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PSCC Formula SAE Aerodynamic Sub-Team

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PSCC Formula SAE Aerodynamic Sub-Team

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This project is a senior design project under the Tickle College of Engineering at The University of Tennessee, Knoxville. The primary goal of this senior design project was to develop aerodynamic tools for Pellissippi State Community College's Formula SAE team. The aerodynamic package was divided into three sections; front wing, floor, and rear wing. The final design resulted in a -2.07 lift to drag ratio, -2.8 lift coefficient, 1.35 drag coefficient, and a balance at 24.6% balance from the front of the car.

I. Introduction

Formula SAE is a student automotive design competition. Formula SAE allows exposure to students to the automotive industry. Universities host teams that operate similar to an automotive firm. Teams work together to build the most competitive car. Within these teams are sub-teams that tackle different tasks. These sub-team tasks include suspension, chassis, powertrain, and budgeting. Even though all sub-teams work together, each sub-team focuses on their own duty. Hopefully, all teams are able to come together to produce a FSAE competition car.

At the end of every season there is a competition for each university team to compete. The competition is broken up into two events; static and dynamic. Static events test the team's knowledge which include cost details, design reasons, and repair cost analysis. Dynamic events test the car's performance which include braking tests, acceleration tests, a time trial, and efficiency test.

The design of a FSAE car is a single seater, open-wheel racer. This means the wheels must be able to be seen from above. The shape of the car's body is limited by regulations, but each team has the ability to make changes. Cars are normally powered by motorcycle engines and cannot have a higher displacement than 710cc.

Pellissippi's FSAE car design given to the aerodynamics sub-team was from 2021. Due to a change in leadership, this sub-team will work on a design for 2023. The aerodynamics design will be configured primarily on Solidworks with Pelissippi's 2021 model, shown in Figure 1 The model provided by Pellissippi is very simple without any aerodynamic components. The 2023 aerodynamic design could be hindered by the dated 2021 chassis.

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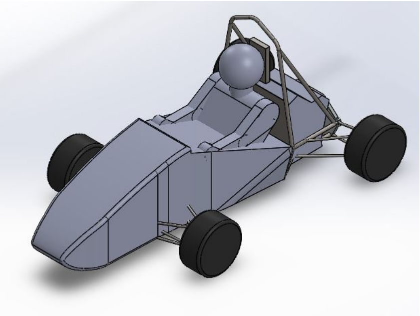

Fig. 1 Car model without aerodynamics

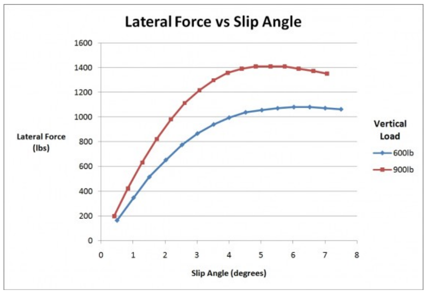

Fig. 2 Laterial Force vs. Slip Angle

The 2021 model provided did show some areas of concern. The nosecone of the car is large due to the bulkhead size and the lowest point of the car is barely off the ground. The 2021 aero designs were also provided with the model. This design consisted of a dual element front wing, a floor, and a dual element rear wing. The front and rear wing were both used in the 2021 competition while the floor was never attached to the car.

Aerodynamics determines many characteristics of race cars. Aerodynamics can help with cooling, efficiency, top speed, lateral grip, and many other things. The goal for this team's 2023 aerodynamic package was to maximize downforce. Downforce is a negative lift force that pushes an object down. A FSAE car is interested in downforce to gain cornering speeds. Downforce helps cornering speed through available lateral grip. Friction force is the coefficient of friction multiplied by the normal force. The coefficient of friction cannot be easily changed in a FSAE car as most teams run very similar tires. The normal force of the car can be changed through weight and downforce. Adding weight is not a reasonable option because of the negative impacts it has on handling, braking, and acceleration. Downforce increases normal force, and therefore lateral grip, through the negative lift generated. This means that a car generating zero pounds of downforce at sixty miles per hour has less grip than a car generating fifty pounds of downforce at sixty miles per hour

II. Front Wing

A. First Design

The front wing's main purpose is to generate sufficient downforce to keep the tires in contact with the ground, as well as direct airflow over the nose and tires. Designing the front wing is a simpler process because it is the only aerodynamic part that has the privilege to see clean air. The first design for this front wing was inspired from the first and second design from the 2021-2022 season. The previous season's front wing's primary element was a S1223 airfoil with a chord of 18 inches at 12 degrees angle of attack. The main idea of the first iteration of this design was to swap the S1223 airfoil for the MSHD airfoil to compare performance.

