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Simulating the Effects of Active Aerodynamics on the Suspension System of a Formula Student Race Car

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ABSTRACT

Active aerodynamics is a growing topic in the automotive industry. With technological advancements at play, it has begun to spread across multiple avenues such as road vehicle ride comfort and the development of active suspension systems. However, the application of active aerodynamics in Formula cars has not been a commonly discussed topic. Furthermore, the effects of active aerodynamics on the suspension system have not been assessed for Formula Student race cars. Therefore, this study looks to obtain an understanding about how actively changing the Angles of Attack of an aerodynamic front wing and a rear wing would affect the suspension system of a Formula Student race car. The study was done by first choosing a wing profile using the XFLR5 software, modelling the front and rear wings using SolidWorks, according to the parametric guidelines of the Formula Student Competition for different angles of attack, analysing coefficients of lift and drag of the wings for each angle of attack using Ansys Workbench, and by performing full-vehicle acceleration and cornering analyses on MSC Adams Car to find how changing these coefficients affects the suspension dampers along the direction normal to the ground the vehicle travels on. This research would help understand the many forces acting on the suspension and to explore further developments in this area such as active aerodynamics in Formula Student race cars in the future.

KEYWORDS: *Aerofoil, Angle of Attack (AOA), Lift, Drag, Formula Student United Kingdom (FSUK), Computational Fluid Dynamics (CFD), Coefficient of Lift (C_L), Coefficient of Drag (C_D), Computer Aided Design (CAD).*

1 INTRODUCTION

1.1 Background

Active aerodynamics is a trending topic in the automotive industry. As a result, applications of active aerodynamics can be observed in various sectors such as racing and road vehicles. Static aerodynamics comes at a price where there is a compromise between the optimal performance levels obtainable by the vehicle aerodynamics in one environment and another. Active aerodynamics seek to improve this by changing the geometric parameters of the wing elements to suit the environment (i.e., straight line, cornering etc.). When implementing such a system, its effects on various vehicle components should first be analyzed. Hence, studies can be carried out to assess how it impacts the different suspension components of a vehicle.

This study was carried out based on a Formula Student race car, to analyze how changing the attack angles of the front and rear wings would affect their downforce and drag coefficients, and as a result, how it would affect the forces acting on the suspension dampers of the car. In this study, the wing profile was chosen after subjecting a group of aerofoils to an XFLR5 analysis. The front and rear wings were modelled based on the selected wing profile using a CAD software. The angles of attack of the modelled wings were changed, and CFD analyses were carried out to calculate their lift and drag coefficients. These coefficients were then used in running two full-assembly simulations on a multibody dynamics software to obtain the results.

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1.2 Objectives

The objectives of this study are to research and develop aerodynamic front and rear wings for a Formula Student race car, to find the coefficients of lift and drag of the wing set-ups using computational fluid dynamics software, and to analyze how these results affect the suspension dampers of a Formula Student race car.

2 LITERATURE REVIEW

Research carried out on the active control of aerodynamic surfaces for ride control in sport vehicles by Carlo Doniselli et al. (Doniselli et al., 1996) have utilized a 12-degree of freedom full car model to analyze the suspension forces. M. Corno et al. (Corno et al., 2014) have conducted research based on a quarter car model, whereas, E. Ahmed et al. (Ahmad et al., 2020) have used the half car model to carry out the research. This research was carried out using the MSC Adams multibody simulation software to obtain the forces acting on the suspension system due to the wide use of the software in the industry and the high accuracy of the results obtained.

For the numerical analysis, the Reynolds Averaged Navier Stokes equations are used. Among these equations, the SST-k-ω and k- ε variations are reviewed. According to Z. Deng et al. (Deng et al., 2020), the k- ε model can be used to express important properties in a turbulent flow. Furthermore, although, the k- ε model predicts the drag coefficient more accurately than the k-ω model, according to F. R. Menter (Menter, 1993), when the boundary layers have adverse pressure gradients, and flow separation, the performance of the k-ω model is higher than that of the k- ε model as the SST k-ω model can account for the principal shear stress transport in adverse pressure gradients. Hence, the SST k-ω model was used in this research. This calculation is done in Ansys Workbench.

According to J. Kiedrowski et al. (Kiedrowski et al., 2020), state of the art front wings consist of multiple elements. Furthermore, increasing the angle of attack of the wing elements would cause it to increase the drag coefficient up to a certain point where the wing would begin to stall. Therefore, in this research the angles of attack of one front wing element were changed and the results were taken into consideration.

According to S. Kajiwara (Kajiwara, 2017), passive type of rear wings that utilize three elements have shown to reduce the drag caused by the vehicle drastically. This research utilized three wing elements out of which two were fixed and the middle element was allowed to swing. This has shown to reduce the lap time of the car. However, in this research, two elements have been used to model the rear wing. A fixed main element and a variable, secondary element.

