Aerodynamic study of Formula-1 car

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***Abstract*—This article explains the aerodynamics study of Formula-1. The Formula One car's design has constantly evolved throughout the sport's history, as teams attempt to both out-smart their competitors and keep up with ever-changing regulations. Since aerodynamic performance is one of the most important factors in a car's design, teams fluid dynamics is the numerical study of moving liquids and gases, to model the flow of air behind the car as it races to the finish line. Fundamental to this study are the Navier-Stokes equations, which are so complex that they cannot be solved directly. The mathematicians turn to powerful computers to provide approximate but accurate solutions. This computation is done using an opensource software OpenFOAM v5.0 with simpleFoam solver and laminar flow condition.**

Keywords*—*OpenFOAM, High-speed, simpleFoam

I. Introduction

Aerodynamics : The properties of a solid object in terms of how air flows around or over it.

Automotive aerodynamics is the study of the aerodynamics of road vehicles. The main goals of which are reducing drag and wind noise, minimizing noise emission and preventing undesired lift forces and other causes of aerodynamic instability at high speeds. For so classes of racing vehicles, it may also be important to produce downforce to improve traction and thus cornering abilities. Aerodynamics is the most important factor in today's motor-sport. The teams and the manufacturers spend countless hours in the wind tunnels to make their car produce the minimum amount of drag but at the same time getting the most downforce that they can. The aerodynamics is the last frontier where improvements can be made and getting the right settings for the right track, could spell win or lose.

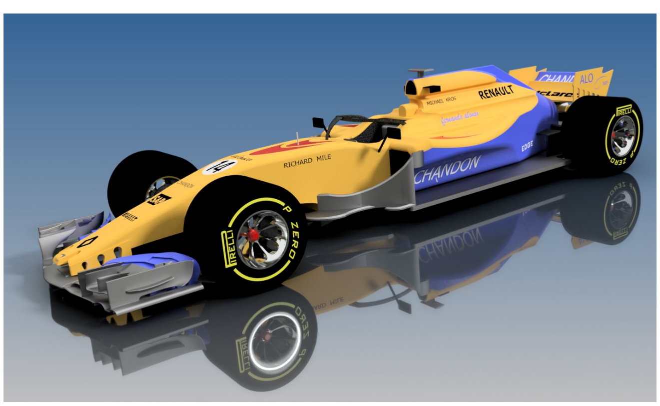

Figure 1: Formula-1 racing car

A Formula-1 car has many aerodynamic devices that used for reducing the lift and drag forces on the car and thereby reducing the lap times. But, the lift and drag forces are inversely proportional to each other. Often one tends to ignore the fact that the combination of the right configuration of all the add-on devices is what contributes to the reduced lap times and not just the design of the individual aerodynamic add-on devices. For example, the lift reduction achieved by an aerodynamic device, say the front wing, comes at the cost of the higher area being exposed to the air leading to an increase in the drag force, but, the additional down force is essential for F1 cars as the high speed requires a huge amount of traction to improve its stability, especially at corners to allow high cornering speed. In race cars, especially the open-wheel types like the ones used in Formula-1, the add-on devices play a major role in the lap timings and ultimately is the difference between the best and the rest.

A. *Types of forces acting on any car*

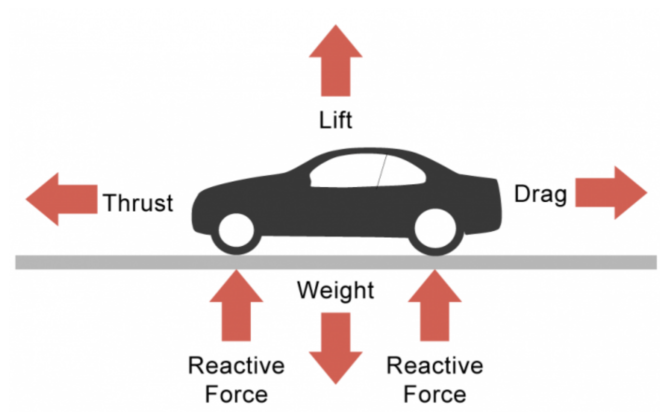

Figure 2: Forces acting on a car

Weight: Weight is a force dependent on object's mass. The mass of the object is multiplied by the magnitude of gravitational acceleration gives weight. This weight has a significant effect on the acceleration of the object.

