Study of Vehicle Aerodynamics

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July 2017, S3++

Abstract. This work reports our study and calculations of the aerodynamic properties of vehicles using experimental and numerical approaches by focusing on 3 types of evaluations:

- the coefficient of drag
- the coefficient of lift
- streamlines

Our experimental perspective was separated in different parts. We first prepared 2 car models, using a software called Salome, with different designs in order to see a clear separation in the values we would get.

First car was simple and very bulky while the other was slick, designed to have the best aerodynamic properties possible. After that we used 3D printers to print the cars and calibrated the mechanism in our wind tunnel in order for it to measure the forces exerted on the cars. Furthermore, we were also able to see streamlines in the wind tunnel, as we inserted the white and dense smoke of liquid nitrogen near the cars. Finally, as we measured forces acting on the vehicles we were able to calculate corresponding coefficients, as well as study streamlines by analyzing the recorded video. All experimental studies were paired with a numerical simulation in software called OpenFoam to compare the results between them and to help with the evaluation of errors in each approach.

Keywords : coefficient of drag, drag force, coefficient of lift, lift force, streamlines, pressure difference, wind tunnel, turbulence, precision of calculations, strain sensors, leverage mechanism, micro controller

Submitted to : *Summer School of Science S3++*

1. Introduction

In this paper we will report our study of the aerodynamic properties of 2 vehicles, for which we studied the coefficients of drag and lift. In order for that to be possible, we first need to comprehend how and what drag and lift are, as well as how we can calculate the coefficients attached to them.

Drag is a force acting opposite to the relative motion of any object moving with respect to a surrounding fluid (which in our case is air).

We can calculate this force using the equation $F = \frac{\rho v^2 CA}{2}$, where v is the relative speed of the air to the car, ρ is the density of air, C is the constant of drag and A is the area affected by drag (the front area of the car in our case).

Lift is also an important factor in the aerodynamics of a car. It is the component of force that is perpendicular to the direction of the airflow. This is due to the difference in pressure in direction of the lift force which acts on the windshield surface producing the force perpendicular to the windshield surface. This is followed by a long line of low pressure on the top of the car, because of the increased speed of the particles due to the high pressure zone. However, since the air flows with less difficulty on the bottom, there is a difference in pressure, and particles having a preference for lower-pressure sector, the particles in the bottom push up towards the low pressure region, thus creating lift.
We can calculate this force using the same equation as before, with modifications to the area affected, being the cross section of the car normal to the lift force, and to the coefficients, which becomes the coefficient of lift.

We can rearrange these 2 equations to find the coefficients, where the density of air, the speed and the area are constants (in our system) and the force varies.

2. Experiments

2.1. Modelling and printing

At the beginning of our project we had to decide what kind of vehicle we would use for the evaluation of aerodynamic properties. We agreed to use 2 types of cars, one would be a regular Toyota family car and the other one a Formula 1 race car. We used these vehicles because they are distinct enough in shape so that we could see differences in coefficients of drag and lift with our apparatus.

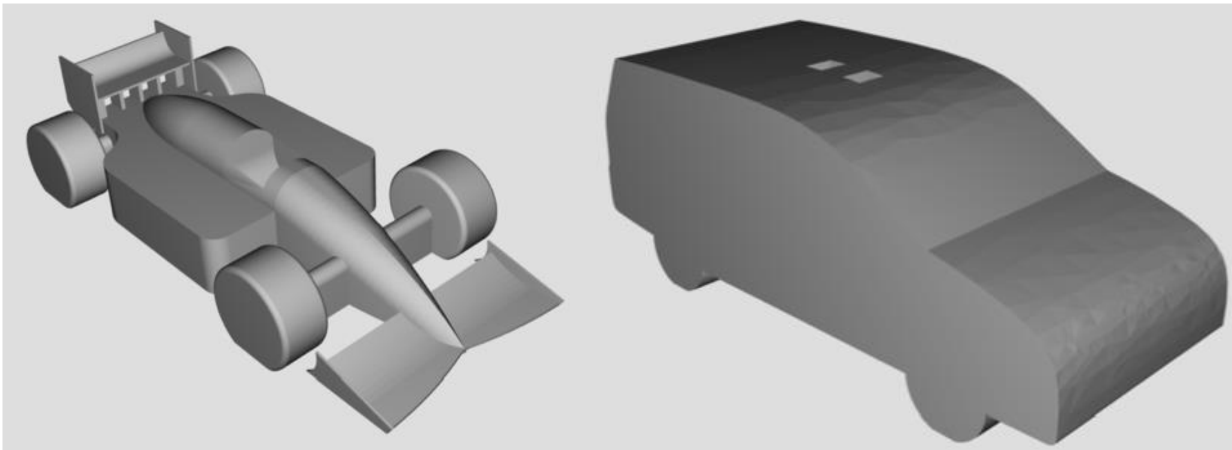

Figure 1. Screenshot of 2 refined models of cars used for our project.

