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Computational Analysis of Benzing Airfoils for Optimization in a Wing Configuration for a Formula SAE Car

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ABSTRACT

Wing selection plays a crucial role for race cars in terms of downforce generation. This is essential to maintain traction which leads to faster lap timings, and maintain efficiency in the performance of the race car. In this paper, the numerical simulation of a Formula SAE (FSAE) Car wing configuration is performed. The main focus involves Benzing airfoils, which are expected to show considerably better performance in terms of downforce production in a race car than conventional airfoils. The wing configuration utilized in this research paper consists of a single main plane and two flaps. The freestream velocity of the flow is in the range of 10-60mph (4-26m/s). The 122 series of Benzing airfoils is utilized for the main plane and the 153 series of Benzing airfoils is utilized for the flaps for manufacturing reasons. Nine different combinations of Benzing airfoils are utilized for the aforementioned wing configuration. It is noticed that an appropriate selection of the airfoils for the main plane and flaps with a fixed angle of attack difference, leads to a 12-15% increase in downforce amongst the Benzing airfoil combinations. Similarly, it is also observed that certain combinations show 12-15% decrease in drag in comparison too poor performing Benzing airfoil combination. Data from an on-track test is used in order to verify the approach utilized in this paper for validation purposes. It is observed that the Benzing airfoil does improve the average cornering speed of the car by around 8% in comparison to the previous configuration of S1223 airfoil as the main plane and the Goe 477 airfoil as the flap.

INTRODUCTION

Airfoil selection for wings of racecars play an important role as they affect the cornering, straight-line speed, slaloming and overall performance of the vehicle [1-3]. In the case of a Formula SAE car, it is essential to know that the restrictions imposed by the rules constrain the length of the front and rear wings. Therefore, it becomes necessary to select airfoils which get the best out of the given wing configuration. The tradeoff observed between the downforce generated and the induced drag produced in a racecar must be checked for optimal performance. This serves as the primary motivation for this research paper. An analytic study conducted [2] shows that high downforce generating airfoil is not ideal for optimum performance due to the presence of induced drag. Experimental track testing shows [3] that analytical prediction for the racecar performance is not ideal since due to simplifications made during the analytic study which does not account for the non-uniform flow which exists in nature. Simplifications of the aerodynamic models for CFD also has its limitations [4] since it tends to predict the downforce accurately in comparison to the drag force experienced by the body. High down force generating airfoils [5] have been studied on the rear wings using inverse airfoil design. Due to the flow constraints on the wake developments of the front wings, they cannot be optimized for high downforce [5]. This methodology proves to be slightly faulty as increased down force on the rear end would lead to over-steering of the vehicles during cornering. A Particle Image Velocimetry (PIV) study [6] of a formula one car shows that it is essential to control the wake of the front wheel since they shed strong longitudinal vortices. Development of high lift airfoils for race-cars with restrictions on the geometry is not always beneficial since induced drag will be generated, affecting the mileage of the car [7-8]. Lamination parameters were investigated [9] in order to reduce the induced drag by tailoring the rear wing, but new airfoils need to be tested in order to verify this approach. Implementation of new aerodynamic configurations were studied [10] with Benzing airfoils in order to observe the impact of increase in the number of elements. This paper deals with the impact of airfoil selection for a simple wing configuration of an FSAE car and finding the best combination of Benzing airfoils taking into account manufacturability as well. A computational approach is used to study the impact of camber and thickness on a fixed wing type configuration. Track test data is used to verify if the approach is suitable for future designs for wings of race cars.

NOMENCLATURE

α	Angle of Attack in Degrees
μ	Coefficient of Viscosity in Ns/m^2
ρ	Density in kg/m^3
a_L	Lateral G-force
c	Chord Length in inches
l	Characteristic length in meters
r	Radius of the turn in meters
C_L	Coefficient of Downforce
C_D	Coefficient of Drag
D	Drag force in Newton
L	Downforce in Newton
m	Mass of the car in Kg
S	Surface area of the wing in $in.^2$
V	Velocity in mph
V_c	Cornering velocity in mph
W	Weight of the car in N

METHODOLOGY

Computational Methodology

In order to evaluate the flow around the airfoils, the κ-ω Shear Stress Transport model is used. The governing equations of the κ-ω SST involve the formulation of the turbulent kinetic energy and the specific dissipation rate [11].