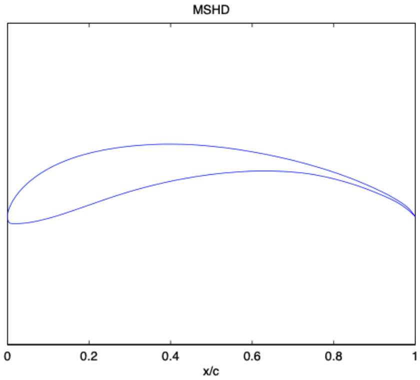

Fig. 3 MSHD Profile

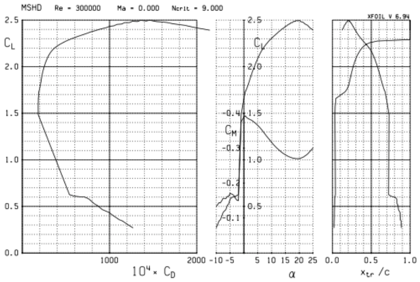

Fig. 4 XFOIL polar plot of the MSHD at Re = 300,000

The MSHD airfoil was a thesis report from North Carolina State University. "The motivation for this research was the face that race car wings are one of the few aero components that can be designed and optimized for high downforce using theoretical aero methods such as inverse design." [1]. Upon reading this paper, the MSHD would potentially be a better airfoil choice due to its purpose of being a high downforce airfoil for motorsport application. This airfoil is also favorited by many FSAE teams that do not have the resources to design their own airfoil. The MSHD is designed to have the highest downforce at 20 degree angle of attack at a Reynolds number of 300,000, shown in Figure 4.

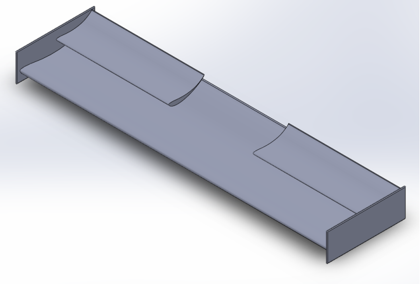

Fig. 5 Isometric view of first design

Fig. 6 Cross sectional view of first design

This design was a 1+2 design where the secondary element is broken into two pieces to provide room for the nose. The main element had a chord of 18 inches and an angle of attack of 10 degrees. The angle of attack was lowered from the 2021-2022 design to ensure design constraints are met. The secondary element had a chord of 6.5 inches and an angle of attack at 13 degrees to match the tail angle of the main element.

B. First Design Results

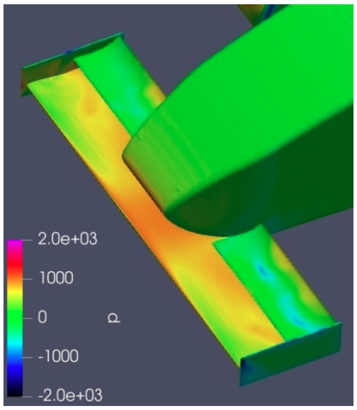

Fig. 7 Isometric view of pressure contour, version 1

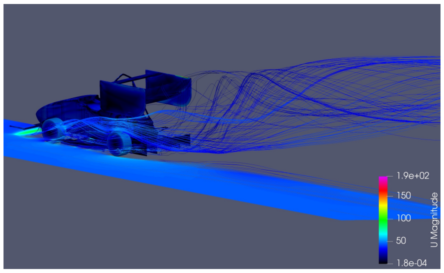

Fig. 8 Streamlines across car, rear isometric view, version 1

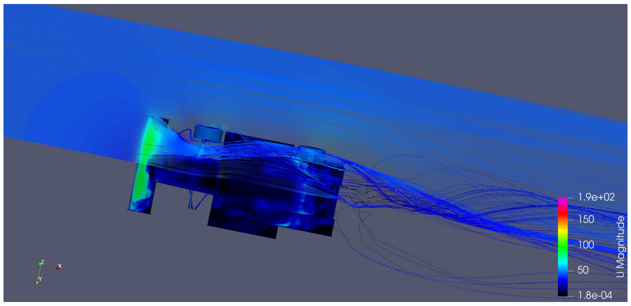

Fig. 9 Streamlines under car, version 1

Version 1 of the front wing yielded 45.5% balance with a coefficient of lift of -0.944. This is an optimal starting result because the balance is near perfect with sufficient coefficient of lift. However, the downforce is coming from where the main element meets the nose, shown in Figure 7. The pressure distribution is not even across the main element, there is a pocket of downforce underneath the nose. While the nose did create a substantial amount of downforce, there is drag. It is also shown that there are lift pockets in the secondary element, which was not expected. This could be due to flow separation.