According to V. Kshirsagar et al. (Kshirsagar & Chopade, 2018), the vehicle should be subjected to a wind tunnel test, CFD simulations and a track test. This research focuses on the Computational Fluid Dynamics aspect among these tests.

Based on studies carried out by Shafi Md. Istiak et al. (Flay et al., 2008), Flat et al (Flay et al., 2008), and Shreyas Vaidya et al. (Shreyas Vaidya & Chinmay Kulkarni, 2017), the NACA4412, E423, and the S1223 airfoils are the most suitable airfoils to be used in Formula Student cars. Hence, these wing profiles were considered when selecting an aerofoil for the research.

3 METHODOLOGY

3.1 Selecting a Suitable Aerofoil

As per the referred literature, three aerofoils were shortlisted. They are namely, S1223, E423, and NACA4412. The aerofoil analysis shown in Figure 1 was carried out on the XFLR5 software, and they portray the pressure coefficients of the shortlisted wing profiles. The following excerpts of the graphs drawn by the software depict the Coefficient of Lift (C_L) and Coefficient of Drag (C_D) variations at different angles of attack simulated at an air velocity of 20m/s.

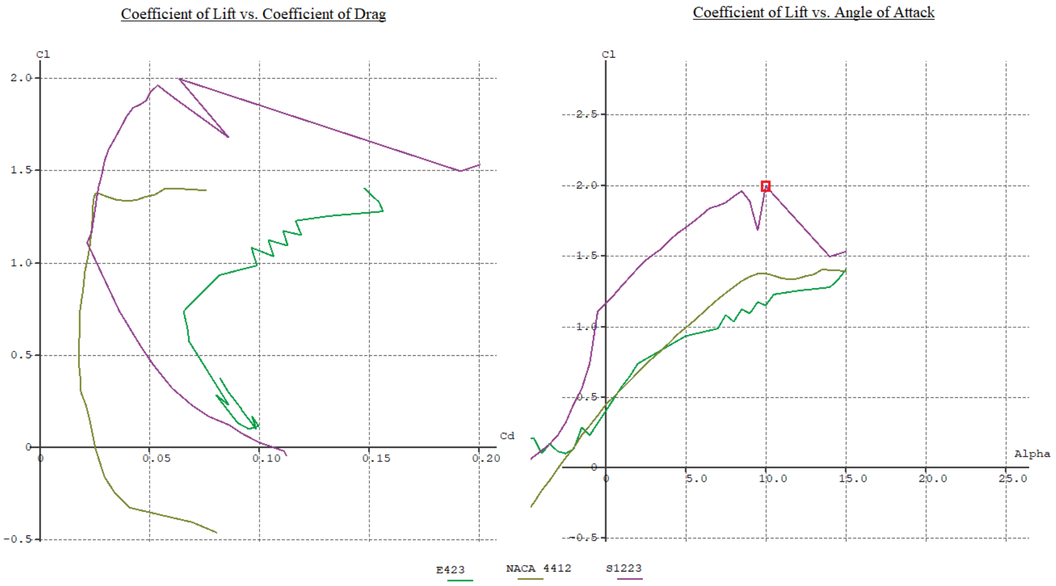

Figure 1. C_L vs. C_D, and C_L vs. AOA of the selected aerofoils

By observing Figure 1, it can be noticed that the S1223 aerofoil provides the best combination between the Lift and Drag Coefficients. Furthermore, it can also be observed that the angle of attack which provides the highest Coefficient of Lift by any of the selected wings, is shown by the S1223 aerofoil at an angle of 10°. This aerofoil will be used in the rear wing elements as well as the front wing elements. The angle of attack will be selected as 10°, based on the results from the XFLR5 simulations carried out.

3.2 Computational Modelling of the Wings

When modelling the front and rear wings on SolidWorks, the parametric guidelines of the FSUK competition were adhered. The span of the front wing was kept at 1520mm, the chord length of the main front element is 500mm, and the chord length of the entire front wing set-up is 700mm. The chord length of the main rear element is 500mm, the chord length of the secondary element is 250mm. The span of the rear wing is 1020mm.