Lift: Lift is due to movement of the air around an object. It is the sum of all fluid dynamic forces on a body normal to the direction of external flow around the body.

Drag: Like wind friction causes drag in an automobile, aerodynamic friction and displacement of air during creates aerodynamic DRAG. Drag occurs any time that air is displaced from its normal condition.

Down-force: Down-force is simply the force acting down towards the ground. On our car we have a force which acts down on the ground to keep the car fixed to the track as it is going around corners.

Thrust: When a body is in motion a drag force is created which opposes the motion of the object so thrust is the force produce in opposite direction to drag that is higher than that of drag so that the body can move through the fluid.

B. Why down-force matters

In the late sixties, the first aerodynamic revolution in race car design had arguably occurred. Prior to this period, early aerodynamics focused primarily on streamlining the bodywork to increase top speeds. This was partly driven by the nature of historical race tracks which were generally characterized by very long straights. Racing cars in this era are geometrically recognizable by their long and narrow 'bullet' shaped bodywork (as well as their tall and slender wheels). However, it soon became apparent that aerodynamic influences were affecting the stability of the car at high speed (the cars were in fact generating lift).

As racing tracks began to shorten and the complexity of circuits increased, it was soon discovered that the limiting factor in determining the performance of a racing car was its acceleration rather than its top speed. In other words, it was the rate of change of velocity that mattered. If a car could accelerate quicker, change direction faster and/or brake harder, then the average speed of the car over a single lap will increase and hence the overall lap time will be reduced. Thus, towards the end of the sixties, the primary focus had shifted from drag reduction to down-force generation. An aerodynamic proliferation of innovative inverted wings began to spread and the era of down-force generation had begun.

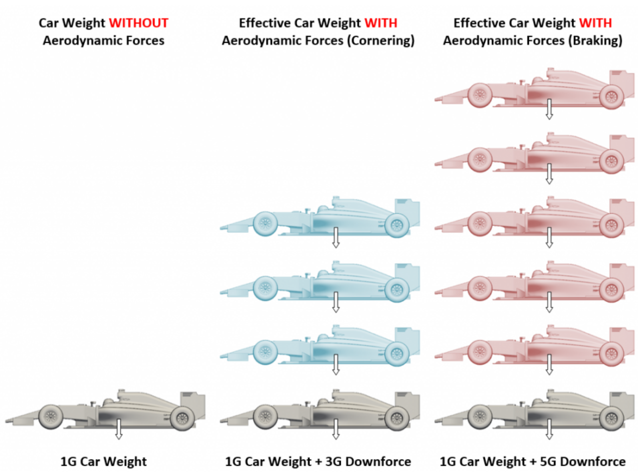

Figure 3: Downforce due to aerodynamics

Over the next 50 years, a down-force driven design process has sculptured the shape of the modern Formula 1 car. The role of down-force is to augment the acceleration of the car, a catalyst to elevate the performance to a higher level. The greater the down-force, the greater the frictional forces between the Tyre and the ground. This leads to an increase in traction which permits the car to accelerate, decelerate and corner quicker. Down-force increases the weight of the car but without increasing the mass of the car.

C. Down-force Generating Components

From a spectator's point of view, a car can be considered in (at least) 3 parts: the front wing, the car's body and the rear wing. Each of the parts can be optimised for the required downforce at a minimum of drag. Practically, however, every component has its influence on the behaviour of the car and cannot be regarded as an individual component. As a result, no element is tested individually, but always a complete scale model of a car.