Star CCM+ provides a discretized platform for the aforementioned equation. The CAD models for the airfoils and the preliminary model for the race car were carried out and the conditions for the computational analysis is carried out between 0-60 mph which correspond to 0-27 m/s. One of the other major advantages of using the κ-ω SST models for prediction is its accuracy in predicting forced convection similar to the DNS models [12].

The governing equations of the Mentor's κ-ω SST [11- 12] are given by

$$\rho\left(\frac{\partial(u_x\kappa)}{\partial x}+\frac{\partial(u_y\kappa)}{\partial y}+\frac{\partial(u_z\kappa)}{\partial z}\right) = P_\kappa - \beta_1\rho\kappa\omega + \frac{\partial}{\partial x}\left[(\mu + \sigma_\kappa\mu_{turb})\frac{\partial\kappa}{\partial x}\right] + \frac{\partial}{\partial y}\left[(\mu + \sigma_\kappa\mu_{turb})\frac{\partial\kappa}{\partial y}\right] + \frac{\partial}{\partial z}\left[(\mu + \sigma_\kappa\mu_{turb})\frac{\partial\kappa}{\partial z}\right] \quad \textbf{(1)}$$

$$\rho\left(\frac{\partial(u_x\omega)}{\partial x}+\frac{\partial(u_y\omega)}{\partial y}+\frac{\partial(u_z\omega)}{\partial z}\right) = P_\kappa - \beta_2\rho\kappa\omega^2 + \frac{\partial}{\partial x}\left[(\mu + \sigma_\kappa\mu_{turb})\frac{\partial\omega}{\partial x}\right] + \frac{\partial}{\partial y}\left[(\mu + \sigma_\kappa\mu_{turb})\frac{\partial\omega}{\partial y}\right] + \frac{\partial}{\partial z}\left[(\mu + \sigma_\kappa\mu_{turb})\frac{\partial\omega}{\partial z}\right] + 2(1- F_1)\rho\sigma_{\omega 2}\left(\frac{\partial\kappa\,\partial\omega}{\partial x^2} + \frac{\partial\kappa\,\partial\omega}{\partial y^2} + \frac{\partial\kappa\,\partial\omega}{\partial z^2}\right) \quad \textbf{(2)}$$

Where κ is the turbulent kinetic energy term and ω is the specific dissipation rate and Pκ is the production term.

The turbulent viscosity is given by

$$\mu_{turb} = \frac{\rho\alpha_1\kappa}{\max(\alpha_1\omega, SF_2)} \quad \textbf{(3)}$$

Airfoil Selection

Benzing airfoils are used and compared with a previously tested airfoil configuration in order to check if they would improve the downforce component on the race car. Benzing airfoils have a different manner of nomenclature in comparison to NACA 6 Digit airfoils. The first two digits indicate the thickness of the airfoil in % of chord length. The third digit indicates the position of maximum thickness in terms of tenths of the airfoil chord length. The fourth and fifth number indicates the maximum camber of the airfoils and similar to thickness, the 6^{th} digit indicates the position of maximum thickness in terms of the tenths of chord length(c).

The 122 series of Benzing airfoils are used for main planes due to feasibility in manufacturing. The high camber observed in the 122 series airfoils, makes it difficult to manufacture using conventional carbon fiber manufacturing process. The thin nature of the 122 series also reduces the life-span of the airfoils in racing if it were to be used as flaps. Given the brittle nature of carbon fiber upon high levels of aerodynamic load acting upon it, thin flaps would provide more maintenance issues in spite of improved aerodynamic performances.

