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A Computational Study to Investigate the Effect of Varying Ground Clearances and Angle of Attack for a Double-Element Front Wing of a Formula 1 Racecar

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Abstract*—Modern open wheel racecars depend heavily on aerodynamics in order to determine success in open wheel championship such as Formula 1 and Indycar. Moreover, as the front wing of a racecar is the first element which comes in contact with the free stream air and it consequently determines the airflow over the racecar, it has been a topic of keen interest for researchers around the world. Owning to the research conducted over the years, a highly developed front wing of a modern open wheel racecar develops about 30% of overall down force generated. However, there exists a number of factors such as varying ground clearances, angle of attack and Reynolds number to name a few, which affect the down force generated by the front wing. In the present study, a double element front wing of a modern racecar was studied to investigate the effect of varying ground clearances and over all angle of attack. A three-dimensional computational study was conducted using the steady state Reynolds Averaged Navier-Strokes (RANS) equations for a highly cambered single slotted double element front wing with an overall chord length of 380mm. The modified NASA GA (W) profile of type LS (1)-0413 was used as wing profile. The overall study was conducted with a moving ground simulation in three phases; a free stream case, in decreasing ground clearances and varying angle of attack with simultaneous decrease in ground clearance. By studying the flow characteristics of the wing at 10 different ground clearances, it was observed that the computational model was able to correctly predict the wing behavior in ground effect and that the down force generated behaves as a function of ground clearance. Furthermore, by studying the lift and drag forces generated by the wing, it was observed that the wing clearly operates in three different regions which can be classified as; a region similar to free stream case, a force enhancement region and a force reduction region. In addition, by studying the effect of increasing angle of attack with decreasing ground clearances, it was observed that for lower values of angle of attack the corresponding very low ground clearances has more impact in decreasing the down force generated. However, for higher angle of attack, the resulting increase in camber has a significant impact than very low ride heights which leads to an increase in down force generated.

Index Terms—**CFD, Double-Element, Front Wing, Ground Effect, Angle of Attack.**

I. INTRODUCTION

Modern open wheel racecars such as Formula 1 and Indycar rely heavily on extremely complex and effective aerodynamics to determine a race win in these championships. However, it was not until 1965 that the first ever wings were seen on a racecar in Formula 1 even though the concept of using inverted airfoils to generate down force was already implemented in 1920 [1]. The first racecar wing implemented in Formula 1 was a rear wing mounted on a Lotus 49B racecar in 1965 and consequently after two weeks the first front wing was mounted on a McLaren. Racecar wings are nothing but conventional airfoils inverted in order to generate negative lift otherwise known as down force [2]. In aircraft industry, the conventional airfoils generate an upward lift with the help of Bernoulli's equation. The pressure difference caused due to the accelerated flow over the upper surface and a relatively slower airflow on the lower surface of an airfoil causes an upward force known as lift. When the same airfoil is inverted and used as a racecar wing, it generates a negative lift also known as downforce which provides more grip through high speed corners and helps racecar attain higher values of lateral acceleration.

Since the early days of aerodynamics in racecars, aerodynamicist and participating teams around the world has acknowledged the importance of aerodynamically efficient racecars for winning races. Throughout the past few decades a lot of research has been carried out to improve the aerodynamic efficiency of racecars. As mentioned earlier, a racecar wing is simply a conventional airfoil inverted. However, when inverted and used as a racecar wing there exists some key differences which have a significant impact in determining the down force generation capability of a racecar wing. The key differences between conventional airfoil and racecar wing are racecar wings operate in a close proximity to the ground and thus have a strong ground effect. Furthermore, they have small aspect ratio and also have strong interaction with other components of racecar [3]. As the front wing of a racecar is the first element that comes in contact with the free stream air, it thus determines the airflow over the racecar and also the underbody flow through side pods and diffuser. Owing to this, the front wing has been a topic of keen interest for researchers around the world and numerous experimental and computational studies have been carried out to determine its behavior. Consequently, a numeric study was conducted by Mokhtar [4] using the S1223, E423, LNV109A and NACA9315 profiles to investigate the effect of varying ground clearance, angle of attack and Reynolds number. It was observed that the varying ground clearance and angle of attack has a significant impact on the downforce generated for all the profiles whereas, in comparison varying Reynolds number had a minimal effect. In addition, Mokhtar also investigated the effect of ground clearance on a NACA0012 profile in a computational study [5] and observed that the downforce behaves as a function of ground clearance i.e. the downforce generated increases with every decrement in ground clearance for a relatively less increment in drag as the decreasing ground clearance results in a higher accelerated flow between wing and ground which ultimately creates higher pressure differences. Furthermore, it was also observed that as angle of attack is increased, the lift generated by the wing increased too as it increases the camber of the wing. Mokhtar and Lanein also studied the effect of using endplates in ground effect on a S1223 airfoil in a numerical study and found that it has minimal effect.