There are four main components each contributing to the generation of down-force. These are the front wing, underfloor, diffuser and rear wing (the bodywork actually generates lift). The front wing is typically responsible for 25% of overall down-force levels whilst the rear wing also accounts for 25%. The remaining 50% is generated by the underfloor and diffuser combination. Each component has been specifically designed to work in conjunction with one another. Hence a front wing that works effectively on one car, may not necessarily work on another. Therefore one of the biggest challenges in race car design is to develop a synergistic set of components that maximize the performance of the car.

Front Wing

The front wing on the car causes about 1/3 of the car's downforce and it has experienced more modifications than rear wing. It is the first part of the car to meet the air mass. Therefore, besides creating downforce, it's main function is to efficiently guide the air towards the body and rear of the car, as the turbulent flow impacts the efficiency of the rear wing.

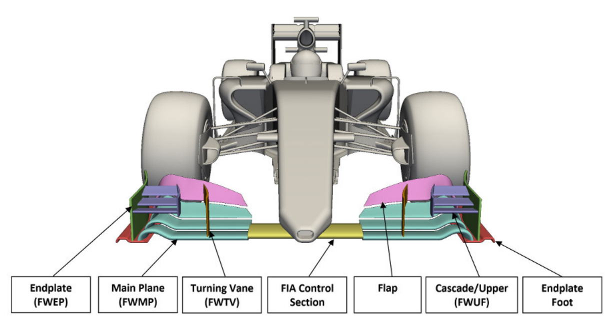

Figure 4: Front-wing

Barge board

Barge boards smooth out and separate the air that has been disrupted by the front wheels.

They separate the flow into two parts:

1. First directed into the side pods to cool the engine.
2. Other is diverted outside to reduce drag.

Figure 5: Barge-board

Rear Wing

The rear wing consists of two sets of airfoils connected to each other by the wing endplates. The most downforce is provided by the upper airfoil . Modern rear wings produce approximately 30- 35 % of the total downforce of the car.

Figure 6: Rear-wing

D. Geometry

The CAD model of the f-1 is obtained from grabCAD and is stored in the triSurface directory. General specifications of the model is listed below:

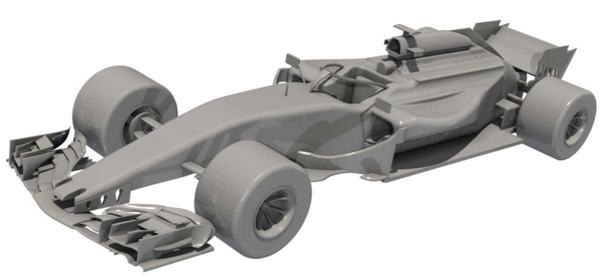

Figure 7: Formula-1 racing car CAD model

Length: 4.6 m Width: 1.0 m Height: 1.0 m

The model is scaled at 10:1 ratio to obtain the model at 46 m * 10 m * 10 m.

E. Meshing

The case directories 0, constant, system are created with appropriate sub-directories (triSurface with the .stl file in constant directory) and dictionaries (blockMeshDict, snappyHexMeshDict surfaceFeatureExtract Dict in system directory).

The blockMesh:

Domain Specifications: A domain size of 300 m * 62 m * 40 m is designed around the model as a single block. The domain is designed with the convention of (1.5x + 3.5x) * 6x *(1.5x + 1.5x), where x is the minimum dimension in the windward side.

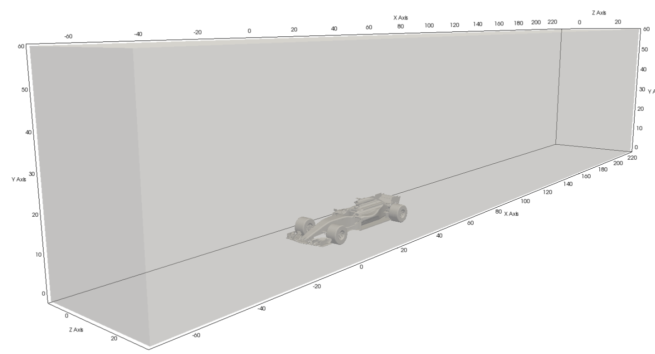

Figure 8: Domain

Refinement:

The domain is graded so as to have fine mesh around the model with AR=1 and courser mesh near the periphery of the domain. The refinement and division are done with care on smooth transitions all over the domain.

