Study and Overview of Aerodynamic Active Rear Wing of High speed Vehicles

Pradeep Madane[1], Kaivalya Pande[2], Prajwal Gote[3], Pushpraj Dongare[4]

[1-4]BE Undergrad Student, Dept of Mechanical Engineering, Government College of Engineering, Aurangabad-431005, MH, India

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Abstract - *In this paper an attempt is made to improve the aerodynamic performance of a race car using Active Aerodynamics. The concept of aerodynamics has come a long way in recent years due to regulatory requirements for emissions reduction and to reduce drag, wind noise and preventing undesired downforce at high speed. The study in this paper aims to change the aerodynamics of high-speed vehicles. Very often, it is considered that vehicle dynamics and aerodynamics does not depend on each other. This study explains the interdependence of aerodynamics and vehicle road dynamics. This paper suggests a schematic mechanism for the actuation of an active aero system involving the utilization of a data acquisition system, which receives input from different parameter measuring sensors. The study of the aerodynamic behavior of the rear wing has been performed through steady state CFD simulations of different orientations of a same model of the rear wing of a race car in Ansys Fluent solver using the k – ε turbulence model. The results obtained from these simulations are represented in pictorial and graphical form. The values of drag and downforce obtained from CFD analysis can further be used as prime reference for designing the mechanism of the particular Active Aerodynamics System.*

Key Words: CFD, Aerodynamics, Flow, Drag, Downforce, Active aero, Control Systems, etc

1. INTRODUCTION

In this modern era of high speed automobiles, aerodynamics plays a major role. Aerodynamic drag contributes to almost 20% of overall drag and that drag affects at high speed. Also, during high speed cornering, the vehicle must be pinned to the road without losing traction and for that, the vehicle must provide more downforce. So to maintain the vehicle performance in both the conditions, active aerodynamics concept is used. Active aerodynamics allow the driver to switch between high downforce condition to low drag condition using electronic sensors, electronic control unit and electronic actuators using the car's brain. This paper briefly describes the active aerodynamics system and how it works and how it helps to improve overall performance.

1.1 Aerodynamic forces

In many aerodynamics problems, the forces of interest are the fundamental forces such as lift, drag, thrust, and weight. Of these, lift and drag are aerodynamic forces, i.e. forces due to air flow over a solid body. There are three basic forces to be considered in aerodynamics that are thrust, which helps to move an object forward; drag, which holds it back; and lift, which keeps it airborne. These properties measured in aerodynamics having different equations:

1. Conservation of mass
2. Momentum of air
3. Energy in air flows

Resolution of forces in aerodynamic is as below,

1. The sum of all upward forces equals the sum of all downward forces.
2. The sum of all forward forces equals the sum of all backward forces.
3. The sum of all moments equals zero.

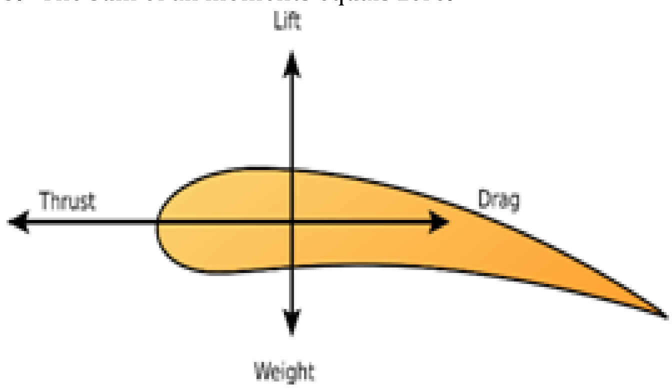

Fig -1: Forces on Aerofoil

Thrust: The forward force produced by a power-plant as it forces a mass of air to the rear (usually said to act parallel to the longitudinal axis).

Drag: It refers to the force that opposes the relative motion of an object through a fluid. It is the force of wind or air resistance pushing in the opposite direction to the motion of the object.