Table.1. Configurations of different Benzing airfoils in the wing configuration

Main Plane	Flaps		
Be 122-125	Be 153-105	Be 153-055	Be 153-175
Be 122-155	Be 153-105	Be 153-055	Be 153-175
Be 122-185	Be 153-105	Be 153-055	Be 153-175
Selig 1223	Goe 477		

Wing Analysis

A preliminary analysis of the wing is carried out for the given configuration in order to select a suitable airfoil. The chosen configuration involves a main plane with two flaps. The main plane is kept at an angle of attack of 8^0. The first flap is kept at an angle of attack of 35^0 and the second flap is kept at an angle of attack of 60^0. Reynolds number range affects the accuracy of simulations [13] since at low values, the readings obtained can show deviation in comparison to coast down tests.

$$Re = \frac{\rho V.l}{\mu} \quad \textbf{(4)}$$

The Reynolds number range for the simulations vary from 5.5 x 10^4 to 1.46 x 10^6. At lower velocities, the readings for the computational simulations may not be as accurate compared to a track test [13]. The domain of the flowfield is made large enough in order to account for the external flow. Table 2 and 3 provide details on the geometry of the wing configuration used and the configuration used in Star CCM+.

Table.2. Benzing airfoil configurations for 2D Analysis

	Chord Length in inches	Angle of attack α in degrees
Main Plane	17.5	8
Flap 1	6.5	35
Flap 2	6.5	60

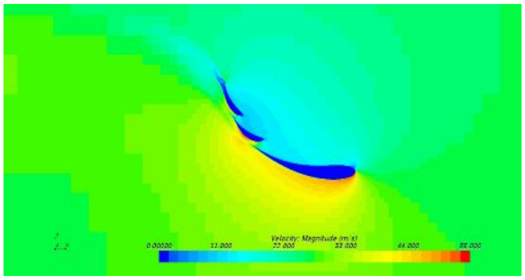

Fig.1. Velocity Contours of Be 122-125 Main plane with Be 153- 175 flap configurations

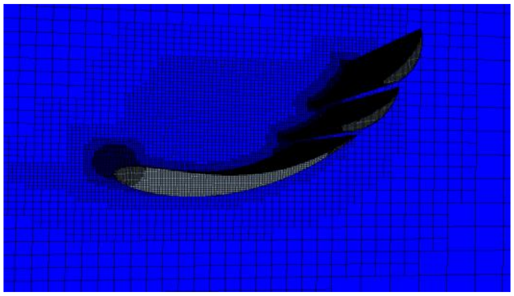

Fig.2. Mesh of the Benzing Wing Configuration

Track Testing

The Formula SAE event conducted at the Michigan International Speedway between May 10 -13, 2017 was used to validate if the decision to select Benzing airfoils over conventional airfoils would provide any form of improvement in the performance of the race car. The only reliable data obtainable which could be compared with the previous year's (FSAE 2016, Michigan International Speedway, May 11-14) competition were cornering velocity and the respective lateral G-force acting on the car. Data from the endurance event of the competition is used for comparison purposes. Given the weight of the car, assuming constant radius and constant velocity [2], the cornering velocity is given by

$$v_c = \left(\frac{W}{\frac{m}{r\mu} - L}\right)^{1/2} \quad \textbf{(5)}$$

The relation between cornering velocity and the lateral g-force which is centrifugal acceleration normalized to gravity under constant radius is given by

$$a_L = \frac{v_c^2}{rg} \quad \textbf{(6)}$$

The lateral G-force observed provides insight into the effect of aerodynamics in terms of improving the vehicle's performance at turns in terms of overcoming centripetal forces. The indication of how the car behaves on the same turns as the previous year's design will be used to validate this approach. It is expected from equation 6 that at the regions of cornering, increased values of lateral G-force would correspond to a higher cornering velocity. Decreased lateral G-force at straight line speeds would indicate smoothness in transition of the car exiting out of the corner. Although, equation 6 is developed for a turn with a constant radius r, it can still be used to gauge the improvement in cornering velocity of the race car.