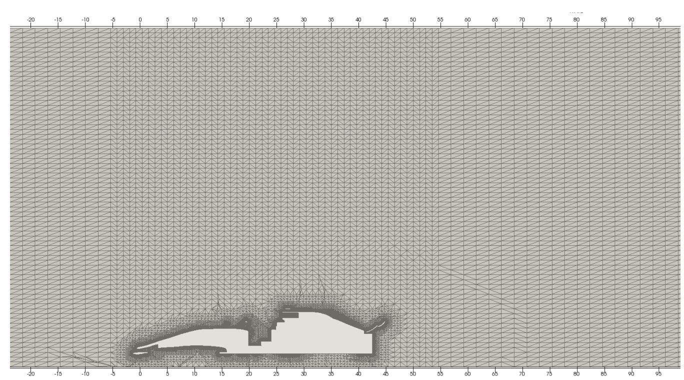

Figure 9: Multiple grading in mesh

Patches and Boundaries:

The sides, inlet, upperWall and outlet faces are modelled as patch. And lowerWall modelled as wall. The complete code can be viewed in the blockMeshDict in system directory.

The snappyHexMeshDict:

The snappyHexMesh is used with the surfaceFeatureExtract utility to mesh the underlying model by following operations:

1) The edges are extracted from the .stl file through the surfaceExtractFeature and is stored as F1.eMesh in the triSurface directory. To run the feature, the surfaceFeatureExtractDict is specified with the .stl file to operate and the settings are tuned to extract all the edges in the .stl file i.e., the model.

2) The domain detects the model and uses casteled Mesh to coarsely remove the blocks that are contained within the model's outline. This is further refined upto the level specified. The refinement surfaces is set to the eMesh generated, to detect the edges, through which the casteled mesh is generated upon.

3) The sHM(snappyHexMesh) dictionary is set with refinements of level 4 to obtain intricate contours of F-1.

Edge refinement level	4
surface Refinement level	(4 5)
No. of Layers	3

Table 1: snappyHexMeshDict

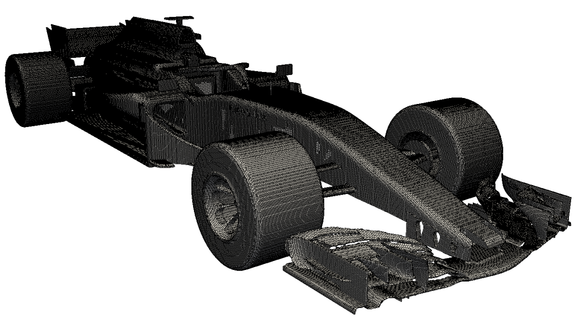

Figure 10: Refined mesh

4) The sHM is carried out in steps of casteledMesh, snap and addLayers so as to check compatibility of mesh. The code for significant operations for the snappyHexMesh and surfaceFeatureExtract can be found in respective directories.

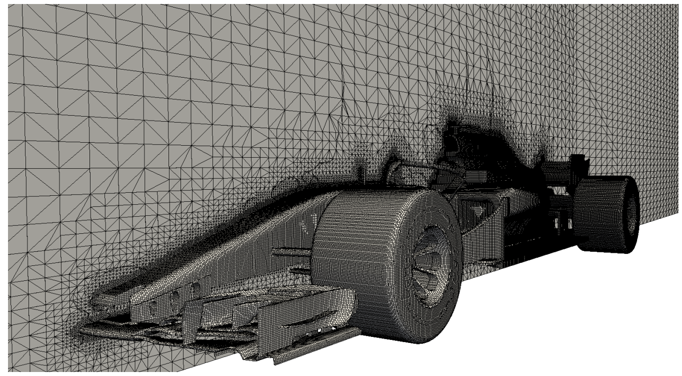

Figure 11: Cut-section of mesh

checkMesh:

The mesh is generated and the checkMesh command is run to locate illegal faces of the mesh, if any. The result returned as MESH OK. The mesh had nonOrthoFaces which were negligibly small and thus were not considered as error.

