DESIGN OF REAR WING OF AN ELECTRIC RACE CAR

Steffan Johan Kirk – S170816
Carl-Emil Grøn Christensen – S170817
Department of Mechanical Engineering, Technical University of Denmark

Supervisor:
Jens Walther
Department of Mechanical Engineering, Technical University of Denmark

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Acknowledgements

We would like to thank our supervisors Jens Walther and Robert Mikkelsen, who allowed us to work on a project we hold very dear. The project let us perform incredibly well for a first time racer at the Formula Student competition in Silverstone, and the Vermilion Racing team will hopefully live on many years ahead.

Furthermore, a big thanks to Rasmus Himborg from Philips Lighting Denmark, for helping us machine the 1/4 scale wing used in the windtunnel tests.

Abstract

Race cars wooo! Formula studee3333nt

Contents

1 Introduction

Vermilion Racing is a newly started Electric race car team building their first vehicle: The Eevee [1]. The teams' purpose is competing against other Universities at the Silverstone race track from the 11^{th} to the 16^{th}. As members of the team, the purpose of this report is to document the design process of the rear wing of the first car, the Eevee, and provide an aerodynamic package documenting drag and downforce.

Aerodynamics is a major decider in racing today. Cornering, not top speed is the deciding factor amongst the teams, and aerodynamics is the key. Drag, lift and side force are the three cornerstones to vehicle aerodynamics. A car's ability to handle depends on the grip of the tyres, and downforce directly increases grip by increasing the downwards load on the tyres without adding a weight penalty. Additionally, drag directly decreases the speed of a vehicle by increasing air resistance, but is of less importance as the car's in this class have far more accelerative power than the tyres can handle [2]. Designing the bodyworks of Eevee is therefore a dance of downforce.

This bachelor thesis attempts to lay down the ground work for designing, optimizing and manufacturing the car's rear wing. Our advisor, Jens Honore Walther, proposed simulating the wing geometry in order to both cheapen and quicken the optimization process, but also gain insight into how flow in front of the rear wing affects lift performance. The purpose of the numerical simulations are ultimately to create an easily producable wing in a very short timespan, that produces ample amounts of negative lift for the time spent in production.

FiXme Note: write about what has been done prior

As this is the first year the team building a car, time and money for production is sparse. To ensure the simulated optimizations are true, a wind tunnel test is performed on a down-scaled wing using Flow Similarity theory. The measurements are compared with the results from a computational fluid dynamics simulation performed in Star-CCM+ to verify the preciseness of the simulations. Based on this, the size, x- and y-distance between the multi-element wings, angle of attack and height relative to the chassis is then optimized for maximum downforce. The multi-element wing is taken from theoretical abstraction to reality with a physical design of the wing. The position, deflection and dimensions of the wing is thoroughly described by the rules of the Formula Student competition, guiding the final design process. In the final chapter, theories regarding strength of sandwich structured composites and carbon fiber molding are handled, in order to descibe the production choices made. Finally, the end result is discussed and possible improvements to the wing and mounting system is listed.

Measurements and tests have been carried out at the DTU Wind laboratory's Red wind tunnel with the help of our supervisor Robert Flemming Mikkelsen the 19$^{\text{th}}$ of June.

The entire project is publicly available on `https://github.com/carlegroen/bachelor_project_racecar_aero`, where all work files, data, various notes and CAD drawings can be found. The Formula Student team at DTU: Vermilion Racing can be followed on `fb.com/FSDTU`.

1.1 Design Philosophy

Designing a car with hundreds, if not thousands different factors is incredibly difficult. Therefore, analyzing which things matters and which don't is crucial to the teams' success. First, the deadline for finishing the wing is soon. This sets a limit on the complexity of the wing's dimensions. Secondly, this is the first iteration of the car, thus no decision can be based on prior experience, and optimization has to wait for the next iteration. Finally, the finances of the car is tight. This forces us to go with a low-cost solution. We therefore have to go for a simple, low cost wing, basing the design solely on litterature and experience other teams have done.