Table 3. Details of the Star CCM+ configuration for analysis

Initial Turbulence Intensity	0.01
Initial Turbulence velocity	1 m/s
Initial Turbulence viscosity	10
Cells	2,882,199
Faces	8,669,502
Vertices	3,127,046
Velocity range	10-60 mph (intervals of 10 mph)
Domain Length	20 m
Domain Height	40 m
Domain Breadth	10 m
Number of iterations	10,000
y+ treatment	Low y+ treatment

Results and Conclusion

Wing Analysis

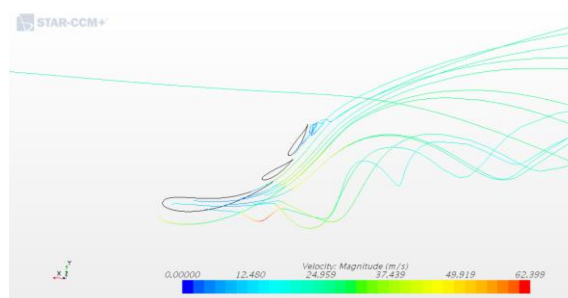

Fig.3. Velocity streamlines for Be 122 125 main plane with Be 153 055 flaps

Preliminary Wing analysis show that there is close to a 12-15% improvement in the Downforce generated by the usage of Be 122-185 airfoil as the main plane with the Be 153-105 as the flaps in comparison to Be 122-185 airfoil as the main plane with the Be 153-175 airfoil as the flap. The Benzing airfoils tend to show a better performance in terms of Downforce generation in comparison to the Selig 1223 airfoil as the main plane with the Goe 477 airfoil as the flaps. The L/D ratio generated by the Benzing airfoils however, show relatively poor performance compared to the S1223 and Goe 477 configuration. The last 3 digits of each airfoil are used to describe the behavior of the configurations in terms of coefficient of downforce generation and drag generation in the figures below (Figures 4-6). The coefficient of drag and downforce are given by