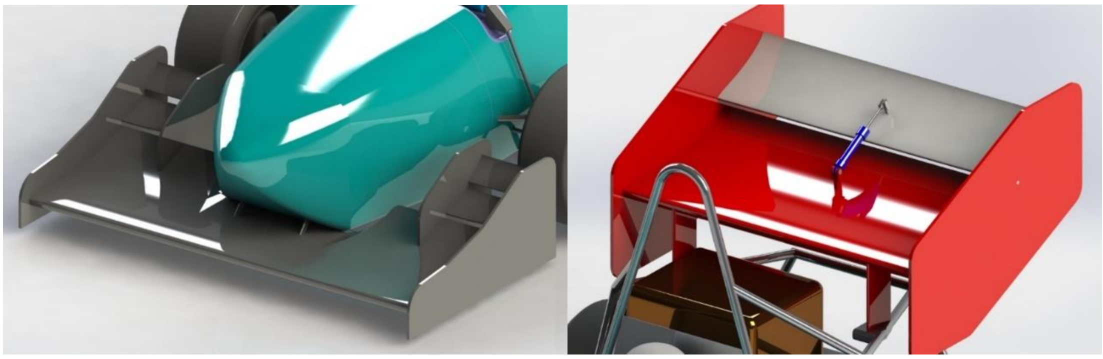

Figure 2. The Front and Rear Wings Modelled for the Study

Figures 2, 3 and 4 show the front and rear wings respectively. The AOA of the second element of the front wing were adjusted to emulate the adjustments made by the active aerodynamic system whereas, the second element of the rear wing was adjusted for the same purpose. In this case, the attack angle of the front wing was changed by factors of 5, starting from 20° whereas, the angle of attack of the rear wing was changed by factors of 10, starting from 20°. Three separate SolidWorks models for the front wing with three different AOAs, and three separate models for the rear wing with three different AOAs were constructed and were used along with the vehicle body developed by the racing team. These models were then subjected to CFD simulations where the lift and drag coefficients were calculated.

