UNIVERSITY of CALIFORNIA SANTA CRUZ

WING EFFICIENCY OF RACE CARS

A Thesis Submitted In Partial Satisfaction Of the Requirements for the Degree of

> Bachelor of Science in Applied Physics

by Marcello D. Guarro May 24, 2010

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1 Motivation

This thesis discusses the measurement of key parameters of a racecar wing, as a demonstration of one of the steps that are part of the overall process of automotive aerodynamic design.

Since the dawn of the automobile in the late 19th century, humanity has seen the underlying idea take on a multitude shapes, sizes, purposes, and meanings. In its early history, the automobile was simply a machine that fulfilled the necessity of personal transport, allowing the everyday consumer to travel from point A to point B with relative ease. However, as the automobile aged, it began to grow into a machine of leisure and sport as can be seen through the introduction of the "race" car for automobile racing and the "sports" car for the everyday automotive enthusiast. By definition these two categories of cars fall under the umbrella of the "high-performance" vehicle, which according to Helmut Flegl and Michael Rauser, is a vehicle that exhibits high acceleration, deceleration and maneuverability.

A racecar by definition is a car that is designed to compete in the sport of automobile racing. In its early years automobile racing was typically a test of driver and automobile endurance but in recent times, while driver ability still has its importance, racing results have become more and more the reflection of vehicle design advancements. If one examines the results of various racing leagues, specifically those of Le Mans Prototype and Formula 1, it becomes evident that the victors within those leagues were those with the optimal racecar designs. To understand the value of a properly designed race car, it is important to first comprehend what exactly a race car is designed to do. In the most basic sense, a race car must exhibit maximum performance in the categories of acceleration, top speed, braking (deceleration), and cornering power (lateral acceleration), as these factors determine how quickly a racecar can navigate through a racetrack. When a car is pitted to compete against other vehicles in the same category of weight and engine displacement (i.e., major factors that are used to define a "race class"), other key features of its design are what determine whether it can edge out the performance of another car.

In the design of a race-car within a given class, a multitude of parameters such as vehicle weight distribution, engine power, and aerodynamics must be optimized in order to achieve maximum performance. Aerodynamics is among the most significant of these parameters, as the aerodynamic characteristics of a vehicle can dictate its strength in categories that greatly matter to automotive racing, such as top speed, lateral acceleration and stability under heavy braking. Like the aerodynamics of an airplane, the aerodynamics of race-cars is complex, requiring for development of a specific design the use of a combination of methods, similar to those used in aircraft design. These include: computational fluid dynamics modeling (CFD), wind tunnel research, and in-world vehicle testing.

A remaining question is: why is the study of race-car aerodynamics important outside of the world of automotive racing? The answer becomes evident when we begin to think of racing, in its entirety, as a researching ground for new automotive technologies. Many of the technological discoveries and developments made in the top-tier racing leagues have trickled their way into consumer vehicles, especially, but not exclusively, in the sports-car category. In the case of aerodynamics, the knowledge acquired from the racing world has led to developments in automotive design to improve high speed stability and improved cornering power at higher speeds, which has thus resulted in the development of safer vehicles.

2 Background

This section discusses the importance of wings in the overall aerodynamic design of a racecar and provides a summary of the technical and theoretical foundations of car wing design.

2.1 Race Car Wings

In the early days of race car design, the principal aerodynamic goal was to have a design that minimized drag in order to maximize top speed. Over the years, however, as racecars started to become faster and more powerful, the need for traction, or adhesive friction between the tires and road surface, during high-speed corners began to become a pressing issue. The easiest and most effective solution to this problem came in the form of wings or airfoils similar to those found on airplanes, which, however, would be now designed to generate, instead of lift, "downforce," i.e. effectively negative lift. These wings would be mounted to the chassis of a racecar to transfer the force generated to the chassis itself and through this to the car axles and wheels. This increases the downward pressure in the contact area between the tire and the road surface, thus also increasing the adhesive friction between these two surfaces. A typical racecar wing arrangement is illustrated in Fig. 1 under the labels "A" and "B", "A"



Figure 1. A Porsche 911 GT3 Racecar with front and rear wings.

It is worth noting that due to the physical constraints on the dimensions of the wings in a car, usable downforce is only generated when the racecar is traveling at high rates of speed. Due to the importance of wing in providing better traction, cornering and overall performance for racecars, much attention and research is focused on their design and implementation on the car body.

2.2 Aerodynamics of Wings

In Fig. 2 below, we have a conventional airfoil (that is, as in a airplane wing) with air moving across it from left to right as identified by the streamlines. (The streamlines represent a pictorial description of the fluid motion of the air particles in a steady-state flow.) The air that travels along the upper surface of the wing is forced upwards and becomes compressed against the air above it, which makes it flow at a higher velocity; in the region below the foil the air gets instead expanded causing it to travel at a lower velocity. Following, Bernoulli's principle, the air traveling in the upper region has a lower pressure due to its higher velocity, whereas a higher pressure is seen in the lower region due to the air lower velocity. This pressure difference acting along the surface of the wing is what generates the net upward force known as lift. This pressure difference is clearly presented by the color of the air medium in Fig. 2 below; the blue and green regions represent areas of low pressure while the orange and red areas represent regions of high pressure.