$$C_L = \frac{L}{\rho v^2 S} \quad \textbf{(7)}$$

$$C_D = \frac{D}{\rho v^2 S} \quad \textbf{(8)}$$

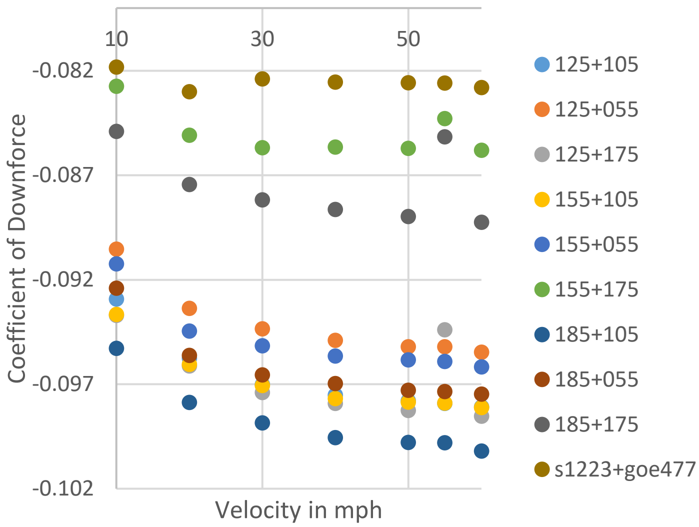

Fig.4. Downforce Generated by Different Airfoils

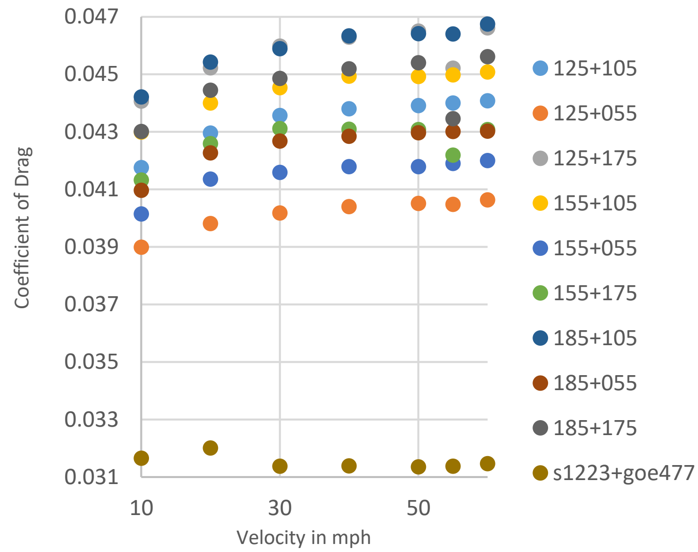

Fig.5. Drag Force Generated by Different Airfoils

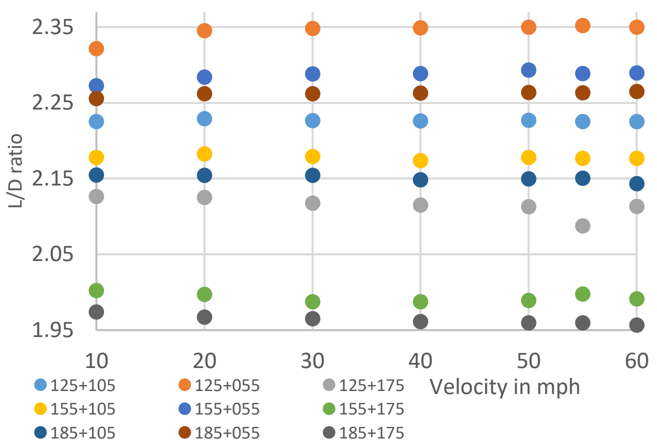

Fig.6. L/D ratio generated by Benzing Airfoils

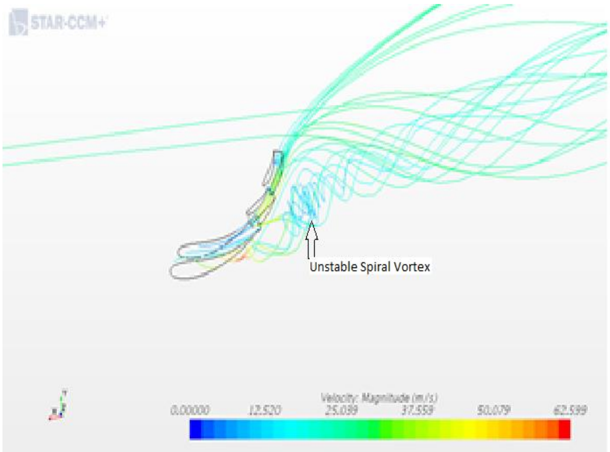

Fig.7. Velocity streamlines for Be 122 125 main plane with Be 153 105 flaps

Performance of Benzing Airfoils

Two types of vortex streamlines were observed at the ends of the wing configuration during the simulation. The first can be considered as a stable vortex streamline, the primary vortex streamline which is stable and is observed in all cases. The second type of vortex streamlines can be considered as unstable vortex streamlines which is observed in most if not all wing configurations without the Be 153-055 flaps. On Preliminary Analysis, the secondary vortex streamlines which tend to generate an unstable spiral vortex streamlines (Figure .7.) could be regarded as the reason for poor performance of airfoils with reduced camber. These unstable vortex streamlines are reduced with the implementation of endplates. Increased surface area of the endplates counteracts the induced drag generated by the trailing edge vortices. However, structural effects must be taken into account alongside the competition regulations.

a. Be 122-125 and Be 153-105

In this combination, the downforce generated from the computational results show considerable increase in comparison to the use of S1223 and Goe 477 combination. The relatively low camber of the flaps, leads to a lower value of drag generated as well compared to other combinations. There is an average of 16.42% increase in downforce generation in comparison to the S1223 combination with the Goe 477 airfoils as the flaps.

b. Be 122-125 and Be 153-055

The low camber provided by the Be 153-055 on the flaps leads to a drag reduction of 7.8% compared to the Be 122-125 and Be 153-105 airfoil combination. This combination leads to the lowest drag generated and shows the highest value of L/D of the airfoils utilized. As shown in Figure 3, the trailing edge vortices on the Be 153-055 airfoil do not initiate the unstable spiral vortex streamlines which leads to increase in drag.