The wing has to have as low weight as possible, in order to ensure optimum acceleration of the car. Thereto, drag has to be kept low, but the effect from drag is near negligible, which will be explained in section 2.1. Lastly, we have to maximize the downforce provided by the wing, but also ensure that the center of pressure is kept as constant as possible. If the frontwing, undertray and rear wing's downforce don't scale equally with speed, the center of pressure will move during acceleration. This will make the car's handling unpredictable, and potentially limit the driver's confidence in the car.

2

Aerodynamic Effects on Vehicle Performance

The first argument to the importance of aerodynamics is based around two facts: The fact that drag is neglible in regards to the Formula Student vehicle's top speed on straights, and the fact that aerodynamically increasing the vehicle's *effective* mass due to downforce increases tyre grip, which in turn allows for higher cornering velocities.

The second part of this chapter covers the importance of centering the effective mass increase due to aerodynamic devices close to the center of gravity – otherwise handling characteristics becomes a function of velocity.

2.1 Drag Effects on Straights

First, let's explain what makes a car fast, and what parameters we can change to improve the speed of our car.. The car's acceleration can be described by Newton's second law as:

FiXme Note: introduce a figure with drag and lift to show what's going on

FiXme Note: stort D eller lille d i ligningen?

$$\sum F_x = m\ddot{x} = F \tag{2.1}$$

Where the sum of forces in the x-direction (the direction of travel) can be expressed as the force already pertained by the vehicle, minus the drag force:

$$F - C_D \left(\frac{1}{2} \rho \dot{x}^2 A \right) = m\ddot{x} \tag{2.2}$$

Figure 2.1: Frontal area of the car with a dummy wing inserted into the CAD model, in order to get an estimate of the drag coefficient C_D.

Where C_D is the drag coefficient of the vehicle, ρ is the density of the fluid it moves in and A is frontal area of the vehicle. Assuming we're moving at a steady speed, the acceleration is 0, hence

$$F = C_D \left(\frac{1}{2} \rho \dot{x}^2 A \right) \tag{2.3}$$

As we were interested in the speed of the car, let's solve for the velocity. The force is given by $F = \frac{P}{\dot{x}}$, where P is the power of the car, which gives:

$$\dot{x} = \left(\frac{2P}{C_D (\rho A)} \right)^{\frac{1}{3}} \tag{2.4}$$

This is assuming we're traveling at terminal velocity – that is, the point where the Driving Force = Friction Force. The terminal velocity of the racer is then easily calculated, as the competition restricts the maximum amount of power to 80 kW, and the frontal area of the car is approximated from the CAD drawing seen in figure 2.1.

FiXme Note: fix calculation to use 0.99 instead of 1.2

FiXme Note: missing radiators

$$\dot{x}_{\max} = \left(\frac{2 \cdot 80\,\mathrm{kW}}{0.85\,(1.225\,\mathrm{kg\,m^{-3}}\ 1.2\,\mathrm{m^2})} \right)^{\frac{1}{3}} = 50\,\mathrm{m\,s^{-1}} = 181.4\,\mathrm{km\,h^{-1}} \tag{2.5}$$

however, given the ruleset a forecasted maximum of 110 km h^{-1} allows a much larger drag coefficient C_D:

$$C_D = \frac{2P}{\dot{x}^3 (\rho A)} = \frac{2 \cdot 80\,\mathrm{kW}}{(120\,\mathrm{km\,h^{-1}})^3\,(1.225\,\mathrm{kg\,m^{-3}}\ 1.2\,\mathrm{m^2})} = 2.82 \tag{2.6}$$

Thus, the car's top speed will only be limited by a drag factor > 2.82, which is far above the drag introduced by the aerodynamic devices.