After we downloaded 3D models of the cars, we used open-source software Salome to modify the models in order to simplify their printing (fusing wheels and wings with the car, creating holes perpendicular to the car so it could fit on the leverage mechanism, etc…). When we finished altering the models, we printed them with Forcebook Ultraprint 3D printer. These models took between 12 and 24 hours to produce.

2.2 Installation of new sensors and adjustment of leverage mechanism

To move on with our project, we had to mount new strain sensors on our leverage mechanism. Theses strain sensors have hole in the middle, making them bendable under a certain force, which will endeavor be displayed by the micro controller linked to the sensors. We chose to install new sensors because the initial ones, which were smaller, didn't give us enough accuracy with the used leverage mechanism. Bigger sensors have a greater deformation area, meaning that the sensor could display the force with more accuracy.

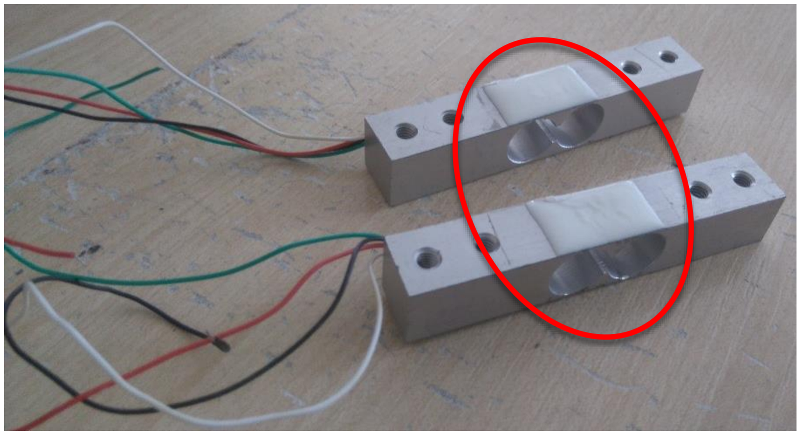

Figure 2. Photograph of the larger strain sensors. Circled area shows the place where they are bent and where the deformation is measured.

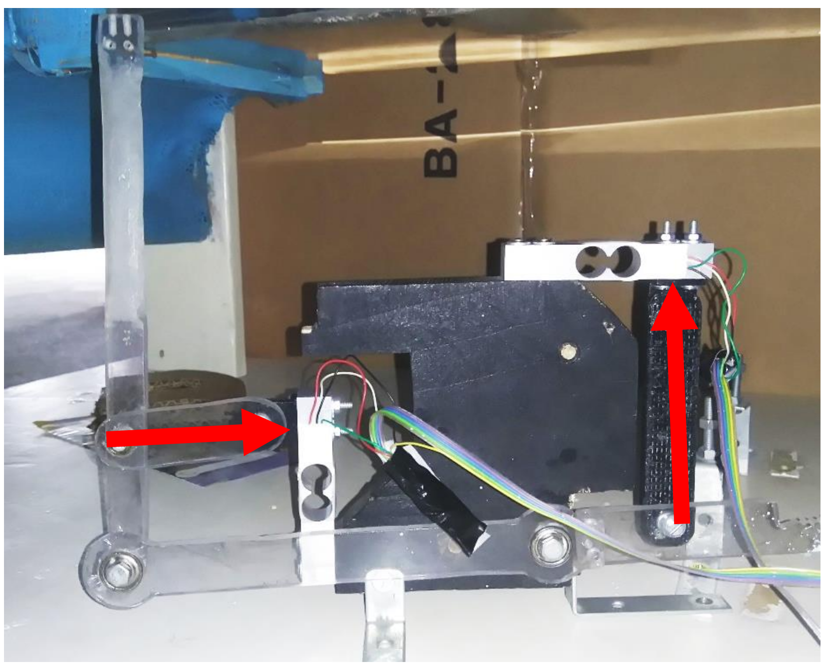

Figure 3. Photograph of the leverage mechanism. The horizontal red arrow shows the measured drag force and the vertical red arrow shows the measured lift force.