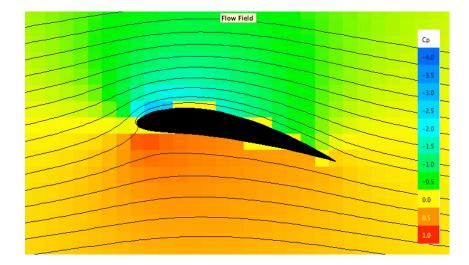


Figure 2. Profile of a conventional wing traveling through air.

In order to produce negative lift, or downforce, for race cars, the wing is simply inverted, so that the air traveling along the upper surface is slower than the air traveling along the lower surface, thus reversing the pressure difference and creating a net downward force.

The net lift or downforce, depending on orientation, of an airfoil is described nondimensionally by equation 2.1 below:

$$L = \frac{1}{2}\rho v^2 A C_L \tag{2.1}$$

where ρ is the air density, ν is the flow velocity, A is the span area of the wing also known as the planform area, and C_L is the lift coefficient.

Airfoils also experience a drag force that acts in the opposing direction of the moving airfoil in the horizontal plane. The drag is a result of the tangential stress (frictional drag) and the pressure distributions that are normal to the surface of the wing (pressure drag). This force can also be expressed non-dimensionally, according to equation 2.2 below:

$$D = \frac{1}{2}\rho v^2 A C_D \tag{2.2}$$

In both equations there is an independent coefficient, C_L and C_F respectively, that is entirely dependent upon the dimensional parameters of an airfoil, including shape, size and orientation, and also upon the descriptive parameters, Mach and Reynolds numbers, of the flow in which it is placed. For a particular wing profile, these coefficients can either be determined experimentally via wind tunnel testing or through complicated numerical computation of the wing profile flow circulation. Calculating these coefficients numerically requires laborious implementation of several theories including: irrotational flow theory, the Kutta-Zhukhovski lift theorem, thin airfoil theory, and the lifting line theory of Prandtl and Lanchester. The derivation of the coefficients using theses theories is discussed in detail in Chapter 15 of *Fluid Mechanics* 4th ed. By Kundu and Cohen.

As mentioned for the equations of lift and drag, much of their value is dependent upon the geometry and orientation of the object in question when moving through a flow. In the case of wings, the lift coefficient can be altered drastically based solely on its orientation with respect to the oncoming flow. This value that describes wing orientation is called the *angle of attack* (α) and more specifically, it describes the angle between the chord line of a wing and the direction of the oncoming flow. A pictorial description can be found in Fig. 3 below.

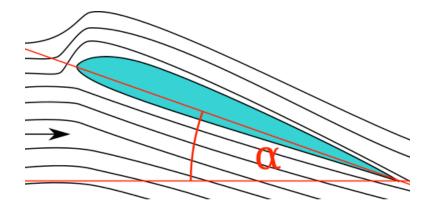


Figure 3. Diagram describing angle of attack.

This parameter is important because the lift coefficient can increase with increasing angle of attack until a maximum lift coefficient is reached. This value is important for race car engineers as they can fine tune how much downforce a race car needs for a particular track.

The Mach and Reynolds numbers are parameters that define the physical nature of a particular flow. The Mach number is a non-dimensional quantity that is simply defined as the ratio of the flow speed to the speed of sound in a particular medium (equation 2.3).

$$M = \frac{v_s}{u} \tag{2.3}$$

In the equation, V_s represents the flow velocity and u represents the speed of sound within a given medium. The value of the Mach number is important because it describes the compressibility effects of a particular flow at some velocity; flows with a high Mach number have higher compressibility effects than flows with a lower Mach number. Since an airfoil compresses the air moving across it in order to generate lift, the compressibility effects of a particular flow affect the values of the drag and lift coefficients.

The Reynolds number is another dimensionless quantity that represents the ratio between the inertial forces to viscous forces (equation 2.4).

$$Re = \frac{\rho V L}{\mu} \tag{2.4}$$

The equation is derived from the equation for the conservation of momentum for a fluid. The terms in the numerator (where ρ is the fluid density, *V* is the flow velocity, and *L* is the length of the object moving through the flow) signify the inertial forces, while the viscous forces are represented by the viscosity coefficient μ in the denominator. In more generic terms, the Reynolds describes whether the flow is laminar or turbulent. More specifically lower values of the Reynolds number characterize a flow as laminar, higher as turbulent, with the value that separates one regime from the other depending on the particular geometry of the situation being considered. The Reynolds number, like the Mach number, needs to be taken into account in wing design, due the effect that the viscous forces have on the lift and drag of a wing. Since both the Reynolds and Mach number describe key characteristics of a particular flow, their values need to be taken into account during the design and testing of a wing in order to ensure proper modeling of the wing in relation to real world race conditions.

One important detail to note about the Reynolds number is in regards to the length term L. Since the Reynolds number describes the conditions of a flow for a given Mach number, one can use the Reynolds number as a scaling factor. This allows an aerodynamics analyst to adjust any combination of the length, viscosity, density, or flow velocity parameters of a particular model to make the Reynolds number the same as for the real word condition the model is intended to simulate. This is an attractive quality as it allows for the aerodynamic testing and experimentation of a design to be conducted on smaller scale models, which in turn makes possible the use of smaller and more cost efficient wind tunnels.

2.3 Research Goals

The focus of my research is on the measurement of the basic aerodynamic parameters characterizing the design of a race car rear wing element. For my project, I constructed a 1:2 scale model of a conventional multi-element rear wing and measured its aerodynamic efficiency and performance using an open circuit wind tunnel. The data collected from my research should provide indications of how viable and useful a small-scale model like the one I constructed may be for race car aerodynamic design and development.

