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Department of Mechanical and Aerospace Engineering
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AERO MAP FOR FORMULA STUDENT

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ABSTRACT

This project focuses on the aerodynamics of a Formula Student race car across a wide range of vehicle attitudes. While there have been some Formula Student projects which look at some attitudes, looking at all the attitude parameters in one sweep is somewhat new. An aero map is the collection of simulation results which sweep across all the attitude parameters the vehicle sees. While it would be ideal to complete a simulation at every combination of attitudes it become unfeasible to complete these simulations within a reasonable time.

What is more important than producing the results, is having a robust method which allows the student team to create an aero map whenever it is need and have methods for extracting useful information from the map and using it as a setup tool during on-track tuning. This project uses MATLAB and MoTeC i2 Pro as tools to create an aerodynamic model for a vehicle model as well as evaluating the effect of a setup change on aerodynamic performance.

To complement the aero map model in MoTeC i2 Pro a differential pressure measurement system was developed to, unlike previous systems, log with the rest of the vehicles sensors to allow for pressure values to be analyzed in the context of the vehicle attitude on-track. The simulation results were also compared with some wind tunnel results to evaluate the strengths and weakness of the simulations.

This project covered a wide range of software and hardware tools for working with and understanding how the vehicles attitude effects the aerodynamic performance and hence the vehicles performance.

NOMENCLATURE

x, y, z – The positions in cartesian coordinates with an origin between the front tyres on the ground plane with the x-axis pointing towards the rear and the z axis point upwards

C_x, C_y, C_z – The x, y, z components of the aerodynamic coefficients of force

M_x, M_y, M_z – The x, y, z components of the aerodynamic coefficients of moment

A – is the reference area of the vehicle (usually the frontal area)

MMS – Monash Motorsports is Monash Universities Formula Student Team

CFD – Computational fluid dynamics

CAD – Computer aided design software in this case NX 12.0 by Siemens

FRH – Front ride height

RRH – Rear ride height

Yaw – The angle between the x-axis and the component of the velocity axis in the x and y directions

CSV – Comma Separated Values files are a standard ASCII based file type for creating tabulated data

FSG – The Formula Student Germany competition is held every year at the Hockenheim Ring

DPMS – Differential pressure measurement system

Attitude – The combination of FRH, RRH, roll, steer and yaw

Aero map – The collection of forces and moments across all vehicle attitudes

INTRODUCTION

Formula Student and Formula SAE are two design and build engineering competitions based on an automobile racing environment (https://www.formulastudent.de/fsg/). Formula student teams in the early 2000s became aware that downforce aerodynamics even at the low average speeds of a formula student circuit can have a performance advantage. In the beginning teams focused on a front and rear wing concept although now many teams also use underbody aerodynamics.

The complexity of the aerodynamic designs by the MMS have progressively become more aggressive, complex and reliant on ‘ground effect’. Ground effect is sensitive to ground clearance which changes as the race car moves around the track. MMS has yet to address the problems with predicting and understanding the effects of vehicle attitudes on aerodynamic performance and vice versa. The attitude of the vehicle in this report will not use the standard vehicle dynamic system of using on heave, pitch, roll and steer instead the vehicle attitude will be characterized by FRH, RRH, roll, steer and yaw.

This yaw angle can be attributed to, cross winds and vehicle slip which occurs when the vehicle is driven to the limit of grip and all 4 tires experience slip. While vehicle speed can influence the Reynolds number and hence the amount of turbulence in the flow this report uses a standard of 16.67m/s vehicle speed as wind tunnel tests by MMS have shown that the vehicle is Reynolds independent.