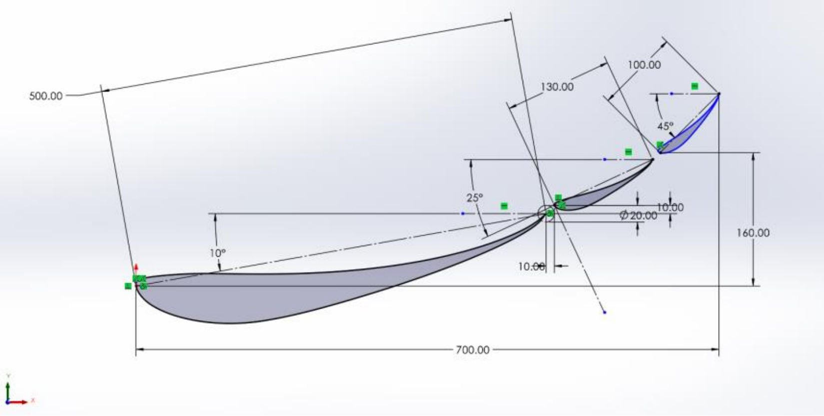

Figure 3. Front Wing Parameters

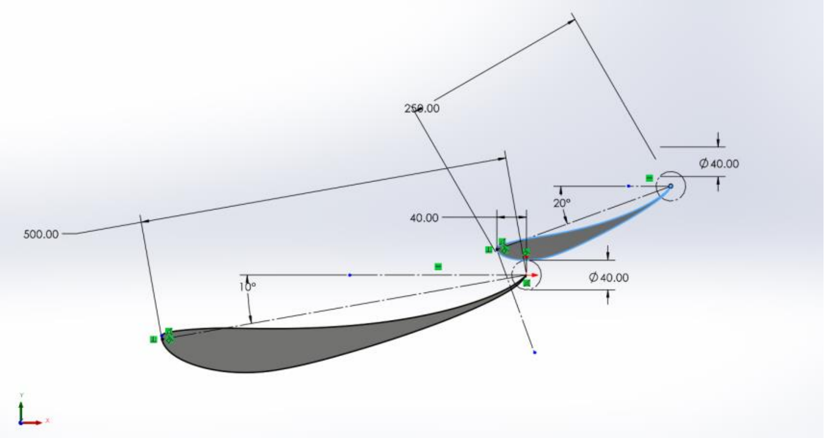

Figure 4. Rear Wing Parameters

3.3 Computational Fluid Dynamics (CFD) Analyses

Table 1. Enclosure Parameters

Dimension	Value
H1	1.25m
H2	7.5m
V3	3.0m
V4	2.5m
Width (Extruded)	3.0m

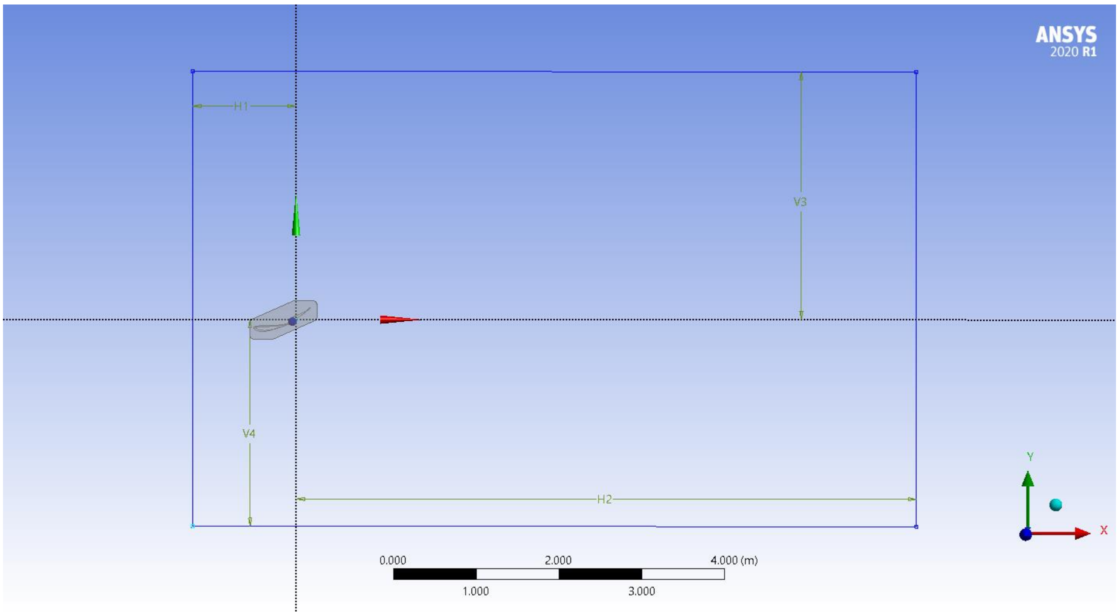

Figure 5. Graphical representation of the computational domain

The CFD analyses for the front and rear wing variations were carried out based on the parameters shown in Table 1 and depicted in Figure 5. Further refinements to the mesh were done by adding another block that was 0.6m in height, starting from the rear edge of the wing. Edge sizing, and inflations were added to refine the mesh. The following are several excerpts from the CFD simulations carried out. The wings were cut in half to reduce the computational capacity required for the simulations. The pressure and velocity acting on the wings were calculated. The contours in Figure 6 show the pressure gradients and the velocity gradients from one of the nine simulations carried out.

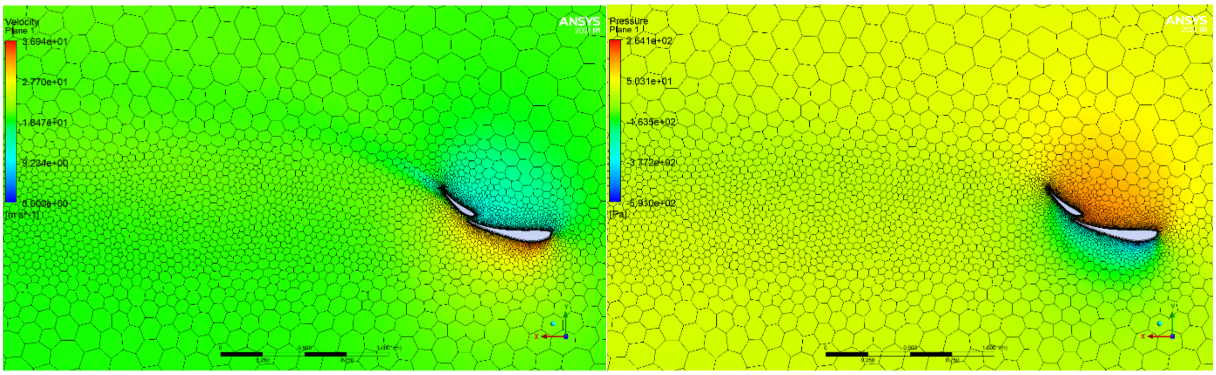

Figure 6. The Hex-Meshed Pressure and Velocity Contours of a 40° Rear Wing

The goal of the simulations shown in Figure 6 was to find the coefficients of lift and drag on the wings, to be used for the MSC Adams simulations. The contours in Figure 6 show the areas where there is high velocity in the front and rear wings. In the high-velocity areas, the pressure is less, whereas, in low velocity areas, the pressure is high. This effect creates a downforce on the wing. This is shown in Figure 6 with respect to the rear wing with an angle of attack of 40°. The Hex Mesh is shown here to depict the refinements of the mesh to improve the accuracy of the study. The simulations for the race car body were carried out on SimFlow and postprocessed using the Paraview postprocessor. The CFD analysis results obtained for different front and rear wing angle of attack combinations are shown in Table 2.

Table 2. Lift and Drag Coefficients and Projected Area required for Adams Analyses

Wing	**Component and/or AOA**	**Coefficient of Downforce** $(-C_L)$	**Coefficient of Drag** (C_D)	**Air Speed** (m/s^2)	**Air Density** (kg/m)	**Projected Frontal Area** (mm^2)
Front Wing	20°	0.30	0.07	20	1.225	238748.28
	25°	0.44	0.07	20	1.225	238748.28
	30°	0.40	0.09	20	1.225	238748.28
Rear Wing	20°	0.49	0.11	20	1.225	240785.84
	30°	0.61	0.16	20	1.225	274851.57
	40°	0.73	0.23	20	1.225	307093.9
Chassis	Chassis	0.31	0.71	20	1.225	947574.6

The coefficients of lift are negative as a result of the forces produced by the inverted aerofoils, towards the ground direction. Hence, this force is known as the ‘downforce.’ The coefficients of lift (in this case, coefficients of downforce) of the front wing seem to have improved up to 25° and dropped at 30°. The coefficients of lift of the rear wings seem to have improved up to an AOA of 40°. The drag coefficients seem to have improved in the front wings up to 30° whereas, the drag coefficients of the rear wing have increased up to an AOA of 40°.