Shown in Figure 8, the front wing set up the flow to be directed into the tires instead of over them. This was somewhat expected, because this design was focused on creating the most downforce instead of properly directing flow. In turn, this design poorly set up the floor performance because it received sparse airflow, shown in Figure 9. It is important to note that this figure displays the streamlines above and below the car due to a software display error. The sparse streams lines that are located at the halfway point of the car are underneath the car, while the brighter bunched up section of streamlines are going over the car.

C. Second Design

Fig. 10 Circa 1990 Formula 1 Vehicle

The second design's goal was to direct flow over the tires. A local computational fluid dynamics (CFD) expert recommended to take inspiration from 1990 Formula 1 vehicles. It appears that in this era of Formula 1 vehicles, the main element was symmetric at a 0 degree angle of attack while the second element is much smaller at a steep angle of attack. When analyzing this design, it was difficult to see how this design would assist in directing flow over the tires while also providing sufficient downforce.

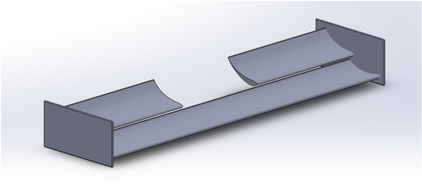

Fig. 11 Isometric view of second design

Fig. 12 Cross sectional view of second design

This design took an unconventional approach. Instead of focusing around the chassis design that was given, the focus was on developing a front wing that would support the next generation chassis. The new design considered a 2 airfoil design with a slot gap. A slot cap can be used to bleed high pressure from the first element and reduce drag. Both chord lengths of the airfoils were at 6.5 inches while the first element had a 10 degree angle of attack and the second element had a 25 degree angle of attack. This design was difficult to optimize due to the shape of the MSHD airfoil. The fore end is thick and tapers off quickly, making it hard to position the second element.

D. Second Design Results

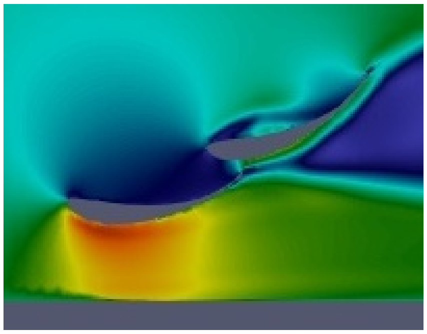

Fig. 13 Side view velocity contour, version 2

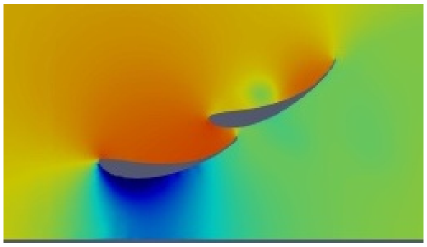

Fig. 14 Side view pressure contour, version 2

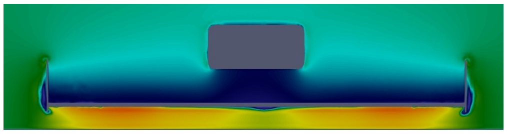

Fig. 15 Front view velocity contour, version 2

Version 2 of the front wing design performed worse than expected, yielding a balance to be 26% and lift coefficient of -0.7. This design was created in hopes that the nose would be able to blend with the front wing for the next generation chassis. When the front wing was attached to the chassis, the first element interfered with the nose and the second element had significant gaps between the nose. These interference's had a major impact on the results for this design. The system does behave normally with high pressure on the top and low pressure on the bottom and has an even pressure and velocity distribution shown in Figure 19. What was unexpected was the second element having a suction pocket, shown in Figure 14. When comparing Figure 14 and Figure 13 the cause could be boundary layer separation.