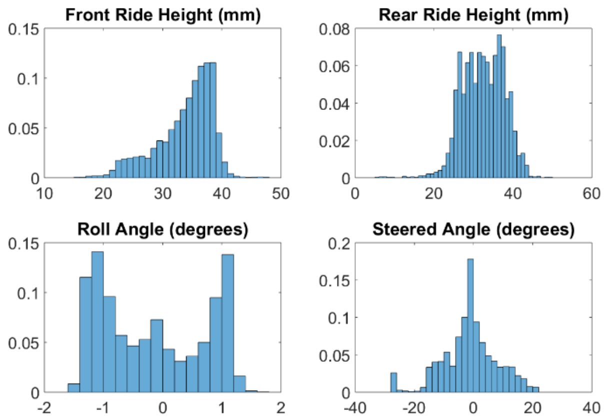

Figure 1 shows histograms of the vehicle attitudes from the fastest endurance lap of the 2018 Formula Student Germany Competition.

Figure 1 shows how the vehicles attitude parameters vary away from their static value during driving which leads to the need for a method to predict aerodynamic loads at these attitudes.

An aerodynamic force map (aero map) describes the aerodynamic forces and moments of the vehicle across its feasible attitude parameters (FRH, RRH, roll, steer and yaw). It would be ideal to create a 5-dimensional matrix for each of the six components of the forces and moments however this would create a variety of challenges including the size of the matrix which in this case could have more than 6000 elements and hence require 6000 simulations. With each simulation taking 6 hours the total time for the simulations would be 36,000 hours or approximately 4 years!

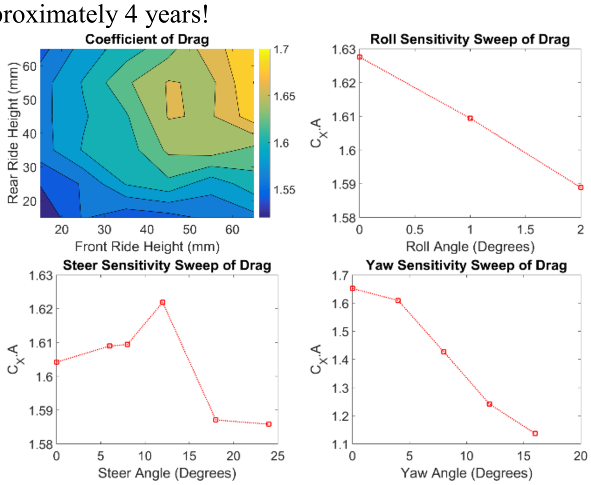

Figure 2 is an aero map for the C_x (ie drag) across the mapped parameter range

Hence this paper simplifies an aero map to a 6 by 6 ride height map (FRH v. RRH), 3 roll angles, 5 steering angles and 5 yaw angles. Each attitude in the map is a variation on a baseline which means that only 47 simulations are required to create the map which takes 3 days to simulate on the MonARCH Cluster and whose results for the C_x.A values can be seen in Figure 2.

For the aero map not to become just an aesthetic plot but a design tool, a variety of analysis tools must be created to allow engineers to use the data contained in the map to predict the effect of setup changes and determine where to focus their design efforts. By automating the map process this allowed designers to focus on analysis and on developing tools for validating the simulations with on-track and wind tunnel data and use the on-track data for tuning and vehicle development.

A TOOL FOR BATCH PROCESSING SIMULATIONS

Defining the attitudes required for the map in an efficient manner which could automatically be converted into a batch of simulations was essential to future proofing the work in this project so that future members of the team could create and use aero maps of their own design for the concepts they were generating.

An implied part of this process is having simulations which can be batch processed which means that the entire simulation process must be scripted and parameterized. This became one of the most significant parts of this project because it allowed the MMS aerodynamics section to transition from straight line (ie no yaw) static attitude simulations which took large amounts of engineers' time to setup and operate to simulations which could be uploaded to the cluster at any desired attitude and added to the queue within 5 minutes allowing for more time analyzing and creating concepts.