A complementary objective is to investigate whether the values of the aerodynamic parameters measured in my model and experimental set-up can be predicted with a computational model.

3 Methods and Apparatus

3.1 Wing Design and Construction

The profile of the wing used for my research follows a design provided by Mr. Darius Rudis.⁷ This profile is shown in Fig. 4 below:

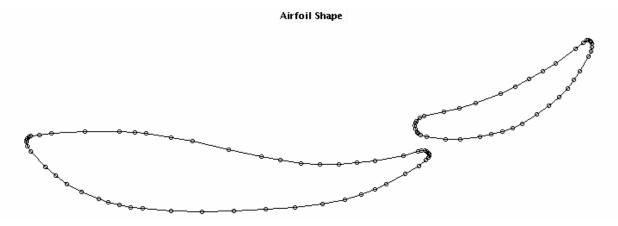


Figure 4. Profile of the wing in consideration for research.

As can be seen, the wing differs from the design of a traditional wing as presented in Fig. 2, in that it uses a multi-element design. Multi-element wings produce far more lift or downforce than a conventional single-element design. By separating the two elements, the effective range of angle of attack is increased leading to increased maximum lift or downforce.¹ The disadvantage of such a design, however, is an increase in drag. In race cars the increase in drag force can be countered with increased engine power output. Although this may seem to result in an overall disadvange, other reasons including flexibility of adjustment and more compact dimensions for same ability to generate downforce with respect to single-element wings make multi-element design to be preferred by many

¹ Katz Joseph. p.130

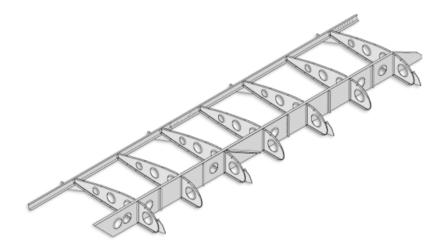
racecar designers. It is worth mentioning that Mr. Rudis developed this wing for use in his 1991 Mustang race car, as can be seen in Fig. 5.



Figure 5. Mr. Darius Rudis 1991 Mustang race car with attached rear wing.

In order to conduct research on this wing design in the small wind tunnel of the UCSC Physics Department, I needed to first construct a small-scale model of the wing. To execute this at the desired level of fidelity, I set out to reproduce in 1 : 2 scale the geometric parameters of the wing profile following the build methods of model aircraft wings.

In conventional wing construction, the wing is put together by a series of *ribs* evenly spaced from one another that run the length of the wing; the ribs are held together by *spars* that run the width of the wing as shown in Fig. 6 below.



Once this framework is set up, the wing is then sheeted with a thin, light, and rigid material, thus resulting in the final product.

In order to maintain design accuracy it was decided that the ribs needed to be cut by a Computed Numerically Controlled (CNC) machining apparatus, as such a machine can easily produce the number of ribs required for construction with good precision and no variability in rib to rib execution. This required the creation of a Computer-Aided-Design (CAD) blueprint of the wing profile for the CNC machine to follow. To do this, I used the CAD software SolidWorks, as requested by my machinist, and reproduced in this software environment the profile design supplied by Mr. Rudis. The CAD blueprint created in this fashion is shown in Fig. 7 below.

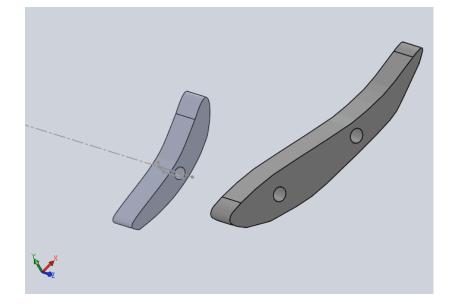


Figure 7. CAD blueprint of the two wing profiles.

The CAD blueprint was then sent to a machinist where 8 ribs of each element were cut out of aircraft grade aluminum. The ribs were then attached to spars as displayed in Fig. 8 below.



Figure 8. Wing ribs attached to the wing spars.

Once the ribs were attached securely to the spars, the wing elements were sheeted with rigid plastic as displayed in Fig. 9.



Figure 9. Wing element sheeted with rigid plastic.

Finally, once the two elements were completed, they were attached to a set of end plates, also forcefitting protruding portions of the spars into matching holes drilled in the plates, to achieve maximum robustness. This resulted in the final multi-element wing shown in Fig. 10.

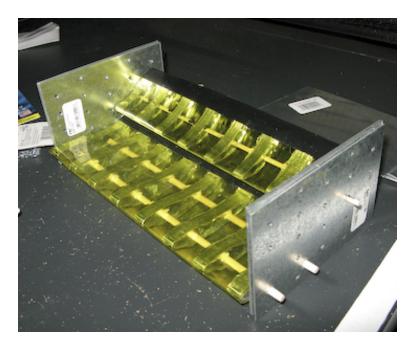


Figure 10. Final multi-element wing.

In addition to the wing itself, a special set-up and measurement apparatus was also designed and constructed, to secure the wing to the wind-tunnel during the tests to be conducted, in a fashion that would permit the desired measurements to be obtained without unwanted distortion or perturbation effects. This is presented and discussed in Section 3.3.1 below.