FiXme Note: insert source

From this derivation, it is clear that the car's abilities at maximum speeds far exceed the requirement of the track. Therefore, the next step is to improve cornering speeds which depend strongly on the tyre's grip on the surface of the road [2].

2.1.1 Downforce Effects on Cornering

Shown before, drag does not limit the car's performance on straights. During cornering, drag is not an issue either, but the grip of the tyres limits the maximum velocity before the vehicle loses traction due to the centripetal force which is given by: [3]

$$F_{\text{centripetal}} = \frac{m\dot{x}^2}{r} \tag{2.7}$$

where r is the distance to the center of the cornering circle. The frictional force the car exerts due to downforce and tyre grip is given by:

$$F_{\text{friction}} = \mu F_{\text{normal}} \tag{2.8}$$

where the normal force is given by both the weight and (negative) lift of the car, which serves as an effective mass increase:

$$F_{\text{friction}} = \mu \left(mg + \frac{1}{2}\rho C_L A \dot{x}^2 \right) \tag{2.9}$$

The vehicle will lose traction when the frictional force is less than the centripetal force.

$$\frac{m\dot{x}^2}{r} > \mu \left(mg + \frac{1}{2}\rho C_L A \dot{x}^2 \right) \tag{2.10}$$

Giving the maximum velocity for a given corner radius before the car skids out:

$$\Rightarrow \dot{x} < \left(\frac{2\mu m g r}{m - \mu C_L \rho r A} \right)^{\frac{1}{2}} \tag{2.11}$$

Again, the forecasted variation in radii of corners is prescribed by the rules to be between 3 m to 50 m [4]. Plotting this for various C_L values between 1.5 to 2.6 [5], assuming $m = 300\,\text{kg}$, $\mu = 1.5$ [6] and $A = 0.99\,\text{m}^2$ as previously used. The result can be seen in figure 2.2.

2.1.2 Load Distribution

The scope of this thesis is not to incorperate a full aerodynamic package, but a quick overview of load distribution is essential to understanding the behaviour of the car.

The effective mass added from negative lift depends on the lift coefficient. It is evident that different items on the car carry different lift coefficients,