Lift: The aerodynamic force caused by air flowing over the wing that is perpendicular to the relative wind. An inverted aerofoil is used as an aerodynamic wing and so the lift force acts in opposite direction and called as downforce.

1.2 Bernoulli's principle

The Bernoulli equation states that an increase in velocity leads to decrease in pressure. Thus, higher the velocity of the flow, lower the pressure. Air flowing over an airfoil will decrease in pressure. The law is directly related to the principle of conservation of energy. It maintains that slower moving fluid exerts greater pressure than faster moving fluid.

$$p + \rho gh + \rho v^2/2 = \text{Constant}$$

$$p + \rho gh = \text{Static Pressure}$$

$$\rho v^2/2 = \text{Dynamic Pressure}$$

Where, p- Pressure, v- Speed, h- Height, ρ- density

1.3 Boundary layer

A boundary layer is the layer of fluid in the immediate vicinity of a bounding surface where the effects of viscosity are significant [1]. There are two different types of boundary layer flow, laminar boundary layer flow and turbulent boundary layer flow. The laminar boundary is a very smooth flow, while the turbulent boundary layer contains swirls or eddies. The laminar flow creates less skin friction drag than the turbulent flow, but is less stable. Boundary layer flow over a wing surface begins as a smooth laminar flow. As flow continues back from the leading edge, the laminar boundary layer increases in thickness. At some distance back from the leading edge, the smooth laminar flow breaks down and transitions to a turbulent flow. From a drag point, it has the transition from laminar to turbulent flow as far aft on the wing as possible, or has a large amount of the wing surface within the laminar portion of the boundary layer. The low energy laminar flow, however, tends to break down more suddenly than the turbulent layer.

There are two effects which have to be considered. First, the boundary layer adds to the effective thickness of the flap, hence increasing the pressure drag. Secondly, the shear forces at the surface of the wing create skin friction drag. At high Reynolds number, it is desirable to have a laminar boundary layer. This results in a lower skin friction due to the characteristic velocity profile of laminar flow. At lower Reynolds number, it is relatively easy to maintain laminar flow. This gives low skin friction, which is desirable.

1.4 Computational fluid dynamics (CFD)

CFD is “solving fluid flow problems numerically” or it is the art of replacing the integrals or the partial derivatives (as the case may be) in the Navier-Stokes equations by discretized algebraic forms, which in turn are solved to obtain numbers for the flow field values at discrete points in time and/or space [2]. Computational Fluid Dynamics is a tool that allows us to solve flow problems that do not have known analytical solutions and cannot be solved in any other way. CFD has advantages like it is fast, provides complete information, easily allows parametric studies which are important in design and similarity constraints i.e. simulations can be performed at full scale. Along with these advantages it has disadvantages like accuracy and reliability, results are very sensitive to large numbers of parameters to be set by the user, verification and validation are imperative and validation requires experiments. So, practical methods of determining aerodynamics include Wind tunnel testing.

1.5 Wind tunnel testing

Wind tunnel testing is accurately reproducing wind flow around full scale or model scale objects in a tunnel-like construction under controlled conditions to study their performance for design research purposes. Wind-tunnel testing is extensively used for validation of Computational Fluid Dynamics simulations. This testing has advantages like they allow the use of models that can be prepared early in design cycles, It include the full complexity of real fluid flow, and importantly they can provide large amounts of reliable data. Thus the question arises, why need wind tunnel testing if we can get all the required data from CFD? The answer is, there are some things which cannot be simulated in CFD softwares and those can be practically simulated in wind tunnels only e.g. testing the effect of textile texture on cyclist aerodynamics, this cannot be “resolved” with CFD. So, the most successful attack on virtually any aerodynamic design problems will be based on application of a combination of results from experimental, theoretical and computational methods appropriately combined and leavened by experience.