Domain	(-70 -2 -10) (230 60 30)
points	4717307
faces	12662487
internal faces	11998456
cells	3982890
faces per cell	6.19172
boundary patches	6
Max Skewness	7.08102
Max Aspect ratio	32.7372

Table 2: checkMesh Results

II. SIMULATION

The CFD analysis of the airflow over the sharp nose bullet train was done using the software OpenFOAM (v-5.0).

A. Boundary Conditions

Airflow enters with 97.22 m/s fixed velocity by inlet patch which is nearby 350 km/hr. Outlet kept inletOutlet as flow velocity 97.22 m/s. Pressure outlet has given a fixed value of 0 atm. front and backplane managed as a slip wall and corresponding velocity given to the lower wall that given at inlet. UpperWall velocity and pressure given as slip as air can leave from the domain. To the train, velocity is given as noSlip and zeroGradient pressure applied.

The list of abbreviations used in the following table are:

1) FV: Fixed Value
2) ZG: Zero Gradient
3) IO: Inlet Outlet

Boundary	U	P
Inlet	FV(97.22)	ZG
Outlet	IO	FV(0)
frontAndback	slip	slip
lowerWall	FV	ZG
upperWall	slip	slip
F1	noSlip	ZG

Table 3: Boundary conditions for U, p & alpha

B. *simpleFoam solver*

Since we want to analyze steady-state turbulent flow for an in-compressible fluid, we have used the simpleFoam solver. We do not need to solve the energy equation due to the incompressibility. The SIMPLE(Semi-Implicit Method for Pressure-Linked Equations) algorithm, which the simpleFoam solver is based upon, is solving the momentum equation (Equation 1) and the Poisson pressure equation (Equation 2).

$$(\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_j u_i}{\partial x_j}) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\mu \frac{\partial u_i}{\partial x_j}) + \rho f_i \qquad (1)$$

$$\frac{\partial}{\partial x_i}(\frac{\partial p}{\partial x_i}) = -\frac{\partial}{\partial x_i}[\rho u_i u_j] \qquad (2)$$

As OpenFOAM utilizes a collocated grid, Rhie-Chow interpolation is used for the pressure-velocity coupling. Following is the SIMPLE algorithm which is the basis of simpleFoam solver:

1) Set the boundary conditions.
2) Solve the discretized momentum equation to compute the intermediate velocity field.
3) Compute the mass fluxes at the cells faces.
4) Solve the pressure equation and apply under-relaxation.
5) Correct the mass fluxes at the cell faces.
6) Correct the velocities on the basis of the new pressure field.
7) Update the boundary conditions.
8) Repeat till convergence.

C. *Force coefficients*

For studying the airflow over Bullet train, we have to calculate the force coefficients or the aerodynamic coefficients, viz. Co-efficient of Lift(C_L), Co-efficient of Drag(C_D) and Co-efficient of Moment(C_M). A force coefficient function was called in the controlDict file. It was defined as follows:

```
forceCoeffs1
{
type                  forceCoeffs;
functionObjectLibs    ( "libforces.so" );
outputControl         timeStep;
timeInterval          1;
log                   yes;
patches               (F1);
rhoName               rhoInf;
rhoInf                1;
liftDir               (0 1 0);
dragDir               (1 0 0);
CofR                  (0 0 0);
pitchAxis             (0 0 1);
magUInf               97.22;
lRef                  46;
Aref                  139.39;
}
```

D. *Results*

The C_L, C_D and C_M values are key figures in aerodynamics studies. We successfully obtained their values as C_L = 0.012, C_D = 0.539, C_M = -0.003 The plot of the force co-efficients against the simulation time is as follows:

The below graph shows the convergence of drag, lift and momentum coefficient. The values show that Drag is higher but the lift coefficient is lower. In the formula-1 racing, lift plays a major role. Only reducing the drag is not the purpose in the racing but maintaining the down-force is very important. With the higher specification of the engine, it can be maintained at high speed but there is the only thing that can help to put a car on the ground is down-force. We successfully determine the value of C_L = 0.012, The front wing on the car causes about 1/3 of the car's downforce and it has experienced more modifications than a rear wing. It is the first part of the car to meet the air mass. Therefore, besides creating downforce, it's the main function is to efficiently guide the air towards the body and rear of the car, as the turbulent flow impacts the efficiency of the rear wing.

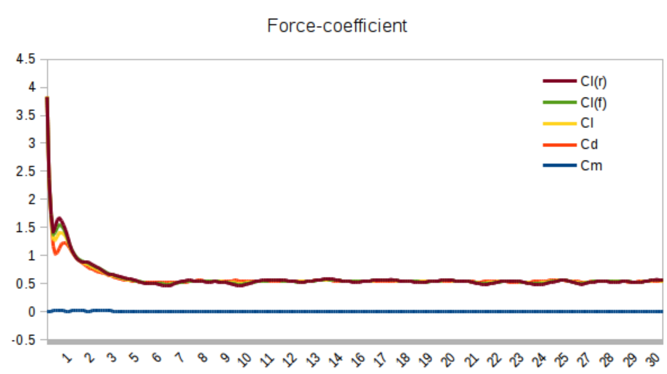

Figure 12: Force coefficients versus Simulation Time

The Residuals plot using Gnuplot shows that values almost converge at 0.05 to 0.005 residuals. Some von-Karman effects also present. Due to von-Karman effect it is not totally converged but for the given problem it is almost converged. The simulation can be run furthermore, then it will maybe converge at 1e-6 value. For the precise value like 1e-6 convergence, it is required to very fine mesh and very long time run the simulation.

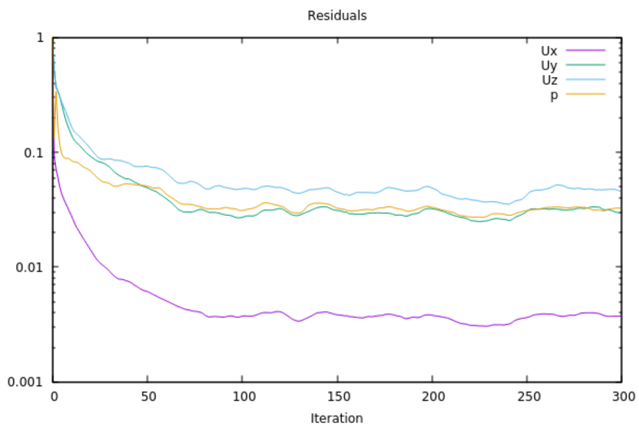

Figure 13:Velocity and presssure convergence residuals

The pressure is distributed over the whole car but the values may be changed due to additional features like front-wing, rear-wing and barge-board. This significant change plays a very vital role during the racing. Every angle of the wings used in the features is important. A minor difference may affect the race.

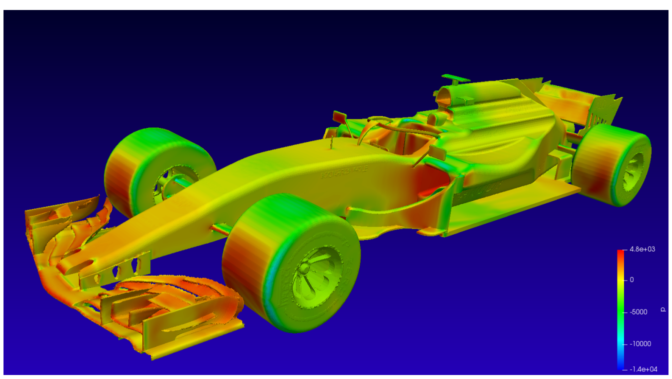

Figure 14: Presssure distribution over Formula-1

The maximum pressure generated on the front-wing and wheel of the car is 4.8e+3 Pa.

