0.001^4)$$

$$I = \frac{\pi}{64} \times (1.504 \times 10^{-12})$$

$$I = 7.38 \times 10^{-14}$$

The calculation above, shows that the second moment of inertia for a cylindrical beam with an outer diameter of 0.005 m and is less than the minimal value required to mitigate a deflection of >10 mm to the beam.

To expedite the process of calculating the minimum beam diameter Table 1 shows the above equation applied to multiply incremental changes to the cross-sectional diameter of the beam. The highlighted row on Table 1 shows the value for the second moment of area (I) for the beam with an outer diameter of 12 mm of which, exceeds the value calculated from Equation 5 therefore, will not deflect more than 10 mm.

Table 1 Calculation of the Second moment of inertia for various instances of outer diameter's

Outer Diameter (m)	Outer Diameter (mm)	Inner Diameter (mm)	Second Moment of Inertia
5	0.005	0.001	3.06E-11
6	0.006	0.002	6.28E-11
7	0.007	0.003	1.14E-10
8	0.008	0.004	1.88E-10
9	0.009	0.005	2.91E-10
10	0.01	0.006	4.27E-10
11	0.011	0.007	6.01E-10
12	0.012	0.008	8.17E-10
13	0.013	0.009	1.08E-09
14	0.014	0.01	1.39E-09
15	0.015	0.011	1.77E-09
16	0.016	0.012	2.20E-09
17	0.017	0.013	2.70E-09
18	0.018	0.014	3.27E-09
19	0.019	0.015	3.91E-09
20	0.02	0.016	4.64E-09

4 Discussion

Aerodynamic forces imposed onto the wing for this report are assumed to be evenly distributed across the span of the wing and a beam bending calculation completed accordingly. However, in practicality this would not be the case as Keogh, et al., (2015), report describes that during cornering the distribution of forces become concentrated towards the edge of the off-side wing. The report states that the reason for the redistribution of the force is because of an increase of airflow over this region of the wing which is caused by an increase in yaw angle as the race car corners. This seems likely as the race car moves from a linear to angular motion whereby, centripetal and angular acceleration is introduced. It's also likely that during braking while entering a corner the nose creeps closer to the ground which could induce the phenomenon known as 'proposing' whereby addition downforce is produced (Dictionary, 2011). However, this report assumes that the bending forces applied to the wing during the race car's top velocity when traveling in a straight line, would be greater than the forces created by the race car whilst cornering.

A single element front wing for a race will likely not be used for a formula 1 design and is more akin to a formula 4 race car. The downforce for this report assumes that the downforce applied is contributed to by the maximum velocity of a formula 1 race car whereas, if the assumption was made for a formula 4 race car, downforce would be significantly reduced, reducing the minimum value of the second moment of area (I), and therefore, reducing the cross-sectional area of the hollow circular beam required.

Based on the material specified for the construction of the structure supporting the wing (steel) it is assumed that a light weight composite would not be used to construct the remaining surface of the wing. Therefore, the weight of the wing should be taken into consideration when evaluating the uniformly distributed load applied to the support structure. Consideration should also be given to the steel endplate attached to the edge of the wing, this weight will be significant in comparison, and add a point load to the 'bending beam' calculation which would require the 'theory of superposition for combined loads' to resolve

Material used for the manufacture for a single element race wing (in particular it's surface), can affect it's resistance to the flow of air over its surface therefore, reducing the potential to create lift (or suction). Various techniques such as Teflon coatings (Hornea & Simon, 2019); covering the suction surface with scale like profiles (Domel, et al., 2018), it is assumed that these techniques have not been used for the design of the front wing for this report.

5 Conclusions

Downforce cannot be quantified solely on analysis of the front wing in isolation (Diasinos & Gatto, 2008), Cravero & Marsano (2022), writes that a decrease in lift coefficient of 52% can be observed on a front wing when in the proximity of an open shrouded rotating wheel. If the front wing for this report is not consider as a component of a system, downforce losses could not be appraised therefore, overengineering it's design.

This report uses a lift coefficient referenced from a report which assumes many variables such as; the angle of attack; shape and curvature of the upper and lower surfaces of the wing; clearance from the road; direction the race car is moving; maximum velocity. These variables must be specific to the type of race car, once quantified, an accurate design of the front wing can be made.

Computer Fluid Dynamics (CFD) should be used to model prototype design of the complete race car to analyse the flow of air and distribution of downforce (Panzariu, 2009) from this the deflection of the front wing could also be observed. After CFD test results are sufficient and a physical prototype has been manufactured and fixed to the car with the designed 'angle of attack', deflection could be monitored during race conditions with a camera (fixed to the nose of the car) which monitors a datum and the deflection of the wing. After a specified period of use the prototype should be deconstructed and analysed flaws such as stress cracks.

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