3.4 Vehicle Dynamics Simulations

Two Adams Car simulations were carried out for nine different Front and Rear Wing combinations. The first type of simulation carried out was a Straight-Line Acceleration Event. This was done to analyse how the vehicle components (in this study, the suspension damper) act when subjected to straight-line acceleration. In this event, a starting velocity of 20kmph at the second gear, and a final throttle of 100 were provided. The vehicle shift gears until the acceleration event is completed after duration of the simulation. The second type of simulation carried out was a Constant Radius Cornering Event for the vehicle. This was done to analyse how the vehicle components (in this study, the suspension damper) react when subjected to a cornering event. For this event, an arbitrary value of 61m was provided as the cornering radius, the starting gear position was given as 2nd, the final velocity was given as 80kmph, and the initial velocity was given as 10kmph. These values were kept constant throughout the entire study. The default parameters of the Adams Car Formula Student race car model were used for the reference model. The Acceleration and Cornering event settings were adjusted as shown in Tables 3 and 4.

Table 3. Acceleration Event Settings

Variable	**Value**
End Time/Duration	50 Sec
Number of Steps	500
Velocity	20 km/hr
Gear Position	2
Steering Input	Straight Line
Start Time	10 Sec
Final Throttle	100
Duration of Step	0.1

Table 4. Cornering Event Settings

Variable	**Value**
End Time/Duration	50 Sec
Number of Steps	500
Initial Velocity	10 km/hr
Gear Position	2
Duration of Manoeuvre	10 Sec
Final Velocity	80 km/hr
Turn Radius	61m