Our initial mechanism consisted of a wooden pedestal and 4 movable plastic parts, through which the forces are transferred. Thus, because the sensors were much bigger, we had to redesign the mechanism to fit them. For that we once again used Salome and our 3D printers.

We welded the new sensors to the wires connected to our Croduino (version of Arduino) microcontroller. This system was connected to an LCD monitor which showed the force exerted on each sensor.

2.3. Calibrating sensors and tryout in the wind tunnel

For the new sensors to work properly, we first had to calibrate them. We took a simple dynamometer and applied forces, on our mechanism, ranging from 0.5 N to 4 N on each sensor. In the same time, we were writing down the values, that our sensors were reading, from the output that came directly from the microcontroller. Afterwards we made a graph from these values to see in which range are they linear because then we know what values to expect when we perform our experiment. In addition, we calculated the gradient of the line to scale the values our sensors were showing. Then we updated scaling factors and uploaded our Arduino code to the microcontroller and verified if our sensors were properly calibrated.

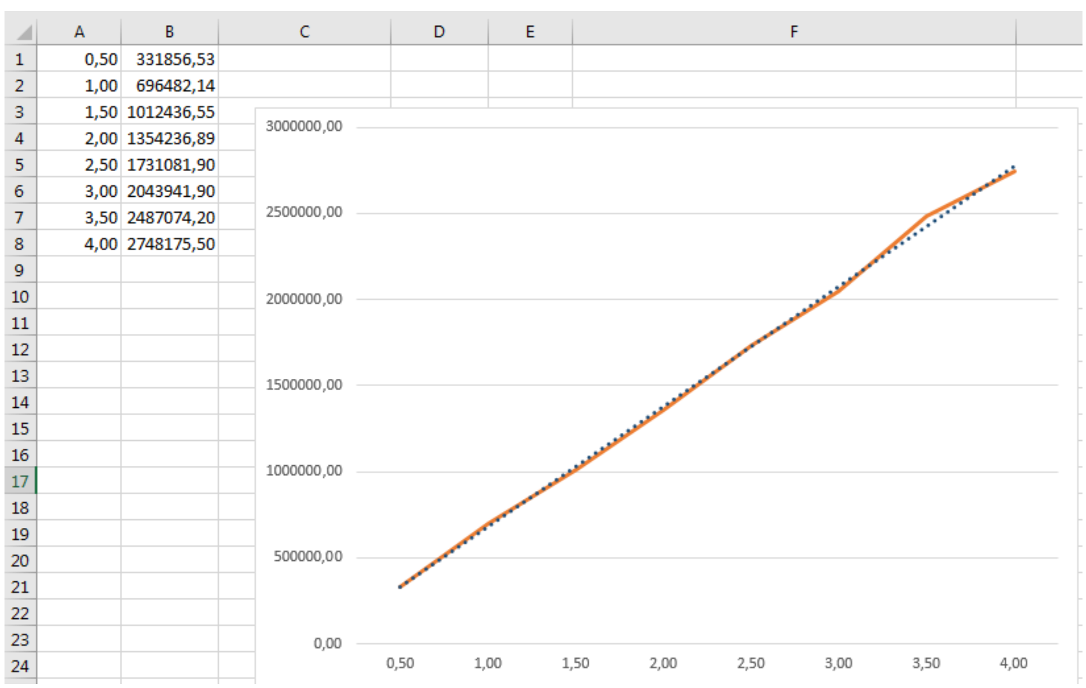

Figure 4. Screenshot of a graph we constructed from the values our sensors were giving. Column A shows values of forces we applied and column B values our sensors were measuring. Orange line on the picture is our graph and blue dotted line is the trend line of our graph.

When we finished with our calibration, we mounted our car models on the leverage mechanism. Then we made a Styrofoam compartment for liquid nitrogen. We used a Styrofoam box with a lid.

Additionally, we carved a hole in the lid for rubber tubes from which the nitrogen would flow. We poured in liquid nitrogen, placed some wrenches in the Styrofoam box, sealed it with duct tape and turned on the wind tunnel. As liquid nitrogen did not flow freely through tubes, because they became frozen, we removed the lid from the box and used our hands to push liquid nitrogen out of the compartment and into the wind tunnel. We were filming our experiment to capture streamlines and analyze them afterwards.