1.6 Flow separation

During the flow over the surface of the vehicle, there are some points when the change in velocity comes to a stall and the fluid detaches from the surface and start flowing in reverse direction forming eddies and vortices [3]. This phenomenon is called ‘Separation’ of the fluid flow or Boundary layer separation. This occurs at different positions like the front hood, front windscreen and more dominantly in the rear part of the vehicle. This separation affects the flow field around the vehicle. Thus the phenomenon introduces the concept of wake. Flow separation causes larger wake and thus drastic loss of downforce and major increases in pressure drag. To avoid bad flow separation, the transitions of the air flows from rooftop to the back window should be smoothed [4]. Aerodynamics efficiency can be increased by designing a streamlined body to avoid bad flow separation.

2. AERODYNAMIC FLOW AROUND THE VEHICLE

The diagram for aerodynamic flow (Fig. 2) clearly shows the nature of the flow around the vehicle. There is a stagnation point in front of the vehicle as air is almost stagnant in those regions. By Bernoulli's principle a high pressure region corresponds to a low velocity region which can be seen in the velocity contours. During the air flow at the vehicle without wing, air gets pulled downward at end creating recirculation zones and thus generating turbulence just behind the vehicle. This nature of flow will affect the aerodynamic efficiency of the vehicle by creating low pressure wake behind the vehicle. To avoid such low pressure wake, an aerofoil wing is added at the rear of the vehicle. The aerofoil will divert the flow according to the attack angle and thus forming a comparatively higher pressure wake than the case without rear wing. In case of aerofoil, the wake generated behind the vehicle depends upon the angle of attack. Low angle of attack will create low drag and low downforce while increased angle of attack will further form low pressure wake resulting in high drag and higher downforce. Thus pressure wake behind the vehicle affects dynamic performance of the vehicle intensively.

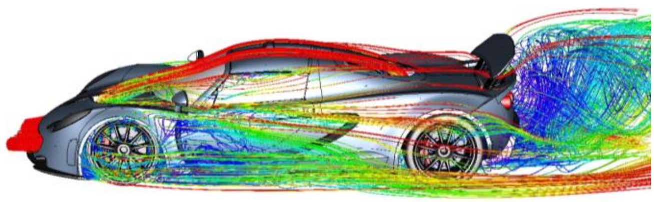

Fig -2: Streamlines showing flow around a vehicle

3. ACTIVE AERODYNAMICS

Aerodynamics massively affects the performance of the vehicle. Airflow around the vehicle creates drag and downforce. This drag and downforce, changes vehicle performance in various track conditions. In case of top speed, the vehicle must provide low drag and sufficient downforce to keep it attached to track while during high speed cornering the vehicle should have more downforce to keep vehicle attached to ground and must not leave the track.

It is known that having higher down force generates the following advantages:

1. Increases tires capability to produce cornering force
2. Improves braking performance
3. Gives better traction

There is a disadvantage of high downforce during high speed conditions as it will slow down the vehicle. The key to provide downforce while maintaining top speed is the minimization of drag. The ideal scenario is one where you direct air pressure where it is needed to keep the car on the road (downforce) without slowing down the car (drag). In recent years wing mounting techniques have evolved significantly to allow variation of the wing angle and widely known as Active wing. The active wing provides sufficient drag and downforce according to the situation. This is called Active aerodynamics of a vehicle. Active wing is normally electronically activated by the car's brain, active aerodynamics also involve active spoilers, vents and wings to keep the car pinned to the road during high-speed driving. By varying the car's aerodynamic aids, the car can strike a balance between efficiency and road holding ability.

4. DATA ACQUISITION SYSTEM AND ACTIVE CONTROL OF AERO ELEMENTS

To operate an active aerodynamic system in a vehicle it is necessary to have a flexible and easy to modify system. Measurement of the vehicle parameters using various sensors is another important goal which will make this aerodynamic system autonomous. This whole active aerodynamic system can be divided into three subsystems, measurement of parameters using sensors, electronic control system, user interface and actuation of system. With electronics active aero reached its own new level.

4.1 Measurement of dynamic parameters using sensors

Various electronic sensors are used to collect the real time data and fed to the control unit.