4 RESULTS AND DISCUSSION

4.1 For a 25° Front Wing and a 30° Rear Wing

- Acceleration Event

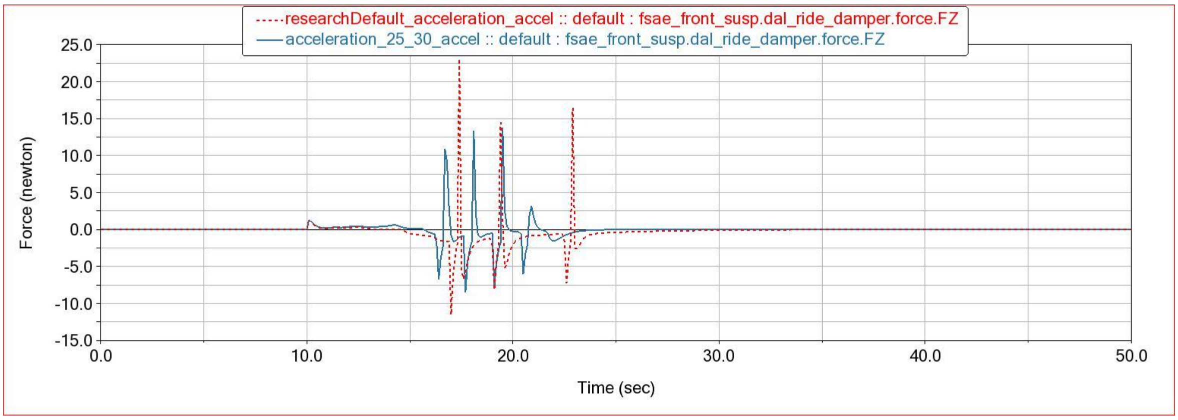

Figure 7. Front-Left Suspension Damper

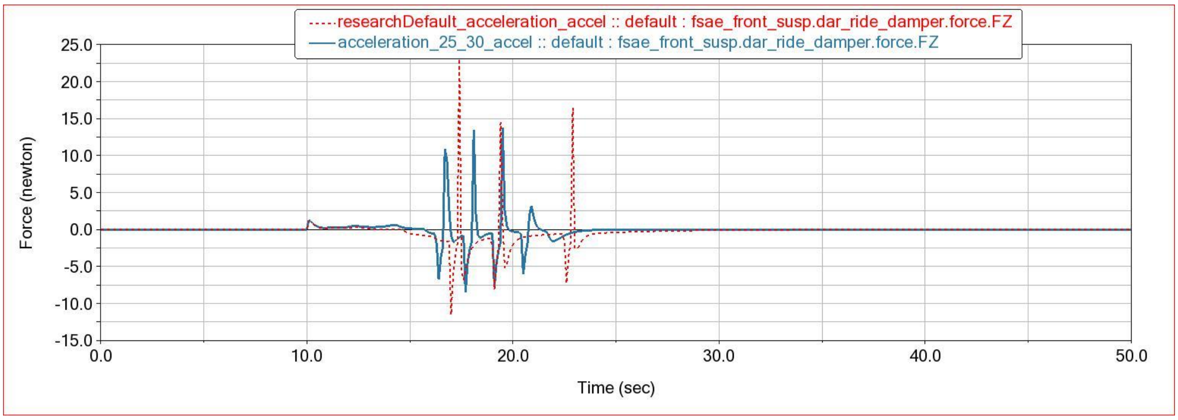

Figure 8. Front-Right Suspension Damper

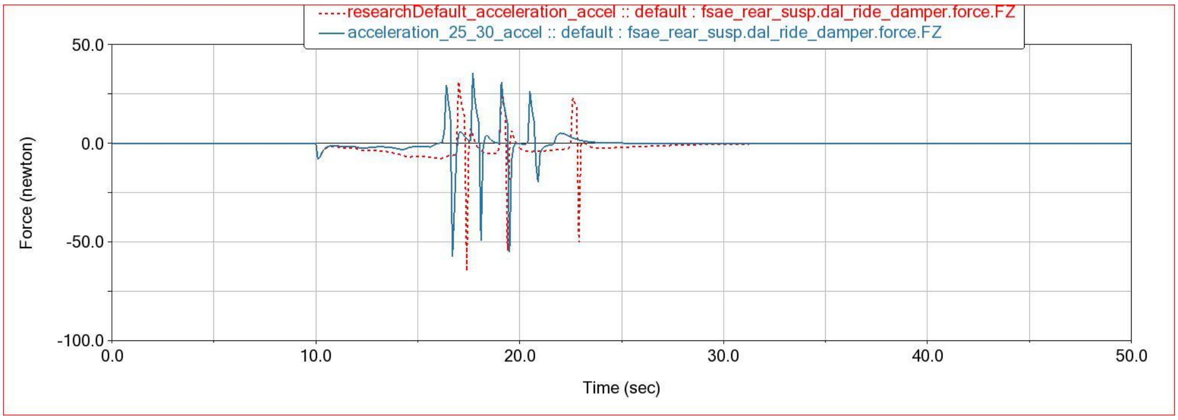

Figure 9. Rear-Left Suspension Damper

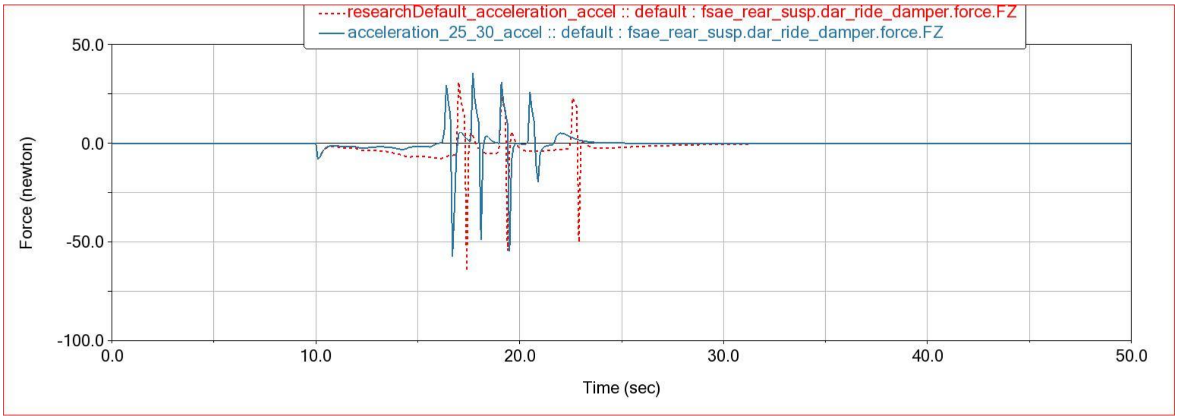

Figure 10. Rear-Right Suspension Damper

In the acceleration event (Figured 7 – 10), it can be observed that the forces acting on the suspension dampers have reduced due to the low downforce coefficient of the newly designed wings. However, it can also be observed that the rate of braking that occurs in the vehicle has improved. The car reaches overdrive at a higher rate. This may be due to the dramatically low drag coefficients recorded by the newly designed wings in comparison to the reference model in Adams Car.