A series of both experimental and computational studies were conducted by Ranzenbach and Barlow [7], [8] and [9] to determine the effect of varying ground clearances on a single and double element front wing. The Reynolds Averaged Navier-Strokes (RANS) equations model was used for a two-dimensional computational study along with a stationary ground simulation to predict the flow over the front wing. It was observed that when subjected to varying ground clearances and studied for down force generated, there exist two distinct regions; a force enhancement region and a force reduction region. A force enhancement region is for ground clearances 0.3c to 0.1c, where down force behaves as a function of ground clearance. Whereas the force reduction region is for ground clearances less than 0.1c where any further decrement in ground clearances causes a decrease in down force and a simultaneous increase in drag. The authors explained the reduction in down force as a result of merging of ground plane and airfoil boundary layers. Furthermore, a similar three-dimensional computational study was conducted by Mokhtar and Durrer [10] on a single element front wing using the S1223 profile in ground effect and they concluded that the merging of ground plane and wing boundary layers was the reason for the force reduction phenomenon at lower ground clearances.

However, Zhang and Zerihan through their series of experimental studies [11] and [12] on both single and double-element front wing of a Tyrelle 026 Formula 1 racecar using a moving ground observed that the force reduction phenomenon at lower ground clearances is caused due to the separation of boundary layers at the trailing edge. Furthermore, from the studies conducted on mulit-element front wing, it was observed that the multi-element wings generate more downforce as the addition element increases the camber. A series of two-dimensional computational studies on the same single and double element Tyrelle 026 Formula 1 wing was performed by Zhang Mahon in [13] and [14]. Through these computational studies the authors were able to accurately predict the behavior of single and double element mentioned front wing by comparing the results from the studies in [11] and [12] with the help of k- ω SST turbulence model. Another similar two-dimensional computational study was conducted by Genua [15] on a single element front wing of the same profile to investigate the predictive capability of various turbulence models in ground effect. It was concluded that predictive capability of the one equation Spalart-Allmarus turbulence model was best suited. The authors also investigated the effect of angle of attack on a mulit-element wing. Through their studies they observed that the camber of the wing increases as the angle of attack is increased which relates to a higher value of maximum lift co-efficient and thus higher downforce was generated. Moreover, a three-dimensional computational study was conducted by Mokhtar and Kachare [16] to investigate the predictive capability of k- ω SST and Spalart-Allmarus turbulence model for a double-element front wing in ground effect. In this study, it was observed that the k- ω SST turbulence model proved to predict the flow and aerodynamic forces generated more accurately than the Spalart-Allmarus turbulence model.

II. PRESENT STUDY

The present study focuses on investigating the effect of varying ground clearance and varying angle of attack by simultaneously decreasing ground clearance for lower ride heights by conducting a three-dimensional computational analysis on a highly cambered single slotted double-element front wing for a Formula 1 racecar.