III. Floor

While designing the floor we worked inside of a few main constraints. The floor could not obstruct any part of the car's existing body or other parts, and it must clear the ground during all dynamic events. Our third constraint is more easily viewable from Figure 16. Working within these constraints did not prove to be hard, but they did limit dimensions. Another limitation for the floor is the chassis design. Pelissippi's team created a chassis with some of the frame inches away from the ground. This restriction needed to be kept in mind as air flow was limited at this choke point.

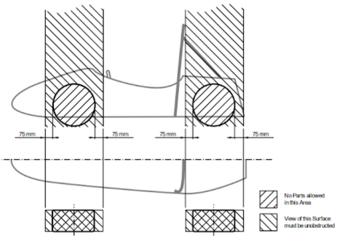

Fig. 16 Allowable area for construction of aerodynamic parts

A. First Design

When creating the first floor design was not inspired from previous examples. The car used in 2021 was run with no floor as the designed floor was doing more harm than help. The floor was not used in competition due to mounting issues. With this design the goal was to maximize the flat floor area within the size constraints, along with putting emphasis on the rear diffuser. The goal of any race car floor is to use this instrumental area to create downforce. This downforce is created by forming a low pressure region under the car which creates a suction-cup effect. The side skirts between the front and rear wheels were designed based on the hypothesis of controlling air between the tires. Air around moving wheels takes a large toll on aerodynamic flow. The skirts were made to help regulate flow between the tires to keep this ‘dirty’ air away from the flat floor’s streamlined air.

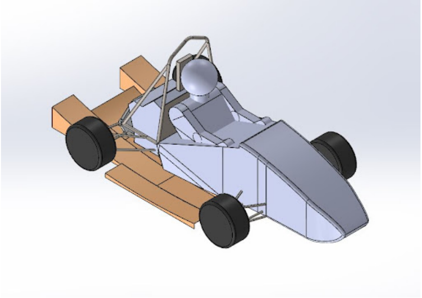

Fig. 17 Isometric view of floor, first design

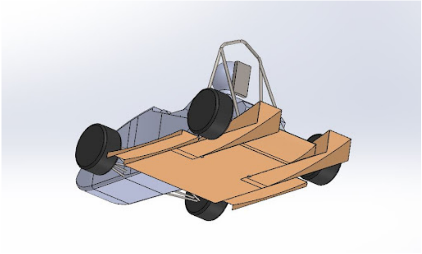

Fig. 18 Rear isometric view of floor, first design

B. First Design Results

The design for this floor was based on maximizing usable area to create a flat floor in front of the rear diffuser. A flat floor helps streamline the air. Creating a flat floor in front of the diffuser allows laminar flow to reach these diffusers while producing less drag. Though this design was a great start, our CFD expert told us that there is much to be gained from the front center of the floor. The analysis that he provided us with showed how the floor was creating drag and pressure at the front, and this needed to be corrected for our next iteration. The main problem with this design was the height of the floor. The flat floor was mounted just low enough to clear the lowest point of the chassis. The drag at the front of the floor was caused by a pocket in front of the mounting pad. In the figure below, air velocity is seen underneath the car. The flat floor and diffuser do increase velocity of the air, but only slightly. This is due to the limited airflow through the diffuser as the floor is so low.

Fig. 19 Velocity profile under floor, first design

C. Second Design

The second design for the floor had most of its focus on diffuser tunnels. These tunnels would flow from behind the front wheel, inside the rear wheel, and out of the rear of the car. This diffuser design starts around the cockpit to push more air to the rear as seen on the Lotus 79 shown in Figure 22. The idea behind this design is a diffuser tunnel shaped like an inverted wing to increase the velocity of air underneath the car to provide downforce.

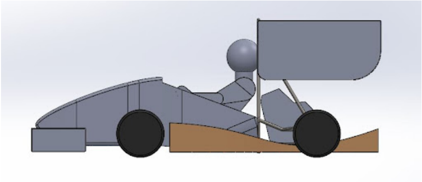

Fig. 20 Side profile of floor, second design

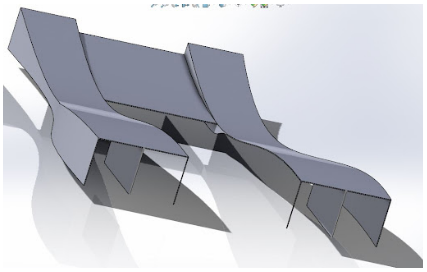

Fig. 21 Isometric view of floor, second design

The Applied Aerodynamics section of Race Car Vehicle Dynamics [2] encourages use of fences or fins. These were added inside of these diffusers tunnels to encourage laminar flow and coax the maximum amount of controlled air down the diffuser path. Airflow coming off of wheels tends to divert flow laterally into the underbody of the car. This dilutes the suction cup effect, which is the goal of the floor in order to provide downforce.