- Constant Radius Cornering Event

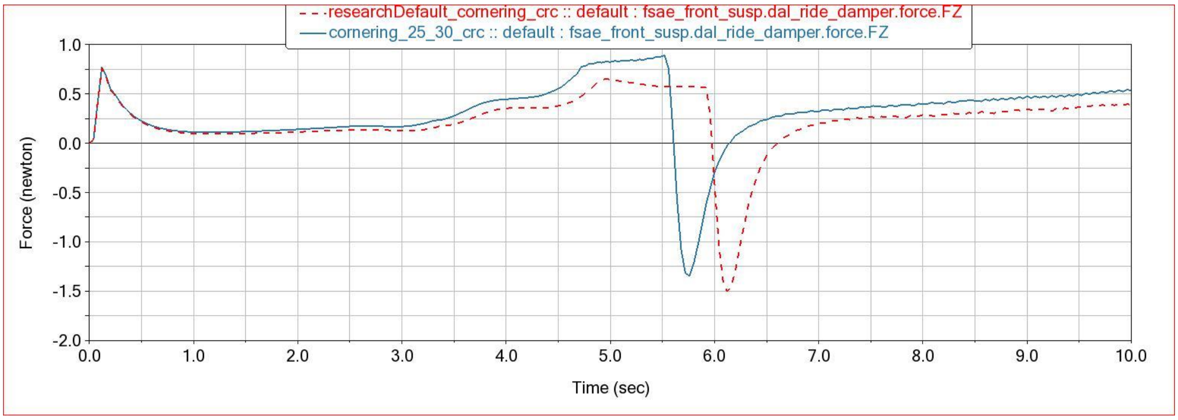

Figure 11. Front-Left Suspension Damper

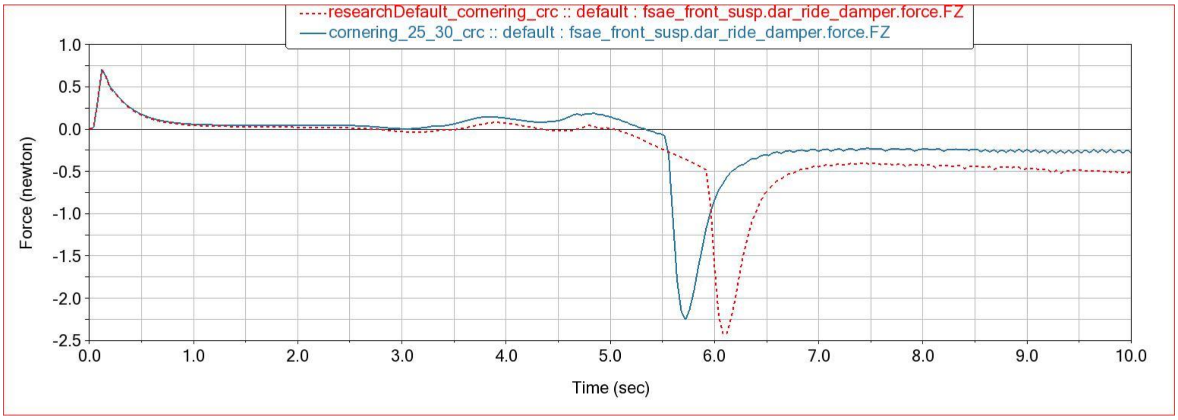

Figure 12. Front-Right Suspension Damper

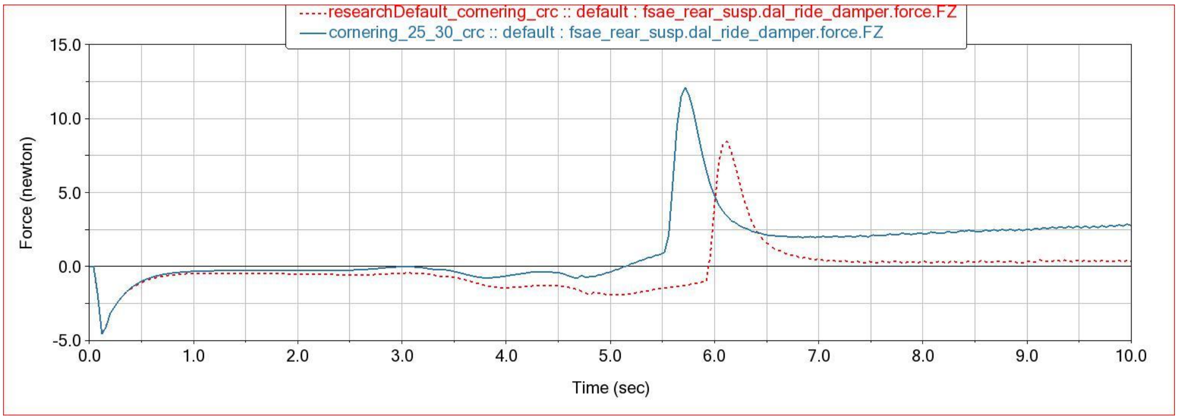

Figure 13. Rear-Left Suspension Damper

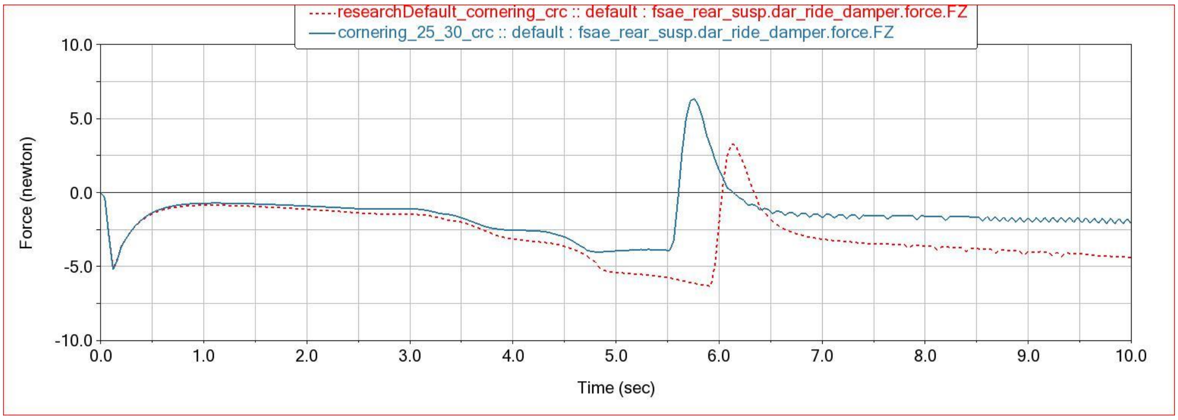

Figure 14. Rear-Right Suspension Damper

In the cornering event (Figures 11 – 14), it can be observed that the forces acting on the suspension dampers are comparatively lower than the reference model. This would be due to the reduced downforce coefficient in the newly designed wings. However, the rate at which the race car approaches the evident force fluctuation has increased in the new design compared to the reference model. It can also be observed that the right side of the race car experiences a higher force due to the centrifugal effect as the vehicle is turning in the left direction. It can also be observed that several dampers experience vibrations during the cornering event. In order to avoid these vibrations, attack angle combinations that show the lowest levels of vibrations may be chosen.

5 CONCLUSIONS

This study was carried out to find out how changing the angles of attack of a rear wing and a front wing would affect the suspension system of a Formula Student race car. The objectives of this study were to research and develop an active aerodynamic system for a Formula Student race car, and to analyse its effects on the suspension system. In order to achieve these objectives, first, a wing profile was chosen, and it was used to model the front and rear wings accordingly. Thereafter, CFD analyses were carried out and the lift and drag coefficients obtained from the analyses were then used to perform acceleration and cornering analyses for the Formula Student race car. From this analysis, the vertical forces acting on the suspension dampers were collected as the result of the study.

- Several combinations of front and rear wing attack angles provide smooth riding with minimum vibrations in the Z direction in cornering and acceleration events.
- According to the study, the combinations for the cornering events are 20° (front) - 40° (rear), 25° (front) - 40° (rear) and 30° (front) - 30° (rear). Among these combinations, 25° (front) - 40° (rear) may stand out due to the high downforce of the wings.
- In an acceleration event, due to the lower drag and the high downforce, 20° or 25° may be chosen as the angle of attack of the front wing, and the angle of attack of 30° may be chosen as the rear wing due to the high downforce coefficient and a lower drag coefficient compared to an angle of 40°.
- Based on the above considerations, a cost-effective method to design the front and rear wings would be to fix the variable element of the front wing at 25° and to adjust the angle of the variable element of the rear wing from 30° - 40° as required.