A. *Wing Model*

The wing profile used for the present study is a highly cambered single slotted double element front wing used in a typical racecar. Both the main element and flap consist of a modified NASA GA (W) profile of type LS (1) – 0413 possessing a finite trailing edge of 1.56mm for main element and of 0.95mm for the flap. In addition, the chord length of main element and flap is 223.4mm and 165.7mm respectively. However, for ease of calculations the total chord length of the wing used was 380mm and all parameters such as ground clearance were normalized by it. For the angle of attack calculations, the overall angle of attack (α_o) of 0^o corresponds to $+3.6^o$ angle of attack for main element (α_m) and a $+15.5^o$ angle of attack for flap (α_f). Also, to study the effect of varying angle of attack, the flow characteristics of wing in three-dimensions were studied at 8 different values of overall angle of attack. For the double element, the flap was placed in away that it has an overlap (δ_o) of 12mm and a gap (δ_g) of 9mm.Furthermore, the wing has an aspect ratio of $AR=2.89$ and a wing span of 1100mm. In the present study, for investigating the effect of varying ground clearance, the flow characteristics of wing at 10 different ride heights was investigated. Ground clearance *(H/c)* was measured as a ratio of the distance between the lowest point on the suction surface of wing and the ground plane *(H)* to the total chord length *(c)*.The described wing model was developed using Solid works 2016 solid modeling software. The figure 1 shows the schematic diagram of the wing model used in the study whereas the figure 2 shows the solid model for the same front wing.

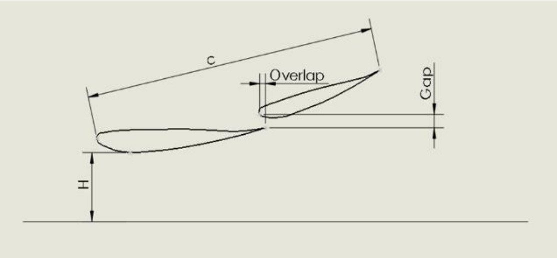

Fig 1: Schematic diagram of wing model

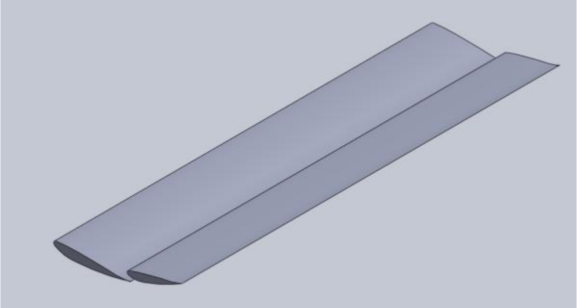

Fig 2: Solid model of front wing.

B. *Numerical Model*

The present three-dimensional study was conducted using STAR-CCM+ a computational package developed by CD-Adapco Inc. STAR-CCM+ is a CFD package which uses a finite volume method code to solve for the structured and unstructured meshes. It primarily makes use of Reynolds Averaged Navier-Strokes (RANS) equations to model the fluid flow which are based off the fundamental physics equations for conservation of mass, momentum and energy. The three-dimensional RANS equations for an incompressible flow are as shown in equation below.

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\rho g_x \quad (1)$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\rho g_y \quad (2)$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g_z \quad (3)$$

A steady state segregated flow model is used for solving the three-dimensional flow in the current study. In addition, a free stream velocity of 30m/s corresponding to the cornering speed of Formula 1 racecars is used which relates to a Reynolds number of 7.86×10^5based of chord length. Also, based on a study conducted by the authors previously [16], the standard *k- ω Shear Stress Transport (SST)* turbulence model is used to predict the three-dimensional flow characteristics of the wing.

The three-dimensional computational study is conducted in a computational domain comprising of a far field of 2000mm in length, 5500mm in width and 1750mm in height. Furthermore, the wing and ground are defined as a wall boundary. A no slip boundary condition with U=V=0 is defined for the wing whereas to get more realistic results a moving ground simulation was conducted with a reference velocity of 30m/s. Furthermore, to reduce the computational resources, all the cases were carried out using symmetry. In addition, from the results in study [16], the unstructured polyhedral meshing model was used with a thin prism layer extruder. Furthermore, a refinement block was used to capture the wake of the wing and the region between the wing and ground plane. Based on the ground clearances, volume mesh contained from 1.5million to 10million cells. The figure 3 below shows the three-dimensional computational used in the study. The computational domain consist of a free stream, multi-element front wing defined as a wall boundary condition and a moving ground plane wall boundary.