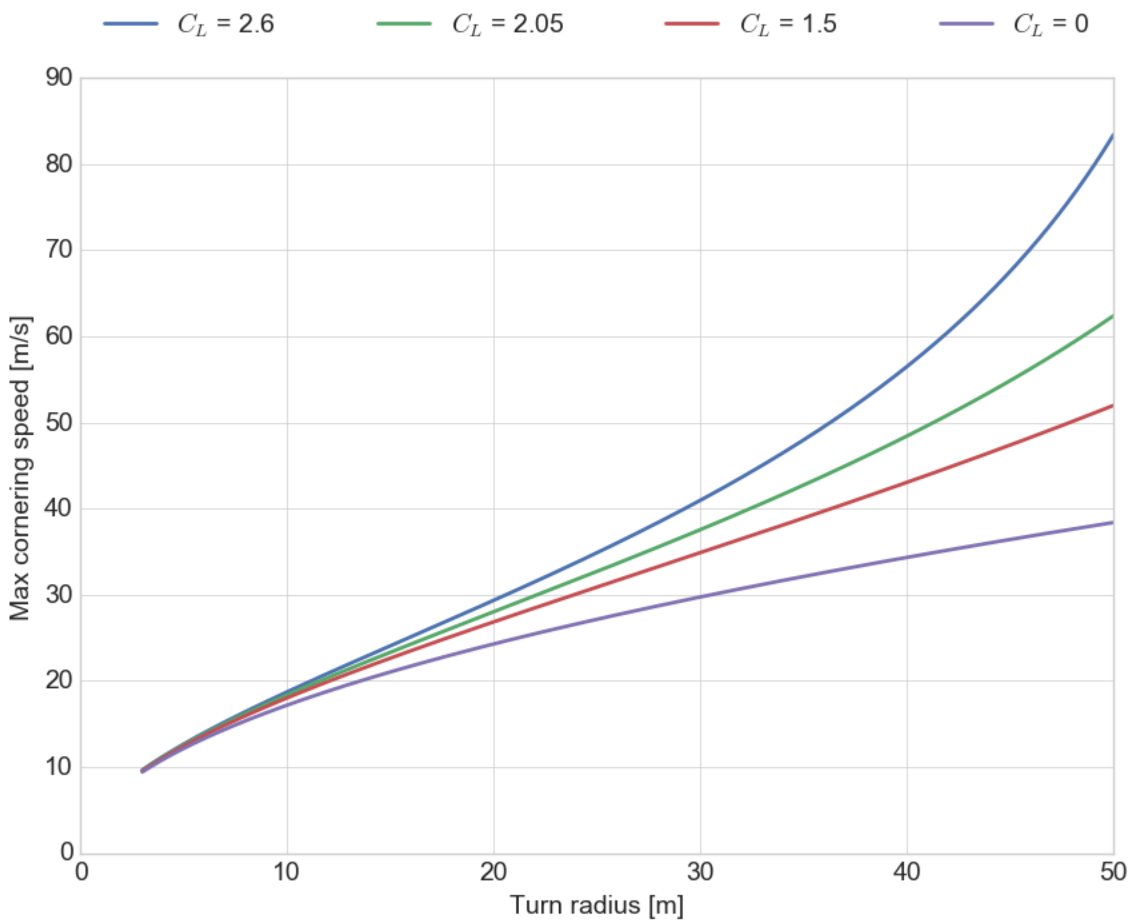

Figure 2.2: Cornering speed as a function of turn radius for various lift coefficients.

thus making the lifting forces over the cars length a function of relative speed. For the unexperienced driver, this is not easily managed as handling characteristics change with velocity. Therefore, it is desirable to have the aerodynamic center of pressure close to the car's center of gravity, in order to have similar handling at all velocities. While this is not handled in this thesis, it is ideal for future iterations and essential for a full aerodynamical package.

3

Airfoils and Inverted Wings

Achieving a large negative lift coefficient C_L can be done in many ways. Inspecting race cars throughout the years show that airfoils have been used as early as 1966 when Jim Hall attached a rear wing to his Chaparral 2E [7]. Since then, the inverted wings have been a staple in the racing industry with various three dimensional geometries affecting the overall performance even further.

This chapter covers the pressure distribution of various airfoils, the selection criterions of the competition, three dimensional geometrical effects and the tools of the optimization trade.

3.1 Airfoil theory

An airfoils is the cross section of a wing.

CLARK Y

FiXme Note: Mostly laminar flow, boundary layer mustn't trip or create bubbles,

Theory of airfoils from katz book, to be written tuesday 19.

3.1.1 Pressure distribution

FiXme Note: Where does downforce come from? Where does drag come from?

3.1.2 Lift and Drag Coefficient

3.1.3 Which parameters does an airfoil have? What can we change

3.1.4 Angle of Attack

3.1.5 Ground Effects

FiXme Note: unsure

3.1.6 End Plates

FiXme Note: something about Navier Stokes equations.

3.2 Comparison of Airfoils

Choosing the MSHD wing. To be written from MSHD article on tuesday 19.

3.3 Multi elements? How many is enough

From katz book, written tuesday 19.

3.4 Optimization Tools

Also from katz book to be written tuesday 19.

Building physical models is cool, wind tunnel time is expensive though

Let's use CFD!

To make sure CFD works, we need to perform experiments to verify simulations work.

Let's make a small scale wind tunnel test and simulate the rest!

4

Wind Tunnel Experiment

Verifying the simulated aerodynamic effects is crucial to ensuring the correctness of the numerical analysis. In order to assess the reliability of the previouisly conducted simulations, a physical measurement of the pressure along the down-scaled wing will provide results for comparison.