c. Be 122-125 and Be 153-175

The high camber of the flaps provides increased downforce generation Drag force generation is considerably high compared to the first two combinations. The L/D ratio is below 2, therefore, this combination may not be appropriate to use in a race car wing configuration.

d. Be 122-155 and Be 153-105

The 20% increase in the camber on the main plane from the previous configuration, does not lead to an increase in downforce generated. As expected, the increase in the camber of the main plane also leads to an increase in drag. The L/D ratio value observed is approximately close to 2.

e. Be 122-155 and Be 153-055

Similar behavior is observed as before and this combination proves to be much worse since it is not much of an improvement from the combination involving Be 122-155 airfoil as the main plane and the Be 153-055 airfoil as the flaps. Although the L/D ratio observed is above the value of 2.2, the downforce generation is greatly reduced.

f. Be 122-155 and Be 153-175

The 15% camber of the main plane combined with the 17% camber of the flaps provides the least downforce generation. This combination also generates the least amount of induced drag. Due to this, it leads to the second lowest L/D value amongst the airfoils tested.

g. Be 122-185 and Be 153-105

The 18% camber of the main plane combined with the 10% camber of the flaps provides the highest downforce generated. However, this also leads to the highest value of induced drag generated. This can be attributed to the increased strength observed in the primary trailing edge vortices. However, the unstable spiral vortex streamline is not observed. The L/D value corresponding to this combination is approximately closer to 2. In comparison to the S1223 and Goe 477 airfoil configurations, it provides close to 18.8% increase in downforce generation.

h. Be 122-185 and Be 153-055

Like in the previous combinations, the Be 153-055 airfoils being used as the flap provides a considerable reduction in drag. It can be said that the Be 153-055 airfoil acts best for flaps in race-cars for varying main planes due to reduction observed in the trailing edge vortices. The unstable spiral vortex structures enhanced due to the increase in the camber of the flaps observed for the Be 153-105 and Be 153-175 flaps are not observed.

i. Be 122-185 and Be 153-175

The Be 122-185 airfoils as the main plane with the Be 153-175 airfoils as the flaps show very poor performance in terms of downforce generation and does generate a lot of drag. This could be due to the increased camber observed in both the main plane and the flaps. It can be seen that higher camber does not necessarily lead to improvement in aerodynamic characteristics for the given wing configuration.

Track Testing Results

Track testing data from the FSAE event at the Michigan International Speedway in Brooklyn Michigan, is used to further evaluate the performance of the Benzing Airfoils. The configuration of Be 122-125 airfoil as the mainplane and Be 153-105 airfoils as the flap was used for the car due to time constraints in terms of manufacturing for the competition due to immediate availability of its aerodynamic characteristics. Unavailability of the instruments to conduct coast down testing within the time constraint for the competition, led to an alternative method to check the validity of the approach used. Data obtained from the competition in the form of lateral G force and the velocity of the vehicle at both the cornering speed and the straightline speed is used to validate the approach. Given the high sampling rate of the accelerometers, the sampling rate is reduced to 50 Hz and is observed over a short time period. Careful selection of data is necessary in order to make a proper analysis. Although the data sets for figures 8 and 9 have been taken over the same time period, noise generated from the accelerometer tends to overpopulate at straight line speeds in the data obtained from the 2016 FSAE event and at cornering speeds at the data obtained from the 2017 FSAE event.

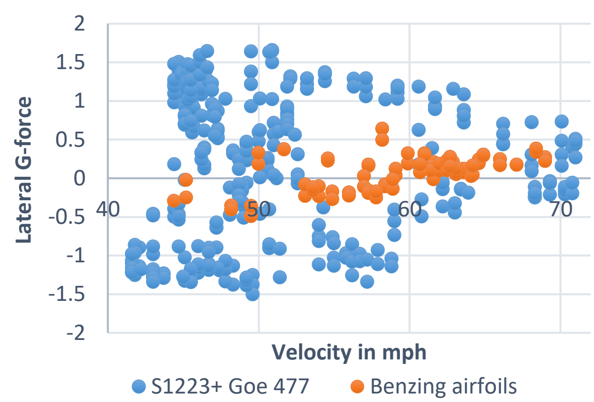

Fig.8. Behavior of the lateral G-force in at high velocities for one instance of time