Once the scripted and parameterized simulations process was completed an intuitive method for creating a parameter sweep (of which the aero map is a sub set) was created using a Python class which could takes in a baseline and sets of parameters to create a list of attitudes which can then be automatically submitted to the MonARCH cluster for simulating. The key features of this process were that attitudes which are duplicates of attitudes would not be added, the attitudes are saved so that they can be used to either replicate a parameter set or to help with converting the results files into an output CSV. Once the simulations are complete 3 lines of code can read the parameter set, collect the data from the simulations and then export the data as a CSV file can be executed with ease. Once the map has been created it is essential for it to be processed to make it useable for analysis and modeling purposes.

USING THE AERO MAP FOR VEHICLE MODELING

The CSV file create by the Python class contains column vectors of values for each simulation including the attitude parameters, force components (C_x.A, C_y.A, C_z.A) and moment components (M_x.A, M_y.A, M_z.A) which need to be transformed into one 6 by 6 array (top left in Figure 3) and 3 one dimensional arrays (top right, bottom left and right in Figure 3) not only for the force and moment components but also their associated parameter so for example the ride height map would need a 6 by 6 array of front ride heights and a 6 by 6 array of rear ride heights.

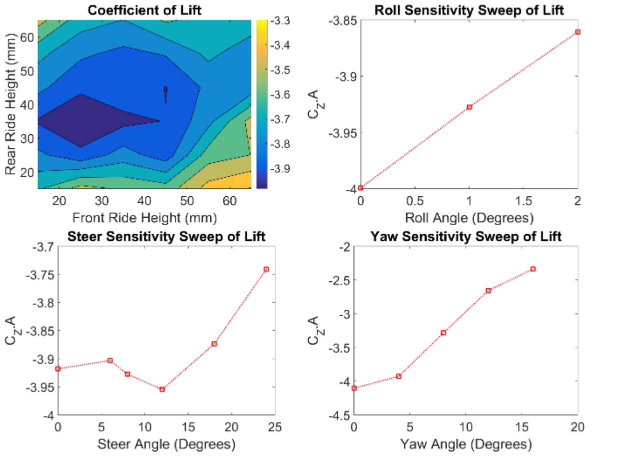

Figure 3 is an aero map for the C_Z.A (ie lift) across the mapped parameter range

Once the data has been transformed into a more useable format it can be used to generate a model which takes in FRH, RRH, roll, steer and yaw then returns both the force components and moment components at the given attitude. This can be done in MATLAB using 1D and 2D interpolate functions or in MoTeC i2 Pro using 2D and 1D map functions. Once the interpolated value for all 4 maps are added together three times the baselines forces and moments must be subtracted from the result. This then produces an approximate for the forces and moments based on vehicle attitude which can be used for on-track predictions or as an aerodynamic model in the vehicle model the day MMS creates a vehicle model.

USING THE AERO MAP FOR VEHICLE TUNING

Before analyzing the aero map created it is essential to understand how front and rear ride heights (the only tunable parameters modelled) relate to each other and how to use that relationship to tune the static ride heights to maximize aerodynamic performance.

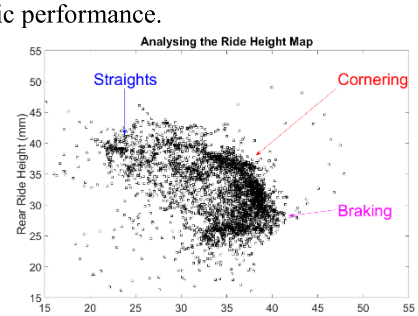

Figure 4 is a scatter plot of front ride heights compared to rear ride heights around a lap of the FSG track with annotations for the key point clusters

There are three key cluster within the graph in Figure 4 which relate to the three key conditions the car sees; straights, cornering and braking. As the vehicle transitions from braking into a corner in travels along an arc via the cornering cluster toward the straights cluster. Once the driver applies the brakes the vehicle rapidly travels straight to the braking cluster.

Now the basics of the ride height map have been put in place it is now important to import the map into MoTeC's data analysis tool (MoTeC i2 Pro) so that the aerodynamic model predictions can be plotted base on on-track attitude data.