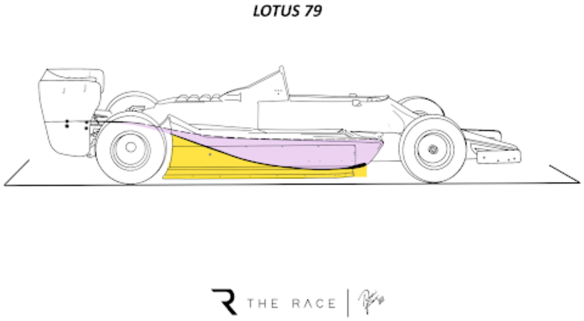

Fig. 22 Lotus race car side profile

D. Second Design Results

Before creating a centerboard for this design it went under CFD analysis with SolidWorks and ran into some problems leading us to discard this design. The floor design was creating lift at both testing speeds of 60 mph and 100 mph. The design was then modified by decreasing the inlet size for the diffuser tunnels. This led to less lift being generated, but it was understood that this design should not be further progressed. The reason why it created lift could be due to the throat, small cross sectional area, of the diffuser tunnel being too limited for the amount of incoming air causing a high pressure point. This high pressure point pushes up against the floor which results in lift

E. Third Design

The third and final design is similar to the first floor design. Both of these designs have a goal to use controlled air under the floor. Our CFD expert recommended by pitching up the front of the floor and raising the floor overall allowing for more air flow underneath the car. Diffuser fences were used, similar to the ones introduced in the second design.

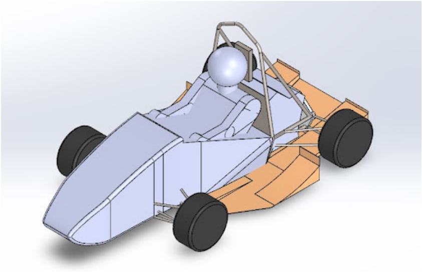

Fig. 23 Isometric view of floor, version 3

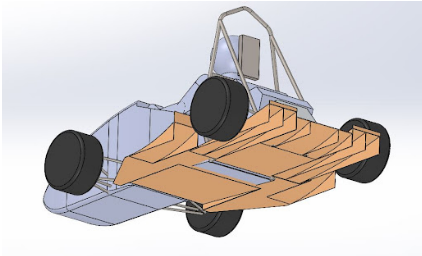

Fig. 24 Rear view of floor, version 3

Gurney flaps have been added to the top end of diffusers in order to create more downforce utilizing air flowing over the floor. These ran in front of the rear wheel and above the rear diffuser in an effort to form even more downforce additional to our low pressure area under the floor. The intentions of the gurney flaps in front of the rear wheel are to direct air over the rear tire to obtain less drag and hopefully more downforce. The effect of the gurney flaps in front of the wheels on air velocity can be seen in Figure 26.

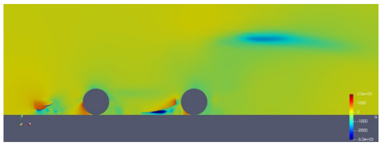

Fig. 25 Velocity profile showing gurney flaps, third design

F. Third Design Results

The results obtained from Design 3 proved to be the best in this case. It provided the most downforce comparatively. Though it did produce more drag compared to the other designs, the downforce gained proves to be more valuable. Figure 26 displays the velocity profile can be seen underneath the floor. Low velocity enters the floor, flow speeds up, and exits the diffuser.

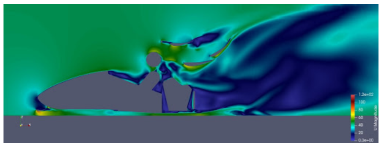

Fig. 26 Velocity profile, third design

IV. Rear Wing

Rear wing design began with background research into other Formula SAE designs. Other teams publish their designs paired with justifications for their decisions. Similarities that appeared in many designs were noted. One of the most common design decisions was to make the rear wing multi-element. Multi-element wings are frequently used in high downforce applications. This is done so a much higher angle of attack can be used. One large airfoil will experience flow separation and stall at a much lower angle of attack than a multi-element foil.