3.2 Wind Tunnel

The wind tunnel used to test the wing follows an open-circuit design. It has, a max flow speed of 20.11 m/s (45 mph), a compression ratio no greater than 2:1, and a test chamber with dimensions 25.4 cm x 40.64 cm x 30.48 cm. The wind tunnel was designed and constructed by Mr. David Dawson, a former UCSC physics student, as part of his senior thesis $project^2$.

² David Dawson "Wind Tunnel Thesis", UCSC Department of Physics 2007.

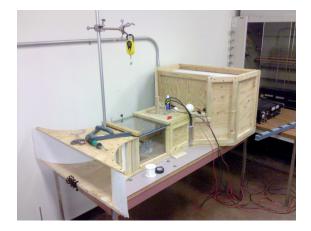


Figure 11. Open circuit wind tunnel.

The flow in the wind tunnel is provided by two 15" electric fans flowing 5500 CFM of air, which are powered by two Sorensen DCR 40-25B power supplies made by the Raytheon Company. Further details on the wind tunnel's design and construction can be found in Mr. David Dawson's thesis.

The design of the wind tunnel permits the measurements of the basic parameters of interest for the research discussed here, that is: downforce, drag, and flow velocity.

3.3 Measuring Apparatus

In order to measure the three parameters outlined in section 3.2 (downforce, drag, and flow velocity), a specific set-up had to be designed and constructed. As mentioned earlier, the objective of such a set-up was to secure the wing assembly to the wind-tunnel, in a fashion that would provide sufficient stability to permit the measurements to be executed without introducing undue distortions in the measurements themselves. The overall set-up system is described below in Section 3.3.1. The individual configurations used for the flow velocity, downforce, and drag measurements are discussed, respectively, in Sections 3.3.2, 3.3.3 and 3.3.4.

3.3.1 Set-up Apparatus

The functions of the set-up apparatus can be summarized as follows:

- A. Allowing the wing to be orientated over a range of angles of attack with respect to the horizontal wind-tunnel airflow, and to be securely locked at any of these angles during a set of measurements.
- B. Securing the wing assembly to the wind-tunnel structure in a way that permits movement in the direction of the force component to be measured, so that the measurement can be taken using a typical scale that registers force based on the induced displacement in a calibrated elastic device.

Figures 12, 13 and 14 illustrate the set-up designed and constructed to achieve the above objectives. In particular, Fig. 12 shows how two outer plates, one on either side, have been added between the wing and the tunnel. At the center of each plate is a hole through which a pivot-bolt screwed into the corresponding wing end-plate can be inserted. A wing-nut is applied at the other end of the bolt, after it goes through the outer plate hole, to tighten the wing end-plate and the outer plate together and lock the wing at any desired angle of relative rotation with respect to the outer plate(s). This is of course implemented at both end sides of the wing and achieves objective A from above.

Objective B is achieved by using rigid metal bars attached to the wind-tunnel walls as directional guides that permit movement of the wing:

1. in the vertical direction only, for down-force measurement, or

2. in the horizontal / wind-tunnel flow direction only, for drag-force measurement.

The guide system is designed as to not permit:

• movement of the wing in both the vertical and horizontal direction at the same time;

• rotation of the wing while subject to the airflow action during a measurement.

Figure 13 shows the system of two vertical bars and corresponding eyelets attached to each of the two outer plates placed between the wing end-plates and the tunnel walls. The eyelets can slide up or down on the bars. This set-up is used when the objective is to permit vertical movement for measurement of down-force (see Section 3.3.3 below).

Figure 14 shows the system of one horizontal bar and two corresponding eyelets attached to each of the two outer plates placed between the wing end-plates and the tunnel walls. The eyelets can slide horizontally on the bars. This alternative set-up is used when the objective is to permit horizontal movement for measurement of drag (see Section 3.3.4 below).

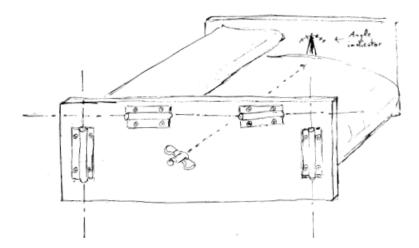


Figure 12. Outer plate apparatus for varying wing angle-of-attack

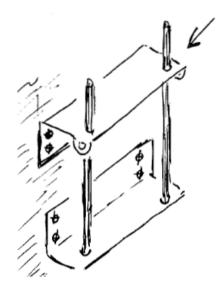


Figure 13. Outer plate eyelets and vertical slide-bar system

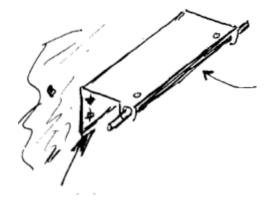


Figure 14. Outer plate eyelets and horizontal slide-bar system

3.3.2 Flow Velocity Measurement

Flow velocity is the easiest to measure of the three parameters of interest. Its measurement can be obtained by means of a Pitot tube with an attached flow meter (Fig. 15), which will compare the dynamic pressure of the flow in the wind tunnel with the static pressure and use the pressure differential to derive the flow velocity by way of Bernoulli's principle. Below is a summary derivation of the flow measurement using the simplified Bernoulli equation (total pressure is equal to static pressure plus the dynamic pressure):

$$p_t = p_s + q \tag{3.1}$$

where p_t is the total pressure, p_s is the static pressure, and q is the dynamic pressure as represented in equation 3.2.

$$q = \frac{\rho v^2}{2} \tag{3.2}$$

In eqn. 3.2 ρ is the air density and v is the flow velocity. By substitution in eqn. 3.1, it follows:

$$p_t = p_s + \frac{\rho v^2}{2} \tag{3.3}$$

and

$$v = \sqrt{\frac{2(p_t - p_s)}{\rho}} \tag{3.4}$$



Figure 15. Dwyer No. 460 Flow meter.