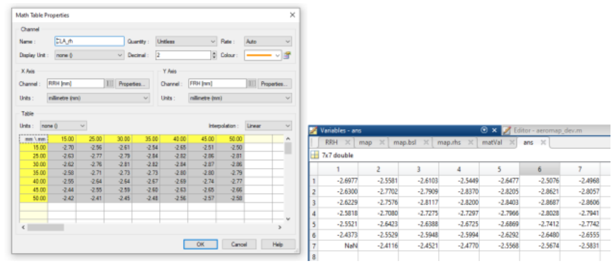

Figure 5 shows how a tabulated MATLAB aero map can be transfer directly to a 2D map channel in MoTeC i2 Pro as a single array

Once the map has been imported the channel for ride heights can be duplicated with an adjustment to show the effect of changing the static ride height. If the original and adjusted ride heights are plotted onto a scatter plot the results would be as shown in Figure 6.

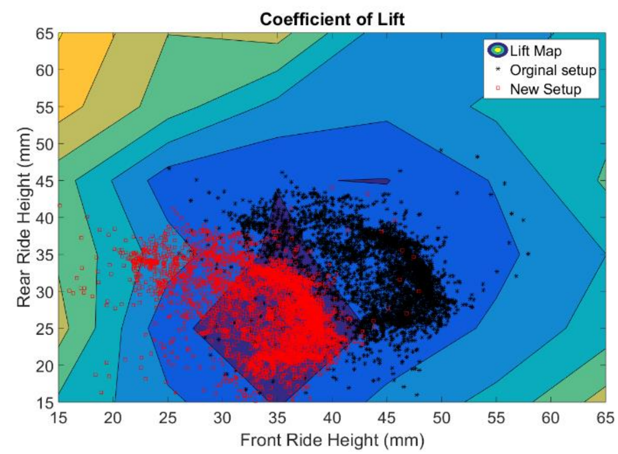

Figure 6 is a scatter plot overlaying the ride height aero map which highlights how changing the static ride heights on the race car can influence what regions of the aero map the vehicle operates in

Figure 6 is overlaid over the C_Z.A (lift) map to show that the cornering cluster has been moved closer to the peak lift region by reducing the FRH by 10mm and the RRH by 5mm. Figure 7 (below) shows the same data except plotted over the track map with the coloring referring to the change in lift due to the setup change described where blue is better. The corners see an improvement in lift which results in more grip and hence higher cornering speeds which is expected to improve performance.

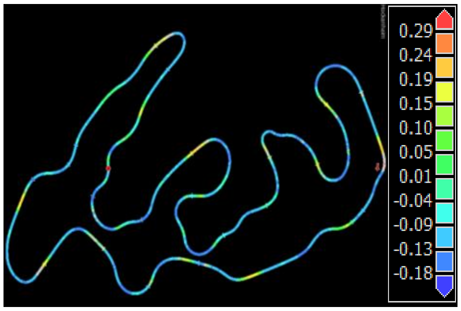

Figure 7 is a map of the FSG track with the C_Z.A changes due to a setup change which highlights that there is more negative lift in the corners which should boost performance

Figure 6 and Figure 7 are just two ways to visualize the aero map on real world data and MoTeC i2 Pro provides many different plots and graphs which can help visualize the map and the effect of changing the vehicles setup. It would also be possible to model the effect of increasing roll, pitch or heave stiffness on aerodynamic performance in a similar way to above.

PRESSURE ARRAY FOR ANALYSING ON-TRACK PERFORMANCE

While simulations proved comprehensive data and the aero map helps cover a large number of attitudes it fails to cover all the possible combinations of attitude parameters which means that in some regions the force and moment predictions have to be extrapolated. To be able to measure aerodynamic data while the vehicle drives would help get a better understanding of how the vehicles aerodynamics change with attitude. The solution to this problem was a differential pressure measurement system (DPMS) which can log like the rest of the vehicle dynamics sensors.