- However, this should be one out of many considerations when designing an active aerodynamic system.

The obtained results can be used to improve the suspension system of a formula student race car to make way for an active aerodynamic system. Similar research on active aerodynamics can be done in order to develop an active suspension system. Furthermore, other components such as the sidepod grills can be controlled using active aerodynamics and research can be carried out to find out the effects of such elements on various aspects of a Formula Student race car.

The results obtained show a considerable difference in the forces acting on the suspension dampers compared to the reference model. However, the accuracy of the study can be further improved to generate better results. This study was focused on the forces acting on the suspension dampers of the race car. Further results such as the displacement of the suspension caused by the aerodynamic changes, the forces acting on other components, other directions, and fluctuations in other variables can be found out using the same simulation. Furthermore, in this study, the forces were analysed along the Z direction. A reference model was used to compare these plots. However, due to the reference plot not being static in each plot, the clarity of the results were somewhat low. Therefore, methods can be used to keep the reference model plot static while the other plots are drawn according to that and not vice versa. Furthermore, in this study, the focus was on obtaining results to have an understanding about how active aerodynamics would affect the suspension system of a Formula Student Race Car. Hence, the aerodynamic optimization aspect was not prioritized. Therefore, in order to improve the accuracy of the research, the aerodynamics can be further optimized or already optimized aerodynamic data can be used. Furthermore, the forces can be analysed in the X-direction to obtain an overall understanding about the force distribution on the suspension dampers from the XZ plane. Moreover, the material selection for fabricating the front and rear wings can be carried out based on Adams Car simulations such as the ones carried out in this study. In the constant radius cornering event, the radius can be changed according to the corner radiuses of the target race tracks. This would improve the accuracy of the results gathered through the cornering event simulation.

The results from this research can be used in improving the suspension system of a Formula Student race car making way for further developments in its aerodynamic load handling capabilities. Furthermore, the individual damper force fluctuation results can be considered when improving the suspension system for developments such as building closed loop active aerodynamic or active suspension systems.

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