3.3.3 Downforce Measurement

To measure the down-force on the wing, a simple apparatus was set up by inserting four vertical bars (two for each side of the wing) into the outer-plate eyelets oriented for vertical sliding movement (as shown in Fig. 13). The, after the bars are attached to the tunnel walls, with clearance to permit the eyelets to slide on them freely, the the wing is attached by means of strong nylon wires to an American Weigh SR-5 digital hanging scale, as shown in Fig. 16 and 17. A detailed schematic of the apparatus is shown in Fig. 18. As the airflow generates pressure on the wing, the vertical bar system neutralizes the drag component and allows only the down-force component to be transferred by the nylon wire attached to the wing to the hanging scale (Scale A) where it is measured.

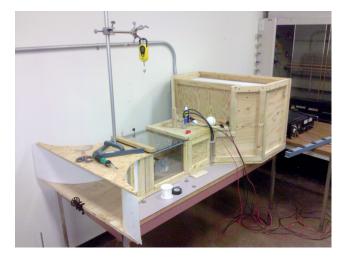


Figure 16. Wind tunnel apparatus, hanging scale in yellow.



Figure 17. Wing hanging from nylon wire inside testing section of the wind tunnel.

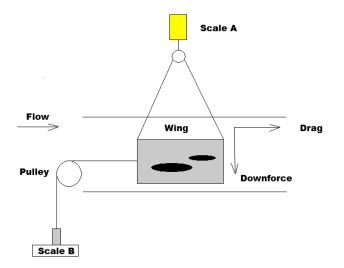


Figure 18. A schematic of the wing attached to the force measuring apparatuses.

Figure 18 also shows the portion of the measurement apparatus used for drag-force measurements (see Section 3.3.3 below)

3.3.4 Drag Force Measurement

The drag force on the wing was measured using an apparatus similar to that used to measure the down-force. In this case, however, the horizontal bars and corresponding eyelets are used instead of the vertical ones, as the objective is to guide the wing movement in the direction of the drag component of

the force. To measure this force, the front of the wing was attached to a nylon cord that runs the length of the wind tunnel and goes through a pulley placed outside of the tunnel. The cord is attached to a scale (scale B in Fig. 18) that measures the drag force. Figure 18 provides an illustration of this entire apparatus.

3.4 Computational Modeling

In order to compare the values of the wing parameters measured in the test apparatus with theoretical predictions, a computation model was used as a reference. The program used to perform the computational modeling is called *JavaFoil* and has been designed and coded by Martin Hepperle.⁸ It is a simple program, but it has the capability to perform potential flow and boundary layer analysis by solving the Navier-Stokes equations using the *panel method* for solving the former and the *integral method* for evaluating the latter. The panel method is a method for solving the potential flow of a geometry moving through a fluid by breaking down the surface area of the geometry into discrete panels and evaluating each piece separately.⁸ The integral method is a computational method of solving differential equations.⁸ Figure 19 below shows the program user interface screen.

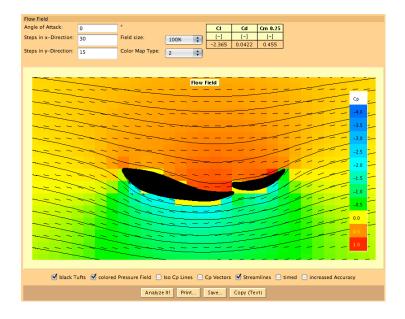


Figure 19. Screenshot of the JavaFoil applet.

4 Data Collection and Analysis

As mentioned in the previous section, the test apparatus used only permits the measurement of downforce, drag, and flow velocity. Compatibly with these limitations, the objective of my test campaign was to measure the downforce and drag on the wing for various wind tunnel flow speeds and wing angles of attack, in order to calculate the corresponding coefficients, i.e.:

- the wing downforce coefficient, which is essentially defined and formulated in the same fashion as a lift coefficient (except for the fact that it acts in the opposite direction) and for this reason will in the following be referred to as C_L, and
- the wing drag coefficient C_D.

The raw data collected to calculate these variables can be found in Appendix A. Once a wing downforce or drag measurements are obtained by means of the cord and scale apparatuses described in Sections 3.3.3 and 3.3.4, the C $_{\rm L}$ and C_D coefficients can be easily calculated using eqns. 2.1 and 2.2, respectively.

It is important to note in regards to the angle of attack, that "0" angle of attack corresponds to the flow being parallel with the chord length of the wing and is where zero downforce is generated.

The part of data analysis carried out was the one concerning the wing lift coefficient (C_L) for various angles of attack. Analyzing this property permits the determination of which angle of attack (α) provides a desired amount of downforce. This is obviously an important piece of information for race teams and engineers when dialing in the specs of a race car for a certain race: some tracks with lots of tight turn and low-speed require large amounts of downforce while tracks of high-speed with few turns require a minimal amount of downforce in order to achieve the best performance in relation to the track characteristics.