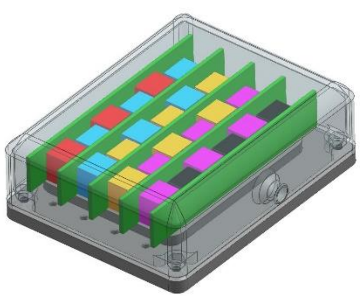

Figure 8 is a colored diagram of the internals of the pressure array with the transducers colored base on which PCB it is attached to

The ability to log with the rest of the sensors on the vehicle differentiates this pressure array from past systems developed by MMS along with the features such as steel barbs for connecting to pressure hose, a compact design thanks to tessellated transducers (shown in Figure 8) and automatic logging over CAN bus with a standard 4-pin DTM connector.

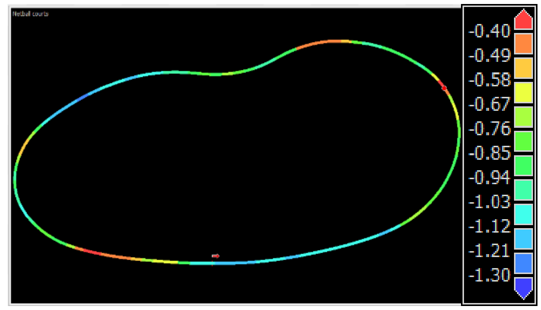

Figure 9 show a map of a small race track with 2 corners and a 10m slalom colored based on the coefficient of pressure reading on a transducer attached to the bottom of the rear wing

Unfortunately, other parts of this project took precedence which meant that while the system was produced it could not be used at more than one testing session before this report. The data from that testing in Figure 9 was produced to show the coefficient of pressure value for one of the transducers in the center of the underside of the rear wing. The pressure coefficients vary far more that the aero map would suggest however this could be a result of flow structures moving over the measured point.

WIND TUNNEL VALIDATION

While the pressure array can be used as design tool a wind tunnel can be used as a validation tool to better understand the strengths and weaknesses of the CFD simulations. To collect data to be compared to the simulations a rake of 10 4-holed probes – whose pressure values can be converted to total pressure and velocity components – was used to generate a grid (rake) of values that can be directly compared to CFD. The rake was mounted onto a traverse which moved in the vertical axis and incremented by 25 mm to cover a Z-axis range of 300mm to 900mm.

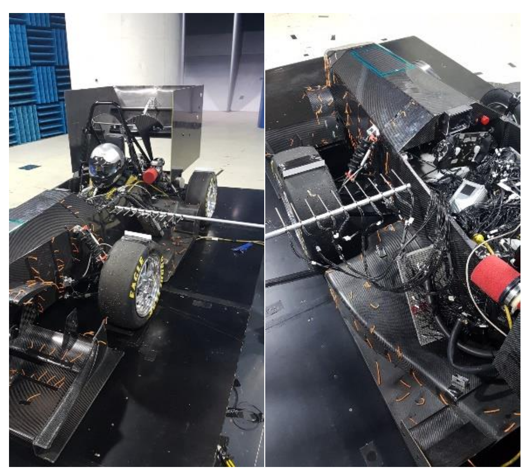

Figure 10 are two pictures of the pressure rake layout used in the wind tunnel to collect pressure and velocity data about the flow downstream of the front wheel

Once the data was collected it could easily be compared to the simulation data such as Figure 11 which shows the total pressure in both the simulation and in the wind tunnel which does a good job of highlighting the regions were the simulations are strong and where they are weak. In Figure 11 the key flow feature is the nose wing vortex at Z = 680mm and Y = 480mm which is tighter and smaller than the vortex predicted by the CFD model even though it predicts the location of the flow structure very well. The more warrying regions is the region between Y = 350mm and Y = 500 and Z = 300 and Z = 500 where the CFD predicts a pocket of very low total pressure which does not appear in the wind tunnel.
The regions of high total pressure which have low turbulence are within 1% error between simulation and wind tunnel which aligns with the expectation that the fluid flow in low turbulent regions is well predicted by CFD while CFD has trouble with predicting the highly turbulent regions. This weakness of the CFD simulations pushes towards more use of the pressure array when developing aerodynamic concepts for the MMS team.