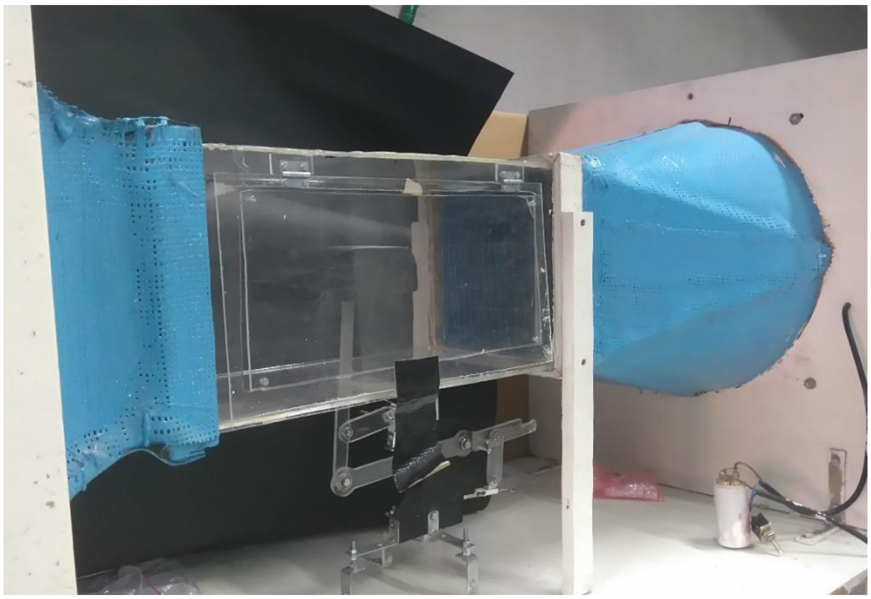

Figure 5. Photograph of the wind tunnel before we remade the leverage mechanism.

3. Numerical approach

The other method we used for obtaining the aerodynamic properties of the model was by numerically simulating the airflow around the model. For this we needed to approximate the solution to the Navier-Stokes equations (1,2) for volumes around the car, but now we are focusing on the theoretical background we used and therefore the method of the simulation will be discussed later.

$$\nabla \cdot (|v\rangle\langle v|) = -\nabla \cdot pI + \nabla \cdot \tau + \rho g \qquad (1)$$

$$\nabla \cdot v = 0 \qquad (2)$$

3.1. The theoretical background

Navier-Stokes equations above describe how fluids such as air behave. In equations we used equation 1 describes how momentum is conserved in fluids (Its name is the Cauchy momentum equation for this reason) and equation 2 tells us that our fluid is incompressible, because that's how air behaves at subsonic speeds. To further simplify the model, in our first equation, temporal term (change of velocity in time) is not considered. Unfortunately, these equations do not have exact solutions except for really easy laminar flows. Because of these circumstances it is impossible to calculate the exact solution for our setup. This is why we needed to use a simulation, which approximate the solution to these equations.

3.2. The simulation

We carried out the simulation by modelling a wind tunnel around the silhouette of the car's model. As both the wind tunnel and our model was symmetric to a plane we could cut the model of the wind tunnel in half saving us processing power and possibly creating some errors in our results but we will mention those in the errors subsection.

After having our model embedded in the wind tunnel we used a software called cfMesh to divide this volume into small parts for which we could simulate the flow using equations 1 and 2. The approximation included two steps. First a linear approximation, but as it can't get us close enough to the solution halfway through we replace it with a quadratic one, which is more precise but can easily lead to wrong results if it's used directly on the boundary conditions.

We used an inhomogeneous mesh as the change in speed and pressure are quicker near the car than at the walls of the wind tunnel. As such we used low resolution on the edges of the wind tunnel and used high resolution in the car's close proximity as well as behind the car where we expected quick changes in the speed and pressure of the fluid. We used the same boundary conditions we had in the wind tunnel namely the air was flowing at $11ms^{-1}$ and we said that the wind speed on any surface, which is the surface of a solid, is 0.

