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Numerical analysis of airfoil arrangement for an active rear wing of formula student race car

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Abstract

Aerodynamics is a crucial factor for a racing car. Different aerodynamic devices are used to improve the aerodynamic performance of the race car. In an open-wheel race car, like formula one, front and rear wings have a huge effect on car performance. The modern technology is introducing an active aerodynamic system to the vehicles. Nowadays, the drag reduction system is used in formula one car which is a part of active aerodynamics. For a small race car, like formula student car, wings need to be large to create expected downforce which also increases drag. So the effect of the drag reduction system is more important for a small race car. In this research different airfoil arrangements are designed and simulated in ANSYS for drag reduction system for formula student race car.

Keywords: Aerodynamics, Rear Wings, Formula Student, Active aerodynamics, Multi Elements Wing

1. Introduction

Aerodynamic features themselves play a role in every car affecting fuel economy, performance, and even refinement. Now, most cars are designed with static aerodynamic devices that perform a continuous function and never change the airflow. Now, this can be great for increasing downforce or reducing drag, but it's very much one way or the other. Step in active aerodynamic technology which electronically adjusts themselves to optimize airflow for certain driving conditions. Active aerodynamics employs self-adjusting front and rear spoilers, open and shut vents, and in motion, height adjustments to keep vehicles firmly planted on the road while maintaining optimum efficiency whether in terms of speed, downforce or fuel consumption. In 2014 J. Patrick et al. [1] researched multi-elements active aerodynamics. This thesis focuses on the design, development, and implementation of an active aerodynamics system on the 2013 Formula SAE car. The aerodynamics package itself consists of five-element front and rear wings as well as an underbody diffuser. Five-element wings produce significant amounts of drag which is a compromise between the cornering ability of the car and the acceleration capability on straights. The active aerodynamics system allows for the wing angle of attack to dynamically change their configuration on track based on sensory data to optimize the wings for any given scenario. The wings are studied using computational fluid dynamics both in their maximum lift configuration as well as a minimum drag configuration. A control system is then developed using an electromechanical actuation system to articulate the wings between these two states. In 2017 S. Kajiwara et al. [2] also researched the active rear wing. In that research, a rear wing designed to improve motoring performance and enhance stability during cornering needs to generate a large downforce at a relatively low speed. If the angle of attack of the rear wing is large, then air resistance is increased during high-speed driving, and thus, fuel consumption is increased due to the large drag values. On the other hand, the performance on high-speed cornering will improve overall lap time with an increased angle of attack.

The objectives of this research are:

i. To choose airfoil for wing arrangement.
ii. To design different arrangements of a wing.
iii. To simulate the arrangement in ANSYS.
iv. To find out the best arrangement for the lowest drag and highest downforce.

2. Aerodynamic forces

A drag force is the resistance force caused by the motion of a body through a fluid, such as water or air. A drag force acts opposite to the direction of the oncoming flow velocity. This is the relative velocity between the body and the fluid. One of the drawbacks of adding an aerodynamics package with wings to a race car is the added amount of drag. It is important to evaluate the effect of drag on the vehicle's top speed to determine how much we can afford without sacrificing on-track performance. The acceleration of the car can be described simply as[3]

$$ma = F - \frac{1}{2}\rho C_D A v^2 \tag{1}$$

Where *F* is the force driving the vehicle forward, *ρ* is the density of air, C_D is the drag co-efficient and *A* is the reference frontal area. The rolling resistance has been ignored here. When the equilibrium between the driving force and the drag force is reached, the acceleration *a* is zero and simplifies to [3]

$$F = \frac{1}{2}\rho C_D A v^2 \tag{2}$$

Downforce is a downwards thrust created by the aerodynamic characteristics of a car. The purpose of downforce is to allow a car to travel faster through a corner by increasing the vertical force on the tires, thus creating more grip. Downforce is actually a negative lift force. The same principle that allows an airplane to rise off the ground by creating a lift from its wings is used in reverse to apply a force that presses the race car against the surface of the track. This effect is referred to as aerodynamic grip and is distinguished from the mechanical grip, which is a function of the car mass, tires, and suspension. The creation of downforce by passive devices can be achieved only at the cost of increased aerodynamic drag (or friction), and the optimum setup is almost always a compromise between the two. The equation of lift force is following

$$L = \frac{1}{2}\rho C_L A v^2 \tag{3}$$

In the case of downforce, the lift force will be negative and the value of the coefficient of lift will be negative. Here *L* is lift force, ρ is air density, C_L *is* coefficient of lift, *A* is frontal area and *v* is velocity.

One of the major benefits of equipping a race car with an aerodynamics package is the increased grip in the tires. The increase in performance due to the extra grip from the added normal load can be investigated and demonstrated by inspecting the theoretical maximum allowed velocity in cornering before the vehicle loses its grip. This is the velocity for which the frictional force is equal to the centripetal force. Assuming a constant coefficient of friction we have

$$mFz = m\left(mg + \frac{1}{2}\rho C_L A v^2\right) = \frac{mv^2}{R} \tag{4}$$

3. Selecting airfoil

In this thesis, we designed a rear wing with five elements. NACA 4412 is used for the arrangement. The details about the airfoil are taken from the website Airfoil Tools[4]. From the graph of Cl vs angle of attack, we get the angle of attack which gives the maximum downforce. From the graph of Cd vs angle of attack, we get the angle of attack which gives minimum drag. Again from the graph of Cd/Cl vs angle of attack, we get the optimum angle of attack for maximum Cd/Cl. This three angle of attack is used to design different arrangements of five elements wing. In fig. 3.1 the NACA 4412 airfoil is given. In fig. 3.2 the graphs of Cl vs Cd, Cl vs alpha, Cd vs alpha and Cl/Cd vs alpha are showed.

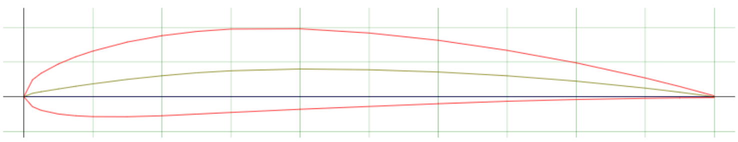

Fig. 3.1: *NACA 4412*

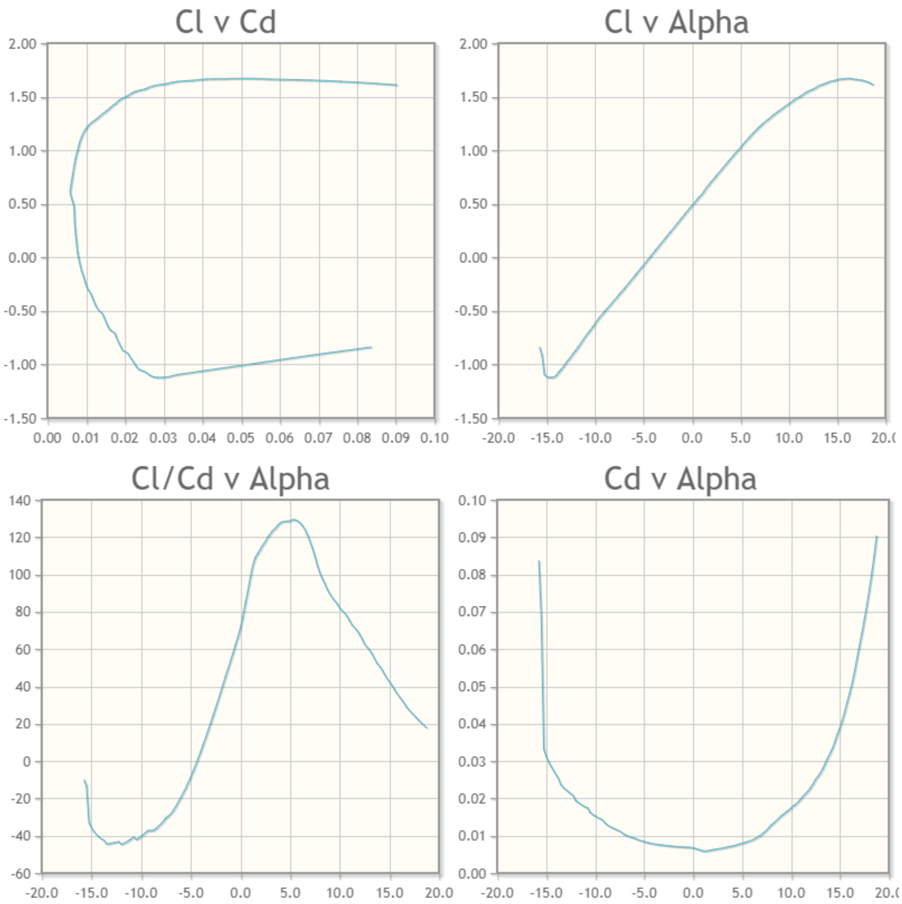

Fig. 3.2: Graphs for NACA 4412

Details:

Airfoil: NACA 4412 (naca4412-il)
Reynolds number: 1,000,000
Max Cl: 1.67 at α=16.25°
Min Cd: 0.00588 at α=1.25°
Max Cl/Cd: 129.37 at α=5.25
Description: Mach=0 Ncrit=9

4. Airfoil arrangement

In this research, airfoils are simulated with different arrangements. In the case of gating the optimum downforce and drag force combination different arrangements are designed. Six different arrangements are simulated.

i. Five elements wing with three moving elements open
ii. Five elements wing with two moving elements open
iii. Five elements wing with three moving elements semi-open
iv. Five elements wing with all moving elements closed

Here the open-element refers the airfoil NACA4412 is in the 1.25-degree angle of attack which has minimum co-efficient of drag, closed elements refers to the airfoil is in 16.25-degree angle of attack which has the maximum coefficient of lift and semi-open refers the airfoil is in the 5.25-degree angle of attack with maximum Cd/Cl. The design of the arrangements is given below. Here, for figures 4.1 and 4.2, all chord lengths are in millimeter and all angles are in degree.

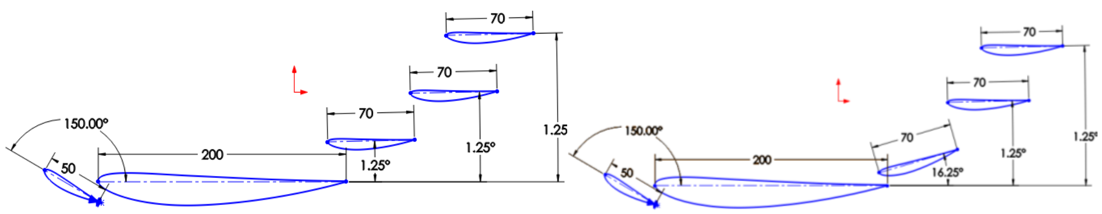

Fig. 4.1: Five elements wing with three elements open & Five elements wing with two elements open

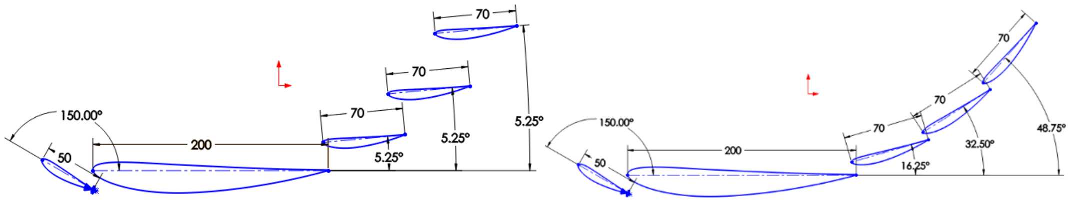

Fig. 4.2: Five elements wing with three elements semi-open & Five elements wing with all elements closed

5. ANSYS Simulation

In this research, ANSYS Workbench 18.2 [5] is used. ANSYS Fluent is used for this aerodynamic simulation. The simulation type is 2D. So the geometry designed by surfaces. First, the airfoil geometry is imported to Solidworks. Then the 2D sketch of the airfoil arrangement is designed in Solidworks. After designing the arrangement, the sketch is sent to the ANSYS geometry using a Solidworks macro tool.

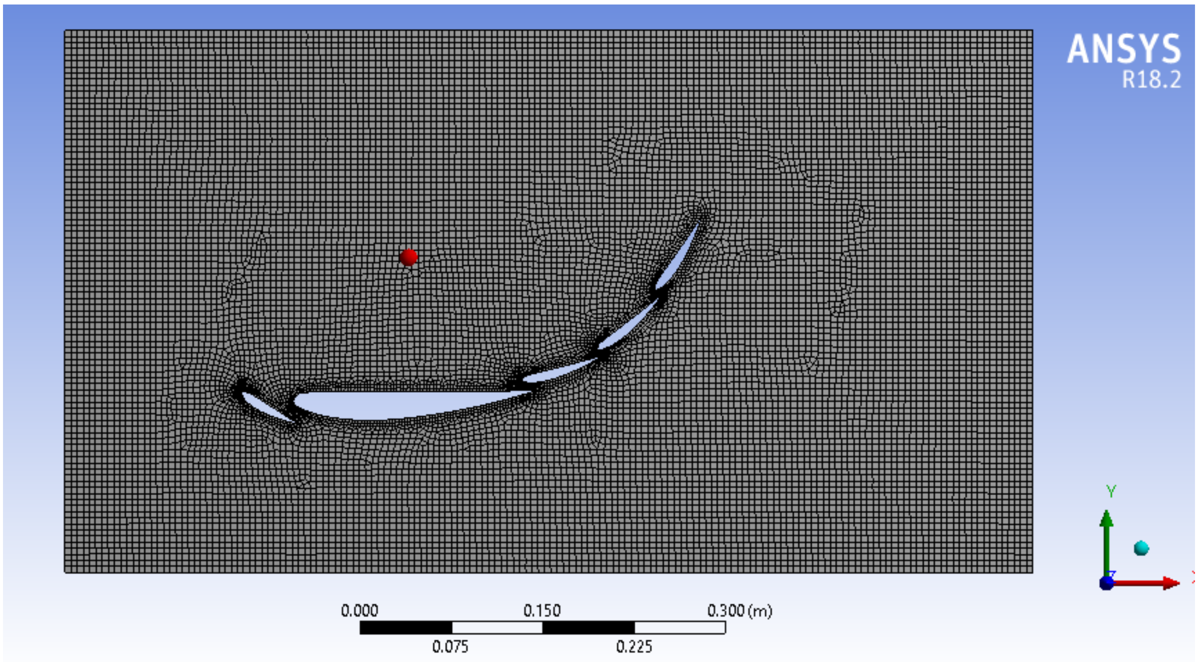

Fig. 5.1: Mesh

Mesh information:
Nodes: 17214
Elements: 16692
Maximum face size: 4.5373e-002 m
Minimum edge length: 9.3578e-004 m

Setup:
Viscous model: Spalart-Almaraz
Solution method: Least Square Cell-Based
Velocity Magnitude Inlet: 41.67 m/s

6. Simulation Results and Discussion

i. Five elements wing with three moving elements open

Firstly the arrangement of five elements wing with three elements open is simulated. This 2D type simulation is run with 200 iterations. In fig. 6.1 the pressure contour is given. Where the maximum and minimum pressures are 1131.65 pa and -4884.19 pa. Here the inlet velocity is 41.67 m/s. The lift force of the arrangement is -549.22N and the drag force of the arrangement is 31.16N.

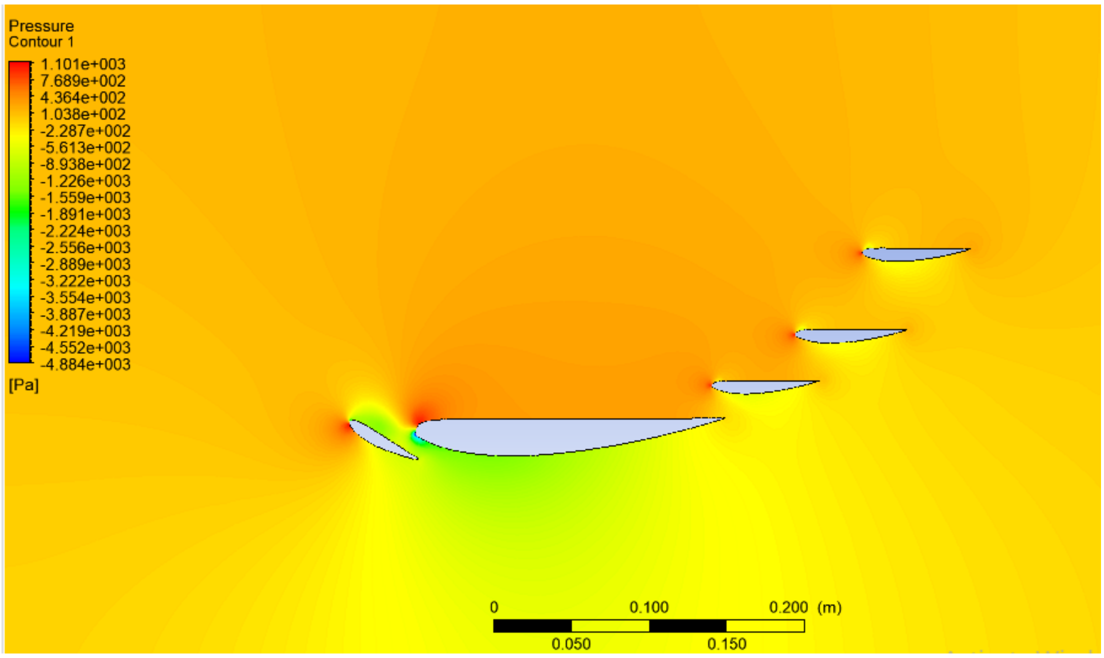

Fig.6.1: Five elements wing with three elements open

ii. Five elements wing with two elements closed

In this simulation, two elements are kept open out of three moving elements. This arrangement is simulated to examine the increased lift for one moving element closed. This 2D simulation is run with 200 iterations. In the fig. 6.2 the pressure contour is given. The lift force of the arrangement is -697.77N and the drag force of the arrangement is 28.94N.

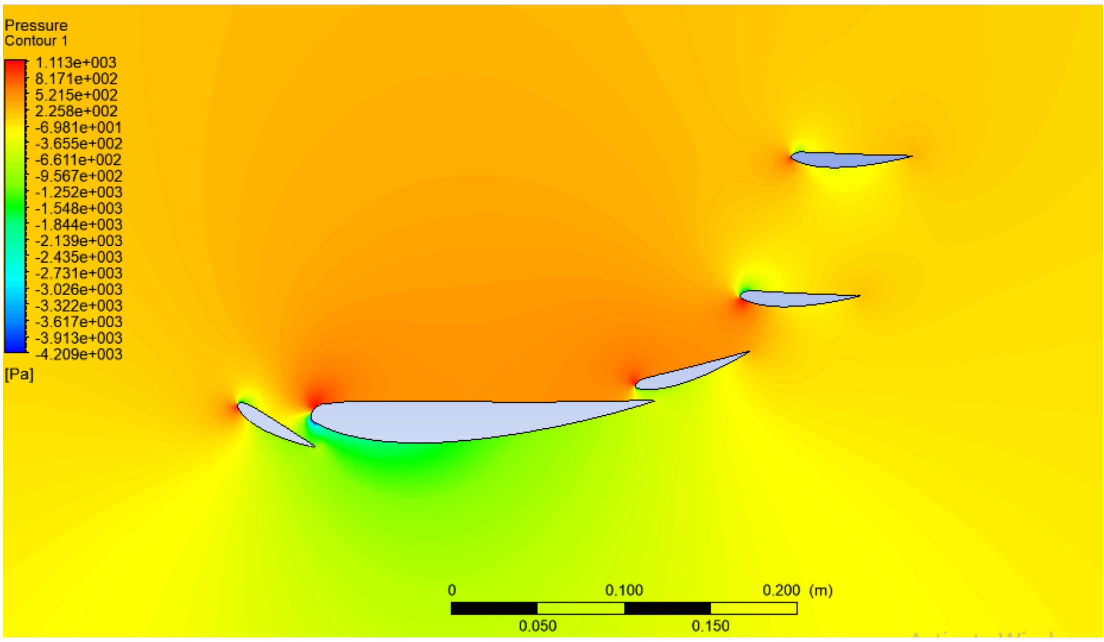

Fig. 6.2: Five elements wing with two elements open

iii. Five elements wing with three moving elements semi-open

The maximum Cd/Cl can get for the angle of attack 5.25 degrees. So for getting the maximum downforce for minimum drag force, an arrangement is designed where the three moving elements are in an angle of attack of 5.25 degrees. This simulation is run with 200 iterations. The pressure contour is given in fig. 6.3. The lift force of the arrangement is -1684.9N and the drag force of the arrangement is 93.7N.

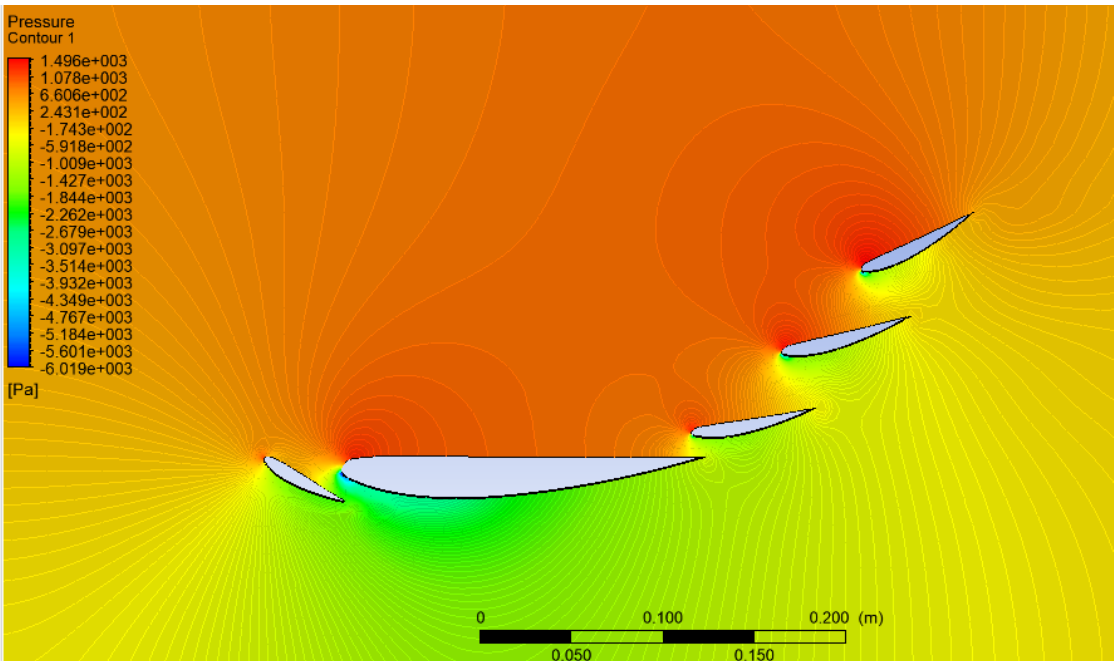

Fig. 6.3: Five elements wing with three moving elements semi-open

iv. Five elements wing with all elements closed

Finally, to get the maximum downforce an arrangement is designed with all moving elements closed which are in an angle of attack of 16.25 degrees. This arrangement is designed for tight cornering. In the tight corners, the maximum downforce is needed. This simulation is run with 200 iterations. In fig. 6.4 the pressure contour is showed. The lift force of the arrangement is -3821.19N and the drag force of the arrangement is 371.65N.

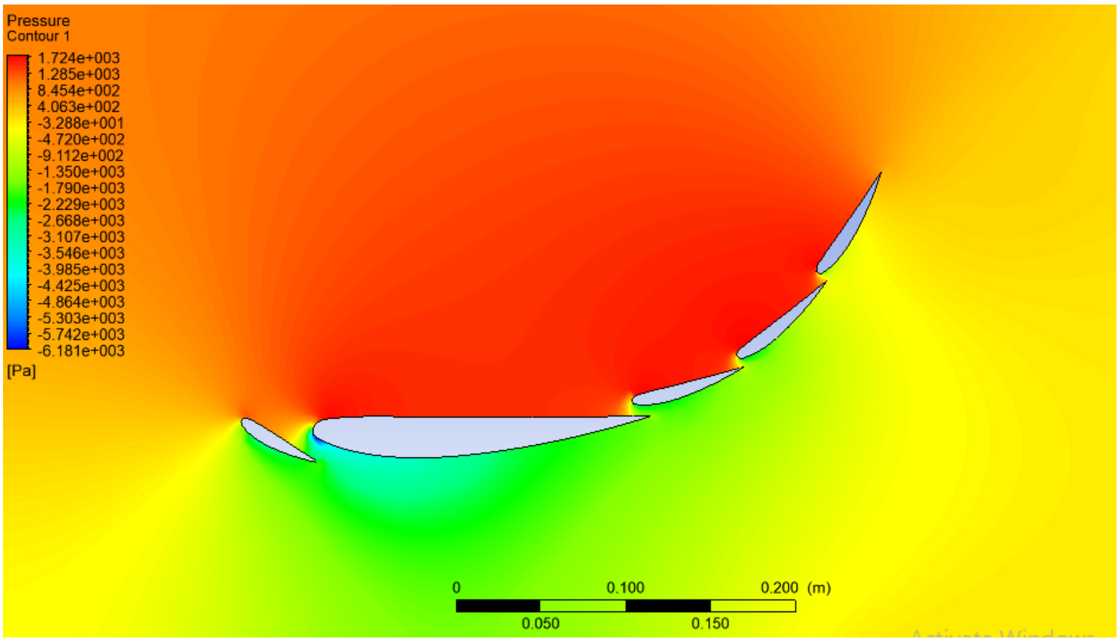

Fig. 6.4: Five elements wing with all elements closed

From the simulations of different arrangements, the best one for the lowest drag and another for the highest lift can be found. Here,

Arrangement 1. Five elements wing with three moving elements open (Drag 31.16 N, Lift -549.22 N)
Arrangement 2. Five elements wing with two elements closed (Drag 28.94 N, Lift -697.77 N)
Arrangement 3. Five elements wing with three moving elements semi-open (Drag 93.7 N, Lift -1684.9 N)
Arrangement 4. Five elements wing with all elements closed (Drag 371.65 N, Lift -3821.19 N)

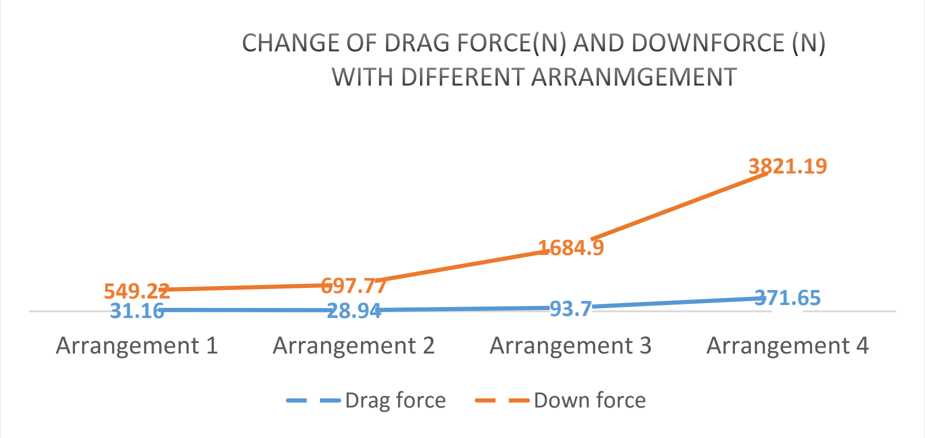

Fig. 6.5: Change of drag and downforce with different arrangements

Here arrangement 2 has minimum drag force and arrangement 4 has maximum downforce. So Arrangement 2 can be used for straight roads and overtaking. On the other hand arrangement, 4 can be used in tight corners. By dynamically changing these two arrangements in the wing, the best performance of minimum lap time can get from the race car.

7. Conclusion

We have selected the airfoil for the wing. Then from the detail characteristics of the airfoil, we have designed four different arrangements according to different angles of attack. The arrangements are simulated in ANSYS. From the simulation result, we found the best arrangement for straight roads, overtaking and tight corners. For getting better performance and reducing lap time, the car needs an optimum downforce with an optimum drag on the straight roads. In the case of overtaking the car needs the lowest drag. On the other hand in the tight corners, the highest downforce is needed. So, the different airfoil arrangements can be used for different circumstances which will reduce the total lap time of the racing car. Using these arrangements a dynamic active wing can be designed with an electronic controlling system for formula student race car.

8. References

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[5] ANSYS® Academic Research Mechanical, Release 18.1, Help System, Coupled Field Analysis Guide, ANSYS, Inc.