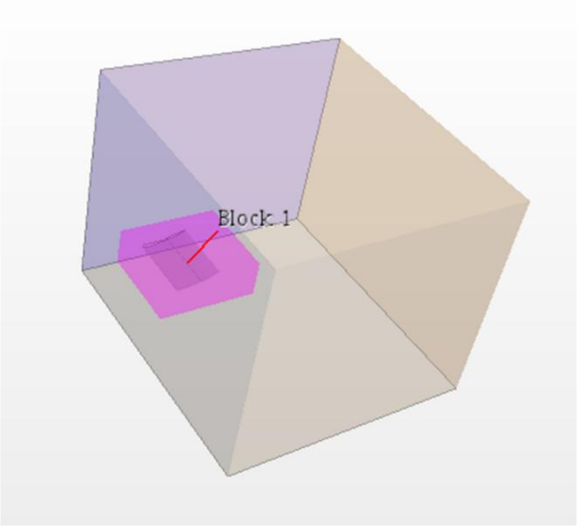

Fig 3: Computational domain used along with the wing model.

III. RESULTS AND DISCUSSION

The present study was conducted in three different phases of a free stream analysis, ground effect analysis and an analysis of varying angle of attack with a simultaneous decrease in ground clearance.

1. Phase I: Free stream

The free stream analysis was conducted at a reference velocity of 30m/s. The figure 4 and 5 shows the velocity and pressure distribution of the double-element front wing in free stream.

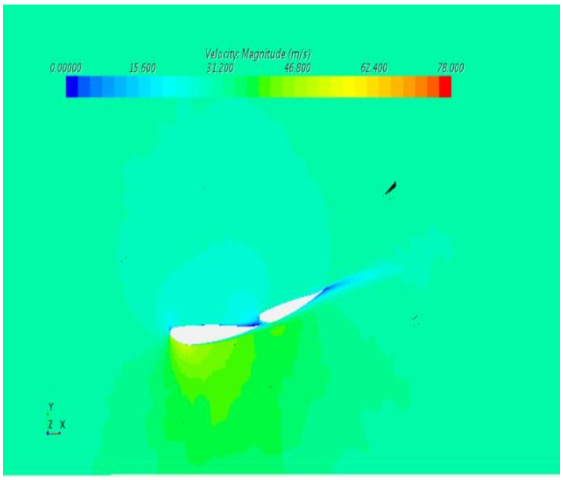

Fig 4: Velocity distribution of a double-element wing in free stream

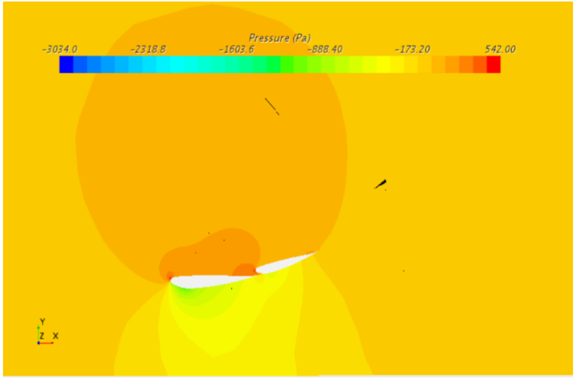

Fig 5: Pressure distribution of a double-element wing in free stream

By observing the pressure and velocity distribution plots it can be seen that the wing generates down force with the help of Bernoulli’s principle. From figure 3 it can be clearly seen that air flows at a higher velocity over the lower surface (also known as suction surface) than compared to the upper surface resulting in a pressure difference between the two surfaces seen in figure 4. This pressure difference produces a downward force know as negative lift or down force that pushes the wing towards the ground and provides more grip. Furthermore, by studying the lift and drag forces generated, it was observed that the majority of the down force was generated by the main element and the flap contributed mainly in reducing the wake of the wing. Also, by observing the wake characteristics of the wing at a distance of 0.1 *x/c*, it can be seen that the wing experiences end tip vortices along its edges which adds to overall drag. Furthermore, it was also observed that along the middle section of the wing the flow is a quasi two-dimensional flow with relatively less turbulence. The figure 6 below shows the wake of the wing in free stream.