Steering Angle Sensor: To measure the variation in the steering angle, the steering-angle sensor based on magneto resistance technology (GMR element) offered by BOSCH is studied. The analog values of the GMR elements are converted into digital information directly on the circuit, which is then sent to the microprocessor via serial interface at the frequency of 100 Hz.

Inertial Measurement Unit: The inertial measurement unit measures up to six dimensions: yaw, roll and pitch rate as well as lateral, longitudinal and vertical accelerations. The inertial sensor designed by BOSCH is used which works according to the Coriolis principle, meaning it utilizes the inertia force of an oscillating mass in a rotating system. Thus, it collects all the dynamic data of the vehicle.

Pedal Position Sensors: This sensor monitors throttle and brake pedal movement. This sensor can be either rotary or linear in operation and is mounted with the operating shaft. The pedal position sensor offered by Active Sensors is suitable for our use.

4.2 Electronic control unit and User Interface

To have integration between the operating mechanism and sensors output, we require an electronic control unit. An electronic control unit is a device responsible for overseeing, regulating and altering the operation of an active aerodynamics system on the basis of input data from the user and different sensors. The DENSO electronic control unit is studied because of its effective user interface. After synchronous reading of all the data from all the sensors the control algorithm of electronic control unit processes the data according to defined control laws and sends commands to the actuation algorithm which then sends the commands to all control units (i.e. Servo motor) of the system. User interface allows the operator to observe the collected data, configure the controller according to dynamic conditions (different modes of operation are possible), and can manually control the aerodynamic elements. The Electronic control unit is also configured to operate in a fully automatic way without any user input.

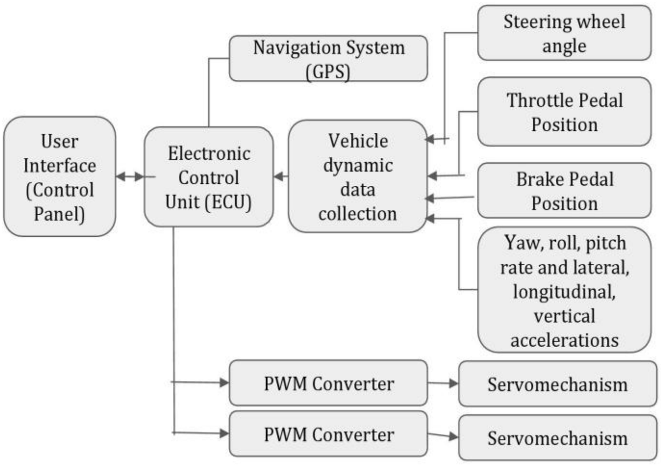

Fig -3: Data collection and Actuation system layout

4.3 Actuation of aero elements

The actuation subsystem includes the mechanism used for operating the aerodynamic elements. The aerodynamic wings are built into two parts (Fig - 9) and can be operated individually to control the downward force and drag during all dynamic conditions like accelerating, braking and high speed cornering. PWM (Pulse Width Modulation) signal-controlled servo motors are used which are connected to RS-485 interface via signal converters. These motors are controlled at the frequency of 20Hz. The aerodynamic wings are connected to the rocker arm which is then connected to the push rod. The push rod (follower) operates on the cam which is attached to the shaft of the servo motor. This actuation mechanism integrated with vehicle assembly such that no major component is directly exposed. The part of linkages that is exposed to flow is designed aerodynamically and so it produces less amount of drag.

5. DETERMINATION OF DRAG BY CFD

The rear wing is designed as an active aerodynamic element. For the same we have to consider the actual aerodynamic effect of the structure of the wing and also which angle of attack to choose in accordance with the vehicle for best streamlined results. For the CFD analysis of the spoiler, Ansys Fluent solver is used. Several versions of the same model of spoiler were analyzed just by varying the angle of attack (AOA). Starting from 0° to 40°, with a constant difference of 10°, in total 5 models were analyzed and all of which were set up using the k - ε turbulence model. A virtual wind tunnel was created around the model. The geometry was meshed in tetrahedral elements using patch conforming method. The boundary conditions such as, a speed of 250 kmph (69.44 m/s) and gauge pressure of 0 Pa were selected. The fluid in the tunnel was air with density 1.225 kg/m^3 and kinematic viscosity of 1.7894×10^{-5} Kg/ms.