Using the lift equation 2.1 from section 2, the lift coefficient was calculated for seven values of α using:

- the downforce measured,
- the air density, ρ, set to 1.2041 kg•m⁻³ in accordance to the accepted value for dry air at 20°C,
- the area of the wing, A, estimated to be $0.038 m^2$,
- and the flow velocity, set by selecting the wind-tunnel fan speed, and confirmed by the flow-meter measurement described in Section 3.3.2 to be 19.3 m/s.

The C_L values obtained in this fashion are shown in Table 1 and Figure 20. The error included in the values comes from the margin of error of the scale used to measure the downforce and the error in the Pitot tube measurement of the flow velocity.

α°	CL
0	-0.00023 ±0.0005
10	0.00909 ±0.0005
15	0.01289 ±0.0005
20	0.02084 ±0.0005
25	0.02384 ±0.0005
30	0.02418 ±0.0005
35	0.02637 ±0.0005
40	0.02418 ±0.0005

Table 1: Lift Coefficient for various angles of attack.



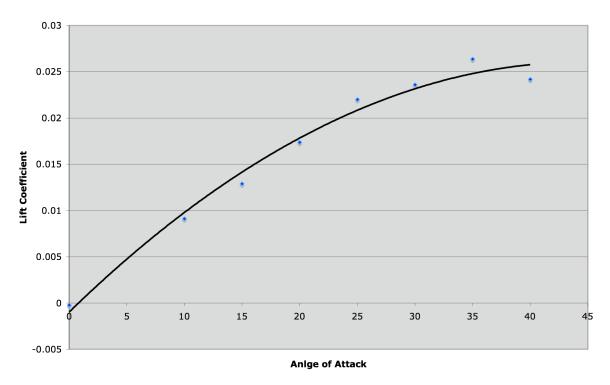


Figure 20. Lift coefficient vs. angle of attack. .

This data was then compared to the data obtained from the computational model for a wing of the same geometry and dimensions, which is shown in Table 2 and Figure 21.

$lpha^\circ$	CL		
0	0.094		
10	0.228		
15	0.529		
20	1.042		
25	1.599		
30	2.176		
35	2.895		
40	2.466		

Table 2: Lift Coefficient for various angles of attack (computational model).

Angle of Attack vs. Lift Coefficient

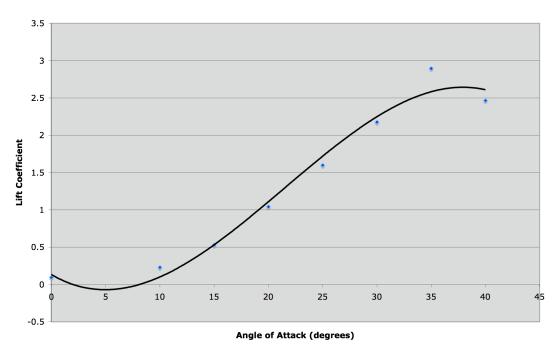


Figure 21. Lift coefficient vs. angle of attack (computational model).

It is clear from the results reported above that the measured data does not agree with the predictions of the computational model. This difference can be attributed to a variety of factors that will be discussed in the next section. In qualitative terms, it can be observed that both the test measurements and the model predictions show the greatest downforce to be achieved when the angle of attack was set to 35 degrees. This can be inferred as the *critical angle of attack* where the maximum lift coefficient occurs as the downforce begins to fall off after 35 degrees, which is evident for both the experimental and computational model. The model shows a law of variation according to some power of the angle of attack greater than unity, whereas the corresponding trend of the measured values is roughly linear in the range of values of the angle of attack covered by the set of measurements.

The second set of data analyzed was that relative to the drag coefficient (C_D) versus various angles of attack. Like the wing downforce coefficient (C_L), the drag coefficient is another important parameter for race car engineers to determine as a function of the wing angle of attack, as it allows them to determine how much extra acceleration is needed (via increased engine power or by running close gear ratios in the transmission) to overcome a certain drag force, which is produced as an unfavorable byproduct of setting the car wing to obtain a given required downforce for a particular race. The drag coefficient was determined using the drag equation 2.1 from section 2, where the drag force measured for the same seven values of α was used along with the same environmental and dimensional parameters outlined in the determination of the lift coefficient. The results of this derivation are shown below in Table 3 and Figure 22.

α°	CD
0	0.00184 ±0.00005
10	0.00219 ±0.00005
15	0.00207 ±0.00005
20	0.00449 ±0.00005
25	0.00553 ±0.00005
30	0.00633 ±0.00005
35	0.00679 ±0.00005
40	0.00714 ±0.00005

Table 3: Drag Coefficient for various angles of attack



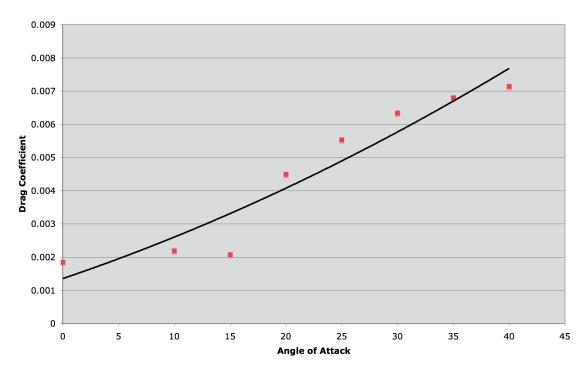


Figure 22. Drag coefficient vs. angle of attack.