FiXme Note: sounds awful. fix

4.1 Aerodynamics

4.1.1 Similarity of Flows

In order to perform tests on the rear wing, it has to be scaled down to fit inside the wind tunnel. This reduces the physical size of the wing, which under equal circumstances changes the flow around it. In order to correctly emulate the simulated flow inside a wind tunnel, the Reynolds number and Euler number have to be the same, assuming incompressible flows:

$$\mathrm{Re}_{\mathrm{m}} = \mathrm{Re} \tag{4.1}$$

$$\mathrm{Eu}_{\mathrm{m}} = \mathrm{Eu} \tag{4.2}$$

Mathematically, the Reynolds- and Euler number are defined as:

$$\mathrm{Eu} = \frac{p_u - p_d}{p v^2} \tag{4.3}$$

where v is the characteristic velocity of the flow, p_u denotes upstream pressure, and p_d denotes downstream pressure, and:

$$\mathrm{Re} = \frac{uL}{\nu} \tag{4.4}$$

where u is the velocity relative to the object, L is the characteristic length and ν is the kinematic viscosity of the fluid.

For a down-scaled model, matching Reynolds- and Euler number requires an increase in velocity, inversely proportional to the increase in length

FiXme Note: skriv det her ud plx.

$$\frac{u_\mathrm{m} L_\mathrm{m}}{\nu} = \frac{uL}{\nu}$$
$$\Rightarrow u_\mathrm{m} = \frac{L}{L_\mathrm{m}} u \tag{4.5}$$

Given the nature of the competition, the average cornering speeds are around $55\,\mathrm{km\,h^{-1}} = 15.28\,\mathrm{m\,s^{-1}}$, which is where downforce is of most importance. As shown in section 4.1.1, the desired velocity in the wind tunnel for the scale model can be found from equation 4.5

$$u_\mathrm{m} = \frac{0.6\,\mathrm{m}}{0.15\,\mathrm{m}} 15.28\,\mathrm{m\,s^{-1}} = 61.12\,\mathrm{m\,s^{-1}}$$

Which in accordance to the range of The Red wind tunnel.

4.2 Equipment

- The Red wind tunnel ($60\,\mathrm{m\,s^{-1}}$ to $65\,\mathrm{m\,s^{-1}}$)
- 1/4 scale wing
- Syringe inserts
- Rubber tubing
- Pressure transducer

4.2.1 Instrumentation

The Red Wind Tunnel

The red wind tunnel is an open loop wind tunnel located at DTU Lyngby. It measures $0.5\,\mathrm{m} \times 0.5\,\mathrm{m} \times 1.3\,\mathrm{m}$ in the test section, with a maximum wind speed of $65\,\mathrm{m\,s^{-1}}$. The wind tunnel functions in low Reynolds number, which fits with the chosen MSHD aerofoil. The system employs a hot wire velocity probe.

FiXme Note: What'd we use to collect data?