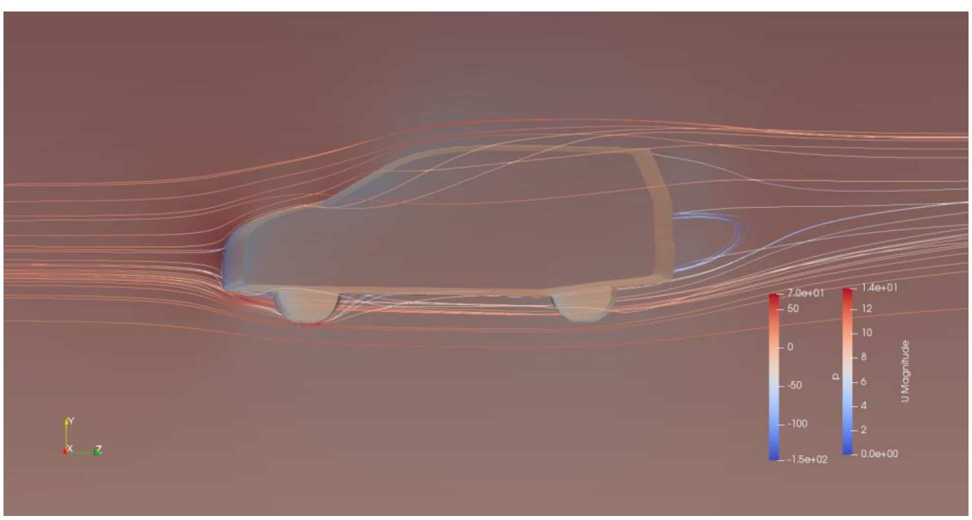

Figure 6. Screenshot of streamlines showing a vortex emerging behind the car, which affects the coefficient of drag.

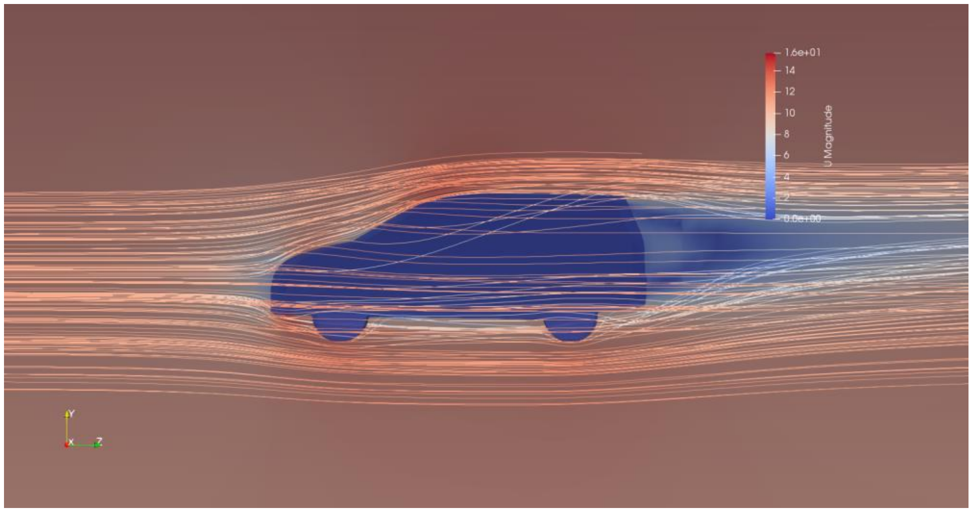

Figure 7. Screenshot of streamlines showing air flow around the car.

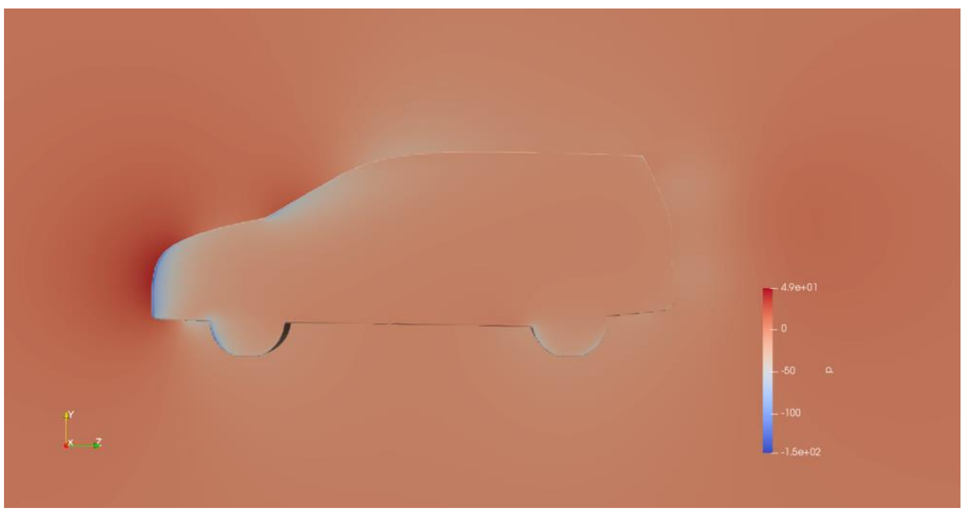

Figure 8. Screenshot showing high and low pressure zones on the car. Blue colored outline shows areas of high pressure, while orange colored outline shows areas of low pressure.