The simpleFoam solver not follows PISO loop so the simulation might differ from the actual values but it is almost near to it. For actual results LES or Turbulence models used to simulate. In this case, laminar flow is used.

III. Post-processing

The post-processing is done through ParaView. The streamlines at time 7, 14, 21 and 30 shows in below image. First two figures show that major amount of air passes through the upside of the rear-wing and very less amount of air passes through the below of rear-wing. All the major air creates an advantage to the down-force.

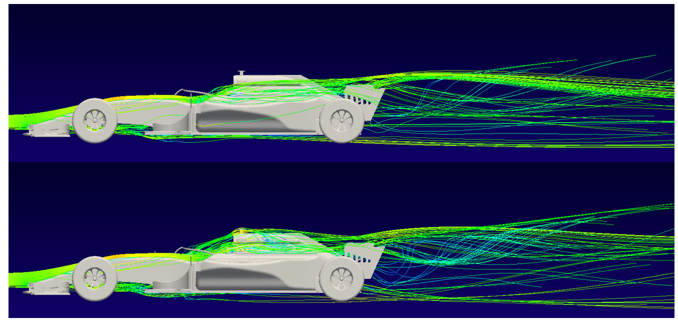

Figure 15: Velocity streamlineas at time 7 & 14 seconds

Below two images show the streamlines at time 21 and 30 seconds. Almost all the air passes above the rear-wing at the fully developed flow. Due to some von-Karman effect, velocity streamlines profile shows an up-down value.

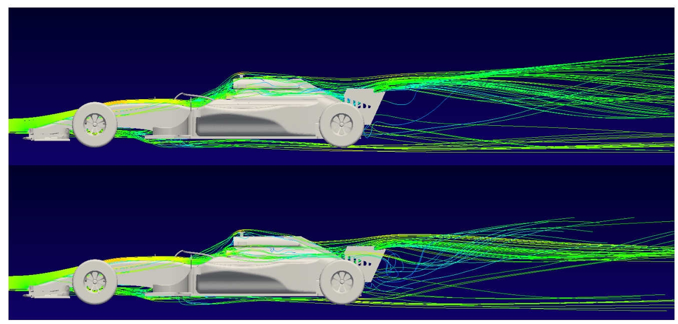

Figure 16: velocity streamlines at time 21 & 30 seconds

As shown in figure 16 due to the front wing and Tyre of formula-1 it creates a low-pressure area at a rear part of Tyre. Front-wing area is the most important part of a racing car because it separates the flow over the whole body of a car. Front-wing affects 60% of down-force and another 40% from whole body and other features. Due to front-wing air doesn't strike directly to the tires so that the drag effect minimizes, It's visible in the image of streamline.

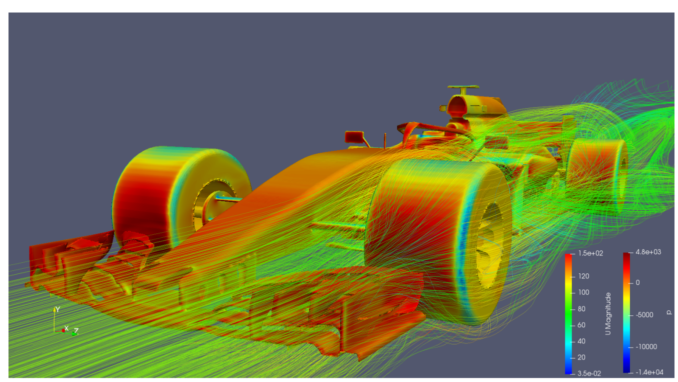

Figure 17:Streamlines over front-wing

When air flows from the body to rear-wing it directly strikes the wing. Some of the air goes from the below the wing and some from above the wing. Due to the angle of the wing air creates a Hugh down-force to the car. This down-force is also playing a very important role during the race.