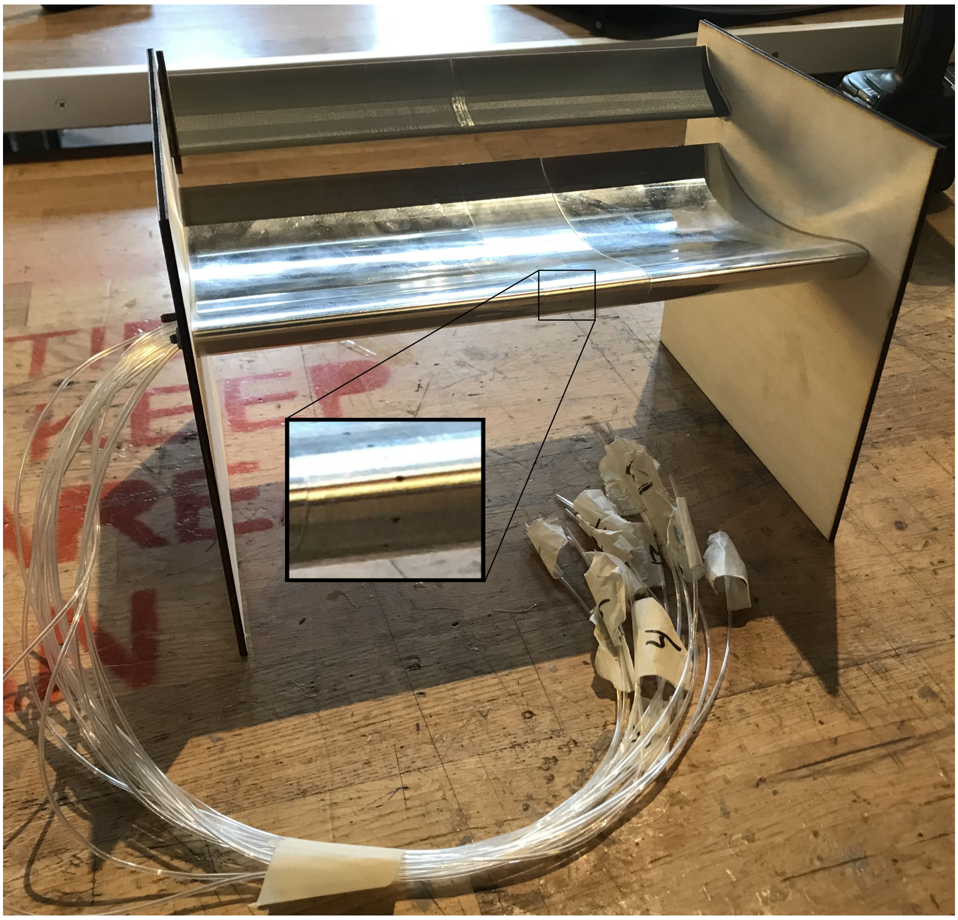

Figure 4.1: Down-scaled wing assmembled with a zoom in on the pressure taps. The length of the entire wing is approximately 250 mm with a total chord length of 150 mm.

4.2.2 Manufacturing the 1/4 Scale Rear Wing

Blueprints

The small scale rear wing is constructed in 6 pieces. The large wing is dissected into three parts. Two regular wings, and a central part with 15 pressure taps.

FiXme Note: Why this wing design? answer: Just a first guess that can be compared with easily later.

Material selection is based on the ease of machinability - a CNC-miller was provided to us, along with ample amounts of aluminium. This scale wing is not to be used in the actual race car, so weight is not a concern. Construction the 1/4 scale wing is not completely trivial. High precision is required for the surface finish, and the pressure taps have to be small in diameter: 0.8 mm. .

FiXme Note: insert work drawings used for producing the wing

FiXme Note: Insert Technical Drawings

Tolerances

Manufactured parts

FiXme Note: Maybe remove this section

In figure 4.1 the down-scaled wing post-production with pressure tubes inserted can be seen with pressure-taps along the centerpiece.

3D-printed parts

Assembly

4.3 Experimental Procedure

4.4 Calibration of External Forces

FiXme Note: How is the downforce measurement measured and how do you take outside factors into account

4.5 Results

5

Simulation

The simulation will run in several parts. First, the wings relative placement between eachother will be optimized in a 2-dimensional environment. This involves, size, x- and y-distance between the multi-element wings, angle of attack and height relative to the chassis to give a good estimate of the wings placement range. Secondly, a 3-dimensional analysis of the entire wing with endplates will be performed. Endplate dimensions will be optimized, and further optimization of the height relative to the entire chassis to finalize the design and placement. Lastly, a complete computational solution to the entire car will finalize the aerodynamical package, and yield the total amount of drag and downforce.

5.1 Star-CCM+

5.2 Finite Volume method

Star-CCM+ employs the finite volume method, which will be covered briefly in this report.