This data can again be compared to the data obtained from the computational model, which is shown in Table 4 and Figure 23.

$lpha^{\circ}$	C _D		
0	0.379		
10	0.201		
15	0.121		
20	0.073		
25	0.054		
30	0.049		
35	0.057		
40	0.108		

Table 4: Drag Coefficient for various angles of attack (computational model).

Angle of Attack vs. Drag Coefficient

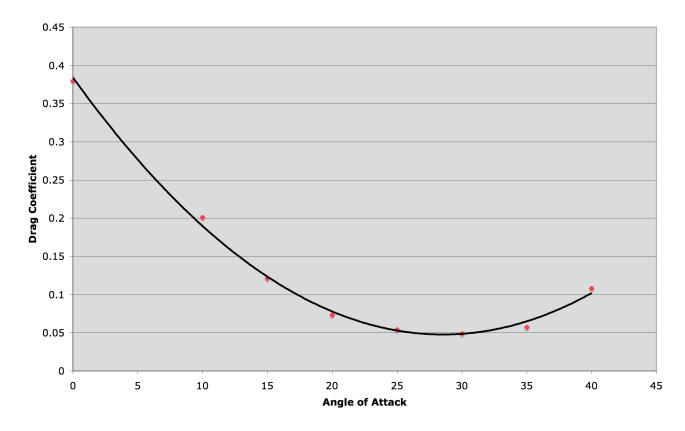


Figure 23. Drag coefficient vs. angle of attack (computational model).

Again, as can be seen from the comparison of the two sets of data, the computational model does not agree with the experimental model. In this case the trends shown by the two sets of results are in evident contradiction. In the computational model, in fact, the drag is predicted to be greatest when the angle of attack is 0, whereas the experimental measurements show the drag to be greatest at 35 degrees, the same angle at which the lift is also the greatest.

The final piece of important data is the ratio of the lift coefficient to the drag coefficient versus various angles of attack. This information determines at what angle the wing is the most efficient in terms of generating downforce without producing an exceedingly high amount of drag. The results obtained from the measuments are shown for this ration in Table 5 and Figure 24. The corresponding predictions by the computational model are shown in Table 6 and Figure 25.

α°	C _L /C _D			
0	-0.125			
10	4.158			
15	6.222			
20	3.872			
25	3.979			
30	3.727			
35	3.881			
40	3.387			

Table 5: C_L/C_D for various angles of attack.



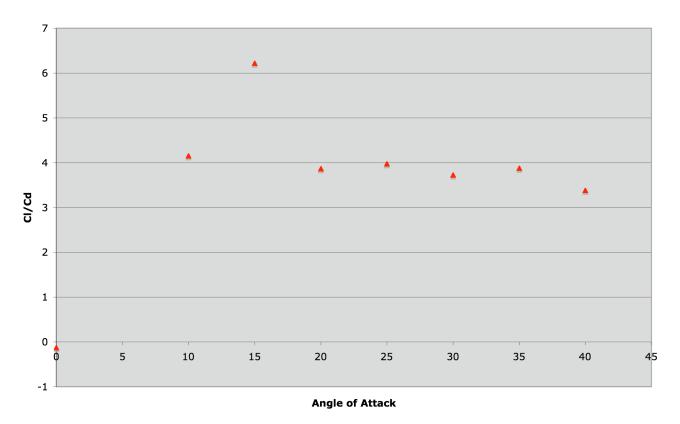


Figure 24. C_L/C_D vs.angle of attack .

Table 6: C_L/C_D for various angles of attack (computational model).

α°	C _L /C _D		
0	0.247		
10	1.134		
15	4.358		
20	14.198		
25	29.611		
30	44.408		
35	50.789		
40	22.833		



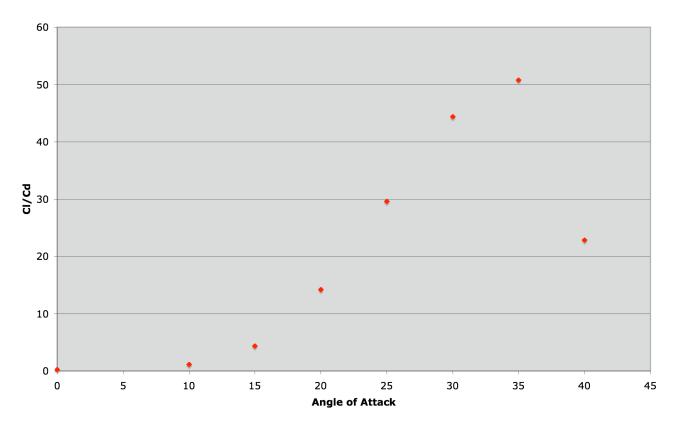


Figure 25. C_L/C_D vs.angle of attack (computational model).

As one could at this point expect, given the outcome of the earlier comparisons of the C_L and C_D values, the experimental values of the C_L/C_D ratio do not agree with those of the computational model. The experimental model tells us that the wing peak efficiency is at 15 degrees of angle of attack, while the computational model shows the highest efficiency in the range of angles considered at 35 degrees, but the trend suggests that the actual maximum would be at an even greater angle.