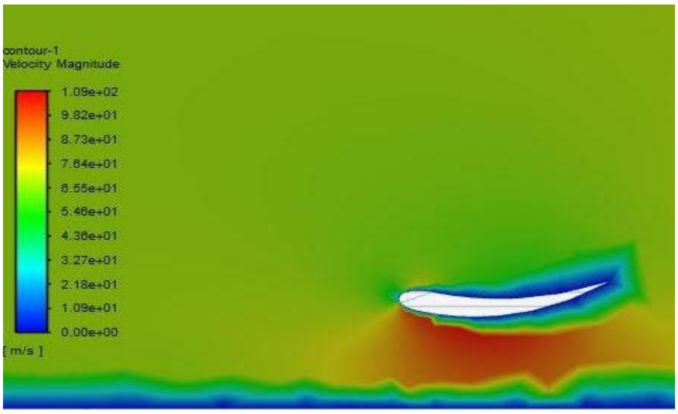

Fig -4: Velocity contours for 0deg AOA

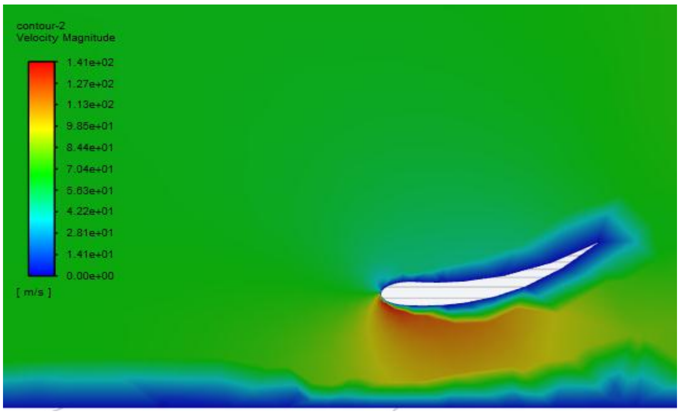

Fig -5: Velocity Contours for 10deg AOA

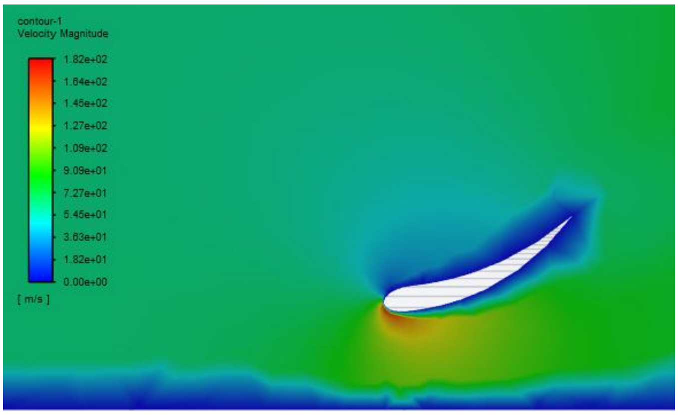

Fig -6: Velocity Contours for 20deg AOA

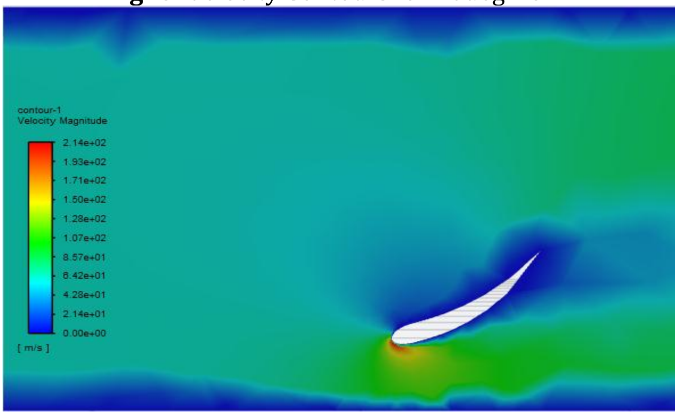

Fig -7: Velocity Contours for 30deg AOA

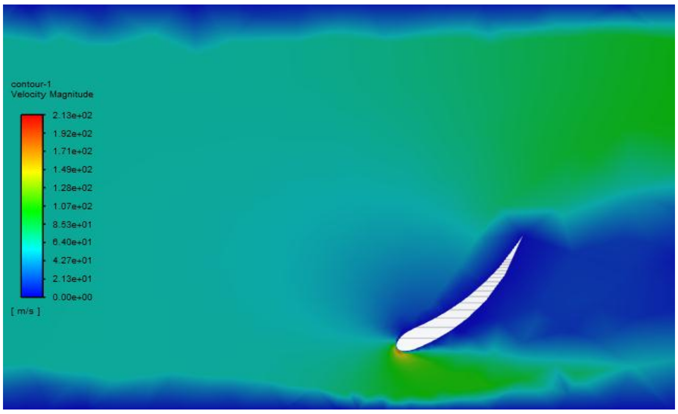

Fig -8: Velocity Contours for 40deg of AOA

The flow features for different angles of attack of wing are shown in Fig 4-8. From that we can conclude that, as angle of attack is changing, at initial angles flow is adjusting itself without much disturbance but as angle is increasing, there is formation of a recirculation zone behind the wing structure and hence creating more drag. Chart 1 clearly shows the increase in drag and downforce coefficient with increase in angle of attack validated by CFD simulations.

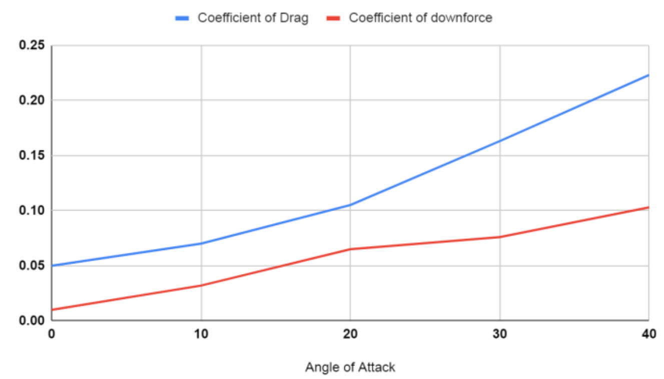

Chart -1: Coefficient of Drag and Downforce Vs AOA

6. ACTIVE AERO AND VEHICLE DYNAMICS

To reduce the tradeoff between high speed cornering, braking and top speed driving performance we have developed an active aerodynamic system at the rear wing which is able to respond according to vehicle road condition. These three conditions are studied to give a more collective aerodynamic and dynamic response to road condition.

Accelerating or Top speed condition: When a high-speed car accelerates in a straight line, it is necessary to have minimum drag and downforce which ultimately reduces the resistance to the motion resulting in increment in speed. To achieve this result, an active aerodynamic system aligns the active rear wing at an angle of 0 deg with respect to the vehicle rear body to minimize the pressure drag and downforce. The aerodynamic wing will maintain the angle by analyzing data provided by pedal position sensor, steering angle sensor and GPS.

High Speed Cornering: During high speed cornering, there is a requirement of comparatively higher downforce to pin the vehicle to the ground so that it won't lose traction. As per dynamic behavior, during cornering, overall weight will be transferred to the outer side providing more downforce to outer wheels and relatively less downforce to inner wheels. So due to this condition, there are chances of the inner wheel to lose traction and the vehicle will spin and go out of road or track. To avoid this situation, we have splitted the rear wings in two halves (Fig -9) and each part works independently. So during high speed cornering, the inner side wing will attain required angle to produce maximum downforce and the outer side wing will attain such a position from which it will reduce drag and produce required downforce. Thus, balancing the vehicle dynamics by using active rear wing. The actuation of the rear wing will be done on the input data from steering angle, pedal position, yaw rate, lateral acceleration and all the parameters measured by inertial sensors.

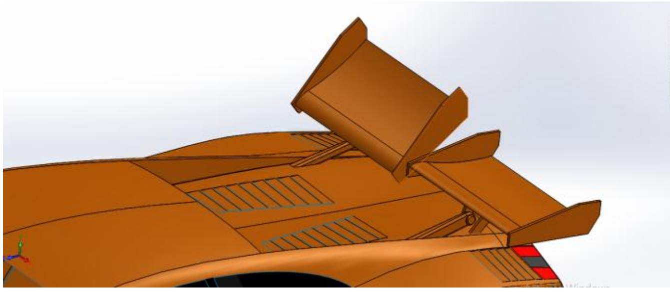

Fig -9: Representation of Active Independent Rear Wing

Braking: In order to increase braking efficiency during high speed, an active rear wing is used. For effective braking, it is necessary to have grip and drag to slow down the vehicle. So the active rear wing takes the input data from the brake pedal position and inertial sensor to actuate the rear wing to its maximum possible angle to provide increased drag. This increased drag reduces the vehicle speed. This kind of braking is also called aero brake or aerodynamic brake.

7. ADD-ON AERODYNAMICS SYSTEMS

1. The MP4-X F1 concept design revealed by McLaren involving plasma flow controllers is in research and development currently. The idea of the active aerodynamic using the electronic devices having minimum or no drag but can be actuated when required to produce drag by electronic devices placed inside bodywork, High-voltage alternating current is passed across two electrodes, which creates low-temperature plasma. This plasma can ionize air molecules passing over a surface, speeding up the airflow. This type of tech could increase a car's downforce dramatically without creating much drag and aero disruption as modern active wings do. Activate the plasma flow controllers when extra grip is desired, shut them off when it isn't. It will require quite a lot of power but McLaren claims that this could be achieved in future when tech develops to a new level.
2. There are multiple venturi ducts along the bottom and rear of the car to increase downforce and help the car hug the road, but too much of it can cause drag and limit top speed. To combat this, there are small flaps at the front of the car that can be opened or closed to direct airflow into, or away from, the venturi ducts. In general, the flap is retracted at specific speeds. This helps to increase downforce and improve handling. Once that speed is increased, the flaps are open to create less drag under the car and improve top speed performance.
3. The concept of Active Rims helps to change the aerodynamics of the vehicle in running mode. The active rims alter their cupping with the aid of centrifugal force from certain designed distance to 0 millimeters, transforming them from sporty spoke wheels into flat disc wheels offering exemplary aerodynamic characteristics.
4. A different kind of flexible deformable surfaces placed in various locations on the vehicle. These deformable surfaces can have the form of airbags, which in an inactive state adhere closely to the body of the vehicle, whereas in an active state (inflated) change their shape and at the same time modify the shape of the vehicle. Such a change in shape would change the value of the aerodynamic forces acting on the car while driving [5].

8. CONCLUSIONS

Study is done on the basic forces in aerodynamics, boundary layer, flow separation and finding out the regions with aerodynamic inefficiency by determining the flow around the vehicle. The key to provide downforce while maintaining top speed is the minimization of drag and is achieved by an active rear wing. This active wing gets actuated by the vehicle brain i.e. electronic control unit by taking input data from pedal positions, steering angle, yaw rate, lateral acceleration etc. from different sensors. CFD of the active rear wing is successfully done to determine the nature of flow, drag and downforce at various angles of attack.

An advanced active aerodynamic system with divided rear wing improvised dynamic performance of the vehicle and thus created the strong relation between aerodynamics and vehicle dynamics. Various add on systems are studied to improvise aerodynamics efficiency. Overall active aerodynamics helps to increase downforce or reduce it according to road conditions by using advanced data acquisition systems without compromising speed.

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