5.3 Mesh Generation

The mesh has to be structured in accordance to best practice. Areas with high velocity and pressure gradiants have to be dissolved in acceptable resolutions, in order to ensure correct results. Running an initial test on a generic mesh shows us where the wing requires greater resolution. Gradiants are easily visible around the wing's leading edge, and generally around the solid bodies. Furthermore, aligning the meshg with the flow improves accuracy and rate of convergence. .

FiXme Note: Noget med konvergens undersøgelse. Måske også grid sensitivity test.

5.4 The Rear Wing

5.4.1 Verification of Simulation Results

Comparison with wind tunnel test.

Evaluation of Verification Simulation

5.4.2 Multi-Element Wing Optimization

Wing was moved around to optimize lift. Here's the results changing the variables.

5.5 The Aerodynamics Package

5.5.1 Undertray, Diffuser, Front Wing and Driver

5.5.2 Everything Together Now

5.6 Results

6

Construction

In order to verify the computational fluid dynamics used, a 1/4 scale wing was constructed. This miniature wing is constructed for performing windtunnel tests, and comparing results with the simulations. If the two are in accordance, the simulated results of the full scale wing can be used with confidence.

6.1 Requirements

FiXme Note: Dimensional requirements from the competition. Show CAD of car-design. Requirements to strength

6.2 Prototyping

6.3 Material Selection

FiXme Note: Overvej CES (for flair jo)

6.4 Composites

6.4.1 Sandwich Structure

6.4.2 Wing Deflection

6.5 Final Design of Rear Wing

FiXme Note: Presentation of CAD Drawings and method of how we will get to this result

6.5.1 Blue Prints

FiXme Note: Rendering

6.6 Manufacturing Final Design

6.6.1 Polystyrene Molds

The molds for the wings were chosen as positive molds, meaning polystyrene molds of the actual wings were cut out and overlaid with resin coated car-

Figure 6.1: The hot wire melts the styrofoam while sliding along the wooden template.

bon fiber. In order to do this, we devised a hotwire-based specialized tool for the job. This can be seen in figure 6.1, and the name of the job is to do it slowly in order to receive a clean surface.

Figure 6.2: Steffan and Nicolai performing a hand layup of the carbon fiber mats around a polystyrene foam core.

6.6.2 Hand Layup

FiXme Note: Show how we did the hand lay up. What went wrong what went well.

6.6.3 Surface Finish

6.6.4 Implementation and Testing

6.7 Testing and Inspection

6.7.1 Reinforcing the mounting

Figure 6.3: Curing the wing in a flat position let the resin pool in the center of the wing, making the surface very rough.

Figure 6.4: Sanding the wing clears the surface roughness, but requires a new layer of sealant. Using epoxy or a lacquer was investigated before settling on epoxy.

7

Discussion

8

Conclusion

bla

Perspective

The Eevee has to be rebuilt next year, and in order to help the effort along for future students, a list of potential upgrades are listed below, with estimates of how valuable each change is in regards to downforce/drag reduction gain.

8.1 Drag Reductive System

A drag reductive system (DRS) is well-known from Formula 1, and has in the recent years been gaining traction (or lack therof :)))) in the Formula Student. It is a natural extension to the aerodynamics of the car, as Formula Student has much less restrictions on aerodynamics than Formula 1. Automatically adaptive DRS, that measures the car's relative downforce and the angle of the steering column could give a big edge on straights, as flipping the wing up to reduce drag increases the top speed.

8.2 Slats, Flaps, Gills and Cutaway

https://www.jmranalytical.com/single-post/2017/04/06/Rear-Wing-Investigation

We already have a multi element wing, but increasing the amount of elements increases the amount of downforce we can pull out of the same design.

8.3 Suspension Integration

- Nice to have downforce directly on the wheels - Gives more unsprung mass though. That might be an issue.

Media

The project gained a lot of media attraction. For the interested reader, more can be found below.

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