The aerodynamics group was directed by the team at Pellissippi State to maximize downforce while giving minimum consideration to drag. For this reason, the design goal was to use as much of the allowed area as possible. This area can be seen at Figure 16

The rules specify that the rear wing “must be no higher than 1200 mm above the ground. . . no more than 250 mm rearward of the rear of the rear tires” and “Inboard of two vertical planes parallel to the centerline of the chassis touching the outside of the front tires at the height of the hubs”. By measuring last year’s car, it was initially found that the rear wing would be bound by a box 42 inches wide, 20 inches tall, and 37 inches long.

While professional racing series limit the number of elements which the rear wing may use, Formula SAE does not. Therefore, additional airfoils mounted at the forward upper limit of the bounding box were considered. A similar implementation was used in Formula One prior to 2004, when three elements were allowed. A similar concept has been implemented by some other Formula SAE teams as well. The primary limitations on the number of airfoils used are the time and cost associated with manufacturing and the weight associated with those elements.

Fig. 27 Formula 1 rear wing

A. First Design

When selecting an airfoil, the first consideration was Reynolds number. An estimated value was found by researching what other teams reported, these numbers were then validated with an estimate of our own based on the speeds predicted for the competition. The other consideration made was thickness. Because thicker airfoils are easier to construct, and the rear wing will be made with several airfoils, airfoils with long skinny tails were eliminated. With all these factors considered, the FX 63-110 was chosen, displayed in Figure 28

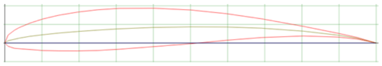

Fig. 28 Inverted FX 63-110 airfoil

The initial design used three of these airfoils in a multi-element main wing and two more airfoils mounted in a slat position. To simplify manufacturing by reducing the number of unique wing molds required, all the elements except the lower mainplane were made to the same size. This design allows the system to have multiple elements with only two molds.

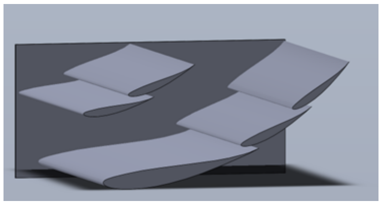

Fig. 29 Rear wing initial design

Moving from this initial design into first version, the main wing was reduced to two elements and the upper system to one. The two flaps retained their similarity such that still only two molds would be required for construction. These flaps were also modified with small gurney flaps to improve their downforce generation relative to their overall size. In an effort to distribute the downforce generation towards the front of the wing while maximizing total generation with the FX 63-110, which has low zero angle of attack downforce, the mainplane was run at an atypically high angle of attack. A simple cut was made to the trailing edge of the mainplane to allow airflow to bleed to the underside of the rear flap without having either scale down the entire mainplane have its tail having positive lift due to its interaction with the flap.

The rounded lower rear corners of the endplates from the previous year's car were also restored to reduce the weight of the endplates.

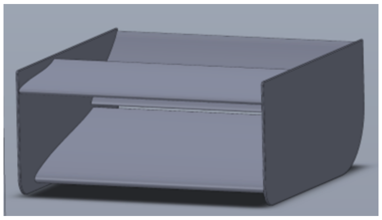

Fig. 30 Isometric view of rear wing, first design

B. First Design Results

After sending the car with the first version aerodynamic package for professional CFD analysis, the team received feedback that the roll hoop was too close to the underside of the main element. This hindered the rear wing's ability to generate low pressure on the bottom side, thus leading to less downforce. The CFD analyst recommended raising the element to minimize this issue. The CFD analyst also recommended mounting the slat at a steeper angle for improved performance.

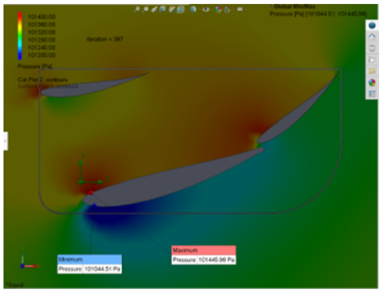

Fig. 31 CFD Results, first design

C. Second Design

While reviewing the mounting of the wing to the body, it was found that dimensions for the bounding box had been to be slightly larger than the correct values. As part of the effort to regain the downforce lost by resizing the wing to fit within the correct bounding box, the decision was made to switch to the S1223 airfoil as used by the previous car due to its favorable low speed performance. This was done after revisiting the assumption the goal was to avoid airfoils with long skinny tails. After discussion with a team member who constructed the previous year's wing, this decision was no longer a priority. The mainplane was leveled off to a more conventional angle of attack as the S1223 has much greater low angle of attack downforce; this also raised the front of the mainplane, reducing the interference from the roll bar in front, unfavorable interaction with the upper flap and the engine under the wing, and allowed the flap to be increased to 38 degrees angle of attack without stalling at the target speed of 30 miles per hour. Cursory verification of the new mainplane placement found that further separating it from the trim element realized negligible improvement in downforce in tests that did not include the effects of the engine mounting. The gurney flaps were extended on the advice of the CFD analyst from 2% of the wing's chord to 0.5 inches. Additional cutouts were made to the endplates above the main wing and behind the upper flap to further reduce the weight of the wing and reduce the domineering visual presence it has on the car overall for the aesthetic element of the competition without severely impacting the wing's performance.

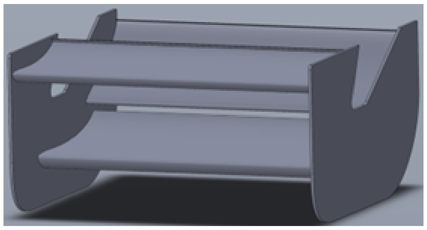

Fig. 32 Isometric view of rear wing, second design

Fig. 33 Cross sectional view of rear wing, second design

D. Second Design Results

For the second version, the CFD analyst gave limited recommendations for the rear wing. A recommendation was made to further examine the flow interactions around the slot gap between the two main elements. Attention was also given to the placement of the trailing edge of the rear flap relative to the endplate: the endplate's extension beyond the flap has negligible benefit, and can either be removed to reduce weight or be used to facilitate moving the entire main wing, which might reduce interference between the upper flap and the mainplane.

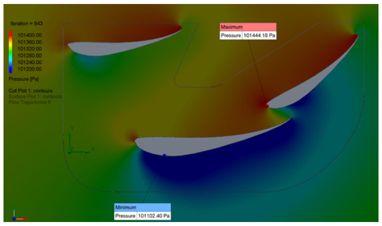

Fig. 34 CFD results, second design

V. Conclusion

A. Front Wing

While the MSHD airfoil showed promise, it is not the optimal airfoil to use for the front wing system. The airfoil is able to provide sufficient downforce, but its shape and optimal angle of attack makes it difficult to work with a small constraint. This front wing system has the ability to be optimized by switching the primary airfoil in the second version for a symmetric airfoil, much like 1990s Formula 1 vehicles, to see if it truly would help with overall downforce. Another option would be to design the car's nose to blend in with front wing, similar to modern day Formula 1 vehicles. Having the nose blend into the wing can assist in forcing the front wing system to generate downforce, as well as reduce drag.

B. Floor

Overall, the floor proved more difficult than originally thought. The limited room underneath the chassis paired with the low speed of FSAE cars led to unorthodox designs. The part most beneficial to downforce used air going over the floor. This floor can be improved by a more finely tuned diffuser angle and a rounded rear diffuser as seen on the Aston Martin Valkyrie. Refining the chassis of the car could also lead to more opportunities for the floor.

C. Rear Wing

Currently, the rear wing's performance is limited by the aerodynamic balance of the car moreso than the absolute limits of the rear wing itself. Further optimization of the rear wing is likely to be able to extract greater downforce if the other aerodynamic devices can match any increase. Otherwise, it may be more optimal to reduce the overall downforce of the wing by resizing elements or the entire structure so that the downforce generation could be moved forward to allow for more downforce without disturbing the overall balance. The distribution of the downforce over the entire vehicle and the interactions between the aerodynamic elements and the chassis are the natural evolution of the project. For the rear wing in particular, the interactions between the wing and the roll bars, engine, and the wing mounts should be considered, and new methods may need to be developed to test these interactions outside of the professional CFD analyses.

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References

[1] Pakkam, S. S., "High Downforce Aerodynamics For Motorsports," 2011.

[2] Milliken, W. F., and Milliken, D. L., *Race Car Vehicle Dynamics*, Society of Automotive Engineers Inc., Great Britain, 1996.