4. Results, possible errors and future improvements

When we finished with experiment and simulation we had to compare our results. In the experiment, coefficient of drag we calculated was 0.59 and coefficient of lift was -0.11. For the simulation the results were 0.65 for the coefficient of drag and -0.21 for the coefficient of lift. We also obtained other important data such as, where and how vortexes form and how the fluid flows. These results can be seen in Figures 6-8 for the simulation and Figure 9 for the experiment.

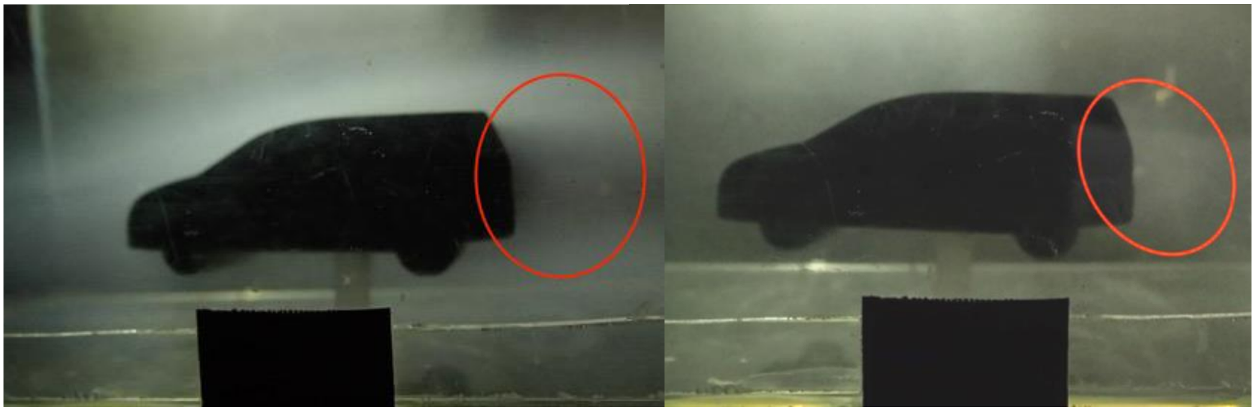

Figure 9. Photographs of streamlines, in the wind tunnel, we got using liquid nitrogen. Circled area on the left photograph shows the vortex which formed around the car and circled area on the right photograph shows air molecules which are left behind after a current of air had passed around the car.

All of these results are for the Toyota model because we did not have enough time to gather data for the Formula 1 model, but also because our gear malfunctioned.

Unfortunately, our results are not perfect as there are some errors. In the experimental part the main error is the fact that we had to calibrate our sensors a few times in order for them to work because one of them malfunctioned so we had to swap them. Because of that we got another error which is stiffness and friction in the leverage mechanism. These two errors are the main reason why we are not able to present data for the Formula 1 model. Furthermore, another error in our experiment could be because of approximating the reference areas.

In the numerical part the main error is the fact that our simulation doesn't solve itself as a function, but rather for a time instance and expects it to stay that way, expects to find an equilibrium. This may lead to, and this has happened here too, that the solver is constantly jumping between solutions. Another problem is the issue with the rounding of the numbers while the program solves incredible amounts of linear equations.

In the future we intend to finish measurements and calculations for the Formula 1 model, possibly use the dry ice instead of liquid nitrogen because we think that the air flow would be thicker and vortexes more visible and finally, we intend to reduce our errors, especially in the calibration of sensors.

Acknowledgements

We would like to thank Matija and Petra for the organization of the Summer School of science S3++, because without them, our project and all the knowledge we got from it could not be possible.

Also we would like to thank the special guests and guest lecturers for their interest in our project, especially Michael Berney, Ph.D. who gave us the idea about dry ice.

Finally, we thank all the other members of the S3++ for all the quality time we spent with them.