Upon the implementation of Benzing airfoils, the average cornering velocity of the car did show improvement by around 8% and the time taken to reach maximum velocity was reduced. The previous race car with the Selig 1223 airfoil with the Goe 477 flaps averaged a cornering velocity of 31.4 mph, in comparison the race car with the Benzing airfoils averaged around 34.1 mph. This can be partially attributed to the increase in Downforce generated by the car upon the implementation of Benzing airfoils.

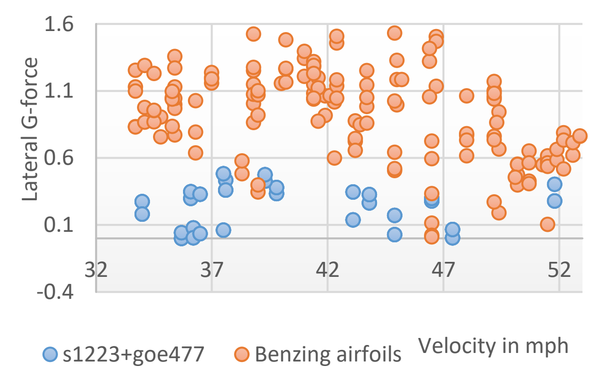

Fig.9. Behavior of the lateral G-force after cornering

The above figure shows the increase in lateral G-force on the race car after coming out of a corner, indicating higher corner velocity. The track data also shows that increased downforce provides smoother transition onto the race track while exiting a corner. It could be argued that due to the increased downforce, the car is able to recover quicker after a turn and overcome centripetal force. The reduction in lateral G-force at straight line velocity shows some positive insight into the implementation of the Benzing airfoils with regards to race car performance. It is advised however, not to extrapolate the downforce characteristics from the track test data using equation 4 due to the assumptions made which may not hold true in real life track tests. However, the track test data does show that with the increase in the Downforce generated, the cornering velocity can be increased alongside providing smoother transition heading out of a corner.

CONCLUSION

Due to limitations put forth by the extent to which Computational Analysis can be carried out with accuracy, it is observed that there exists an optimum configuration amongst the airfoils wherein the Downforce generated can be maximized. It is quite difficult to carry out the simulation of the entire car to observe the effect of the Benzing airfoils due to the increased computational load.

One of the major drawbacks of the Benzing airfoils observed during computational analysis, lies in the fact that the region of highest camber is situated at the center of the chord length. If the maximum camber of an airfoil is to be positioned at the mid-point of the chord length of the airfoils, minimal camber in such instances provide optimal performance if it were configured as a flap. This leads to minimization of unstable spiral vortex streamlines which can be attributed to the increase in drag in the wing configurations. It can be concluded that increase in camber amongst the flaps in wings of a race car lead to poorer performance, when the angle of attack in a given wing configuration is fixed.

However, within the results obtained from the simulations, the configuration of Be 122-125 airfoil as the main plane with the Be 153-055 airfoil show the best performance. The configuration of Be 122-155 airfoil with the Be 153-175 airfoil proves to be poor as it is neither generating high down force nor does it provide a high L/D value. The Be 153-055 airfoil acts as an excellent flap configuration since the reduced camber at the midpoint of the airfoil leads to decrease in the unstable spiral vortices at the leading edge. Further research must be conducted alongside experimental data to validate the optimum angle of attack for the wing configurations of an FSAE car.

Track testing provides a more insightful view on the cornering velocity of the vehicle as a function of downforce generated. There is approximately 8% increase in the average cornering velocity with the implementation of Benzing airfols. At straight line speeds, Benzing airfoils show reduction in the lateral g-force generated during the exiting of a corner in comparison to the car with the S1223 and Goe 477 airfoils. From the computational analysis and the track testing data, it can be seen that the lift to drag ratio may not provide a clear picture of the implementation of airfoils on the actual performance of a race car.

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