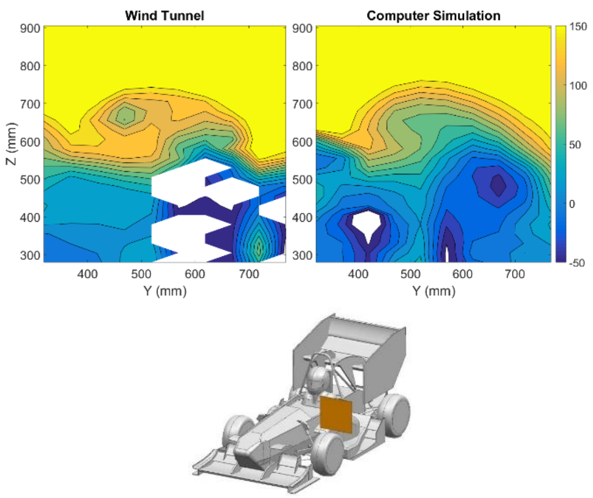

Figure 11 is a comparison between the predicted total pressures on the plan in the bottom diagram by CFD compared to the valued collected in the wind tunnel

The data collected from the pressure rake and traverse was some of the most detailed and valuable data the Motorsports Team has collected. It is suggested that this method be used whenever possible in the future to collect data on the flow structures around the vehicle when in the wind tunnel.

CONCLUSIONS

This project focused on understanding the aerodynamic loads on a Formula Student race car across the feasible set of attitudes and how vehicle setup could be used to take best advantage of the aerodynamic loads. The loads could be predicted using a set of 47 CFD simulation which included a 6 by 6 map for FRH and RRH, a map of 3 roll angles and 5 map points for both yaw and steer individually. These simulations were completed by an automated system which used a parameterized script to complete the 47 simulation in ANSYS Fluent on the MonARCH cluster.
The aero map data could be converted into an aero function which takes the FRH, RRH, roll, steer and yaw of the vehicle and returns the force components and moment components about the vehicle's axis. This can be used within a vehicle model or as in this report coupled to on-track data to help determine the effect of setup changes on the aero dynamic performance.
So that on-track data could include some pressure measurements a DPMS was designed to work with the vehicles CAN bus so that the pressure data could be analyzed in the context of the entire vehicle. While the system was successful the tight timeline did not allow for proper collection of data and analysis.
The data from the wind tunnel, on the other hand, proved to be far more useful that data previously collected because rather than collecting force values from the wind tunnels Kistlers a rake of 10 4-hole probes was used to produce a grid of data points of the 3-components of velocity, total pressure, static pressure and dynamic pressure which helped understand the CFD simulations strengths and weakness.
This project successfully covered a wide range of processes centered around understanding the aerodynamics of a Formula Student race car as its attitude changes around the track and showed how the simulation data could be used to analyze the impact of vehicle setup changes on the aerodynamic performance.

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REFERENCES

Franklyn J, Kelecy, Coupling Momentum and Continuity Increases CFD Robustness, 2008, https://www.ansys.com/-/media/ansys/corporate/resourcelibrary/article/aa-v2-i2-coupling-momentum-and-continuity.pdf
Hashan Mendis, Better meshing using ANSYS Fluent Meshing?, 2018, https://www.linkedin.com/pulse/better-meshing-using-ansys-fluent-hashan-mendis/?published=t
Mark Keating, Accelerating CFD Solutions, 2011, https://pdfs.semanticscholar.org/b209/aceb802f67e862bd49dc4f1b2748a7ff9a17.pdf
Xin Zhang, Willem Toet and Jonathan Zerihan,2006, Ground Effect Aerodynamics of Race Cars