5 Conclusion

It can be argued that two conditions would need to be satisfied as supporting elements of proof, in order to consider the results obtained from the experiment discussed in this thesis as valid for a real car design application:

- 1. a validation of the experimental results by way of comparison with an already validated theoretical model, and
- the correct "scaling" of the experimental model set-up to reproduce the real world conditions, i.e., in terms of the physical measurements being taken, a reproduction of the Reynolds number regimes that correspond to race car conditions.

With respect to the first point, as it has already been pointed out in the preceding section, it was not possible to achieve the desired validation with the computational model at my disposal. Although some qualitative trend of the variation of the downforce (or "lift") coefficient with the wing angle of attack was confirmed, the quantitative results differed substantially. The situation was even more markedly diverging with respect to the drag coefficient calculations, which differed between experiment and computational model both in qualitative and quantitative terms. The marked differences then were, as one would expect, propagated into the calculations relative to wing efficiency.

Since the computational model used in the comparisons is an open-source piece of software that comes with very limited documentation of built in assumptions and range of validity, it is impossible to identify with certainty the possible causes of the above mentioned differences. The computational model, for example, does not use the flow velocity as an input (i.e., as an independent variable upon which the model predictions have some functional dependence). This would appear to indicate that it is to be applied in a range of flow velocity where a strong dependence of lift and drag on velocity does not exist. However the model documentation does not contain indications as to what such range may be.

Another likely cause of the observed differences may be associated with the fact that the wind tunnel apparatus used is generating turbulence in the airflow, whereas the computational model is based on an assumption of perfectly laminar flow. A turbulent flow can greatly reduce the amount of lift generated by a wing. One reason why turbulent flow may be produced in the wind tunnel is that the wind tunnel is not truly a straight-through open design, since the fans that draw air at the end of the tunnel are mounted at a 90-degree angle with respect to the test chamber. This 90-degree bend can be seen in Fig. 10 and can generate a lot of eddying that can back-propagate to the measurement section of the tunnel and produce even there substantially turbulent flow.

With respect to the second factor mentioned above, i.e., the question of model vs. actual car wing scaling, a significant issue also exists. As mentioned in Section 2, in order to transfer the results obtained from an experimental model to a real world design, the Reynolds numbers for the two models must be the same in order to ensure that the flow conditions are identical. If we apply this principle to my experimental model at 1 : 2 scale for the flow velocity of 43.7 mph (19.3 m/s) permitted by the wind tunnel, the equivalent conditions in fluid-dynamics terms would be for a full scale wing experiencing a flow velocity of 21.9 mph (9.7 m/s). It is important to note that in actuality the downforce generated by race car wings only becomes significant and effective at flow velocities greater than 80 mph (35.8 m/s). Thus, at 21.9 mph such a wing is generating very little downforce if any at all. Due to the limitations of the wind tunnel, measurements and associated analyses for flow velocities greater than 43.7 mph could not be performed. This prevented the ability to take measurements at the relevant regimes, and calculate values for the lift and drag coefficients that could be representative of actual race car conditions. It is possible that this issue is also relevant in terms of the differences with the predictions of the computational model, since it is presumable that the latter

has been designed to generate values corresponding to airflow velocities in the range of interest for actual race car conditions.

In conclusion, I believe these issues could be overcome in future experimentations if it were possible to construct and safely operate a larger wind tunnel that:

- a. would have fan power sufficient to generate flow velocities in the order of at least 100 mph;
- b. would be designed to guarantee a regime of laminar flow in the test section.

With these considerations, a high velocity laminar flow could be achieved and the results could be better compared with computational model predictions, and could also be representative of the conditions reached in actual car wing operational regimes.

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Angle of Attack	Velocity (m/s)	downforce (kg)	drag (grams)		
0	19.3	0.9	17		
		0.905	16		
		0.89	15		
		0.9	17		
		0.895	19.7		
10	19.3	0.115	18		
		0.11	17		
		0.105	20		
		0.11	18		
		0.1	17		
20	10.2	0.175	45.2		
20	19.3	0.175	45.3		
		0.195	38.6		
		0.185	37.5		
		0.17	35.1		
		0.18	39.7		
25	19.3	0.21	48.5		
	1913	0.2	46.6		
		0.22	47.8		
		0.185	49.3		
		0.22	46.3		
30	19.3	0.205	57.3		
		0.22	55.3		
		0.205	52.1		
		0.195	54.4		
		0.225	56.1		
35	19.3	0.23	61		
		0.235	57.8		
		0.225	59.1		
		0.23	57.4		
		0.225	58.4		
40	19.3	0.2	58.5		
40	15.5	0.215	63.7		
		0.205	59.1		
		0.21	64.3		
		0.21	60.2		

Appendix A Raw Data for Experimental Model

Figure 1.A. Raw data for experimental model.

Appendix B Raw Data for Computational Model

Mach	0							
Element:	1	2						
Angle of								
Attack	0	10	15	20	25	30	35	40
Cp*	-36.64	-24.138	-13.854	-6.99	-3.29	-2.82	-2.46	-10.360
CI	-0.094	-0.228	-0.529	-1.042	-1.599	-2.176	-2.895	-2.466
Cd	0.379	0.201	0.12139	0.07339	0.054	0.049	0.057	0.108
Cm 0.25	0.232	0.201	0.459	0.42	0.49	0.458	0.361	0.308

Figure 1.B. Raw data for computational model.

It is important to note that the negative values for the lift coefficient correspond to downforce.