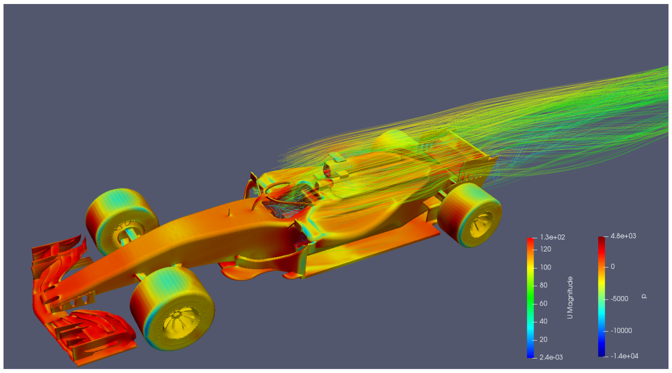

Figure 18: Streamlines over rear-wing

As the streamlines visualization from the image, it shows that barge-board gives direction to the air so that air can pass through the features of the body. Due to barge-board it can get a maximum advantage of air and reduce the turbulence vertices after the features.

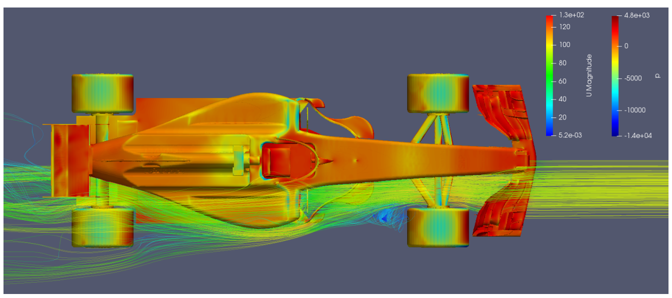

Figure 19: Streamlines over barge-board

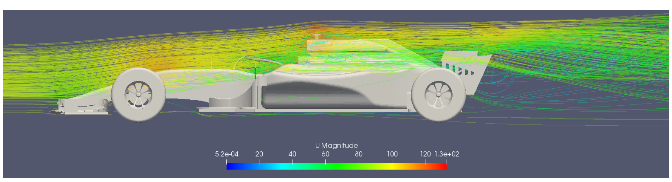

Figure 20: Fully developed laminar flow

At time 30, fully developed flow streamline indicates the major flow is on the rear-wing and upper diffuser of the car.

IV. Conclusion

After a detailed study of aerodynamics in an F1 car, we can say that F1 car is most aerodynamic of all the vehicles. The design is made such that it cuts through the air with minimum air friction and channelize the air flowing over up to the rear wings. It gives highly reduced drag and lift force acting on the car body. It generates more amount of down word force making the car stable at very high speeds. It is the pinnacle of racing sports technology.

The drag force, downward force, lift coefficient, and drag coefficient have been obtained. The pressure and velocity for all cases are presented in the form of contours and graphs. It can be seen that the thickness of the aerofoil for the flap wing influences the down force and the drag force of the rear wing module (combination of main wing and flap wing). Increases the downforce and drag force produced by the rear wing. From all the obtain results, it can be concluded that the short flap wing is favourable when facing a circuit that have more straight track. it can reduce the drag force significantly therefore will increases the speed of the F1 car.

The complexity of automobile and race car aerodynamics is comparable to airplane aerodynamics and is not limited to drag reduction only. The generation of downforce and its effect on lateral stability has a major effect on race car performance, particularly when high-speed turns are involved. In the process of designing and refining current race car shapes, all aerospace-type design tools are used. Because of effects such as flow separations, vortex flows, or boundary-layer transition, the flow over most types of race cars is not always easily predictable. Due to the competitive nature of this sport and the short design cycles, engineering decisions must rely on combined information from track, wind tunnel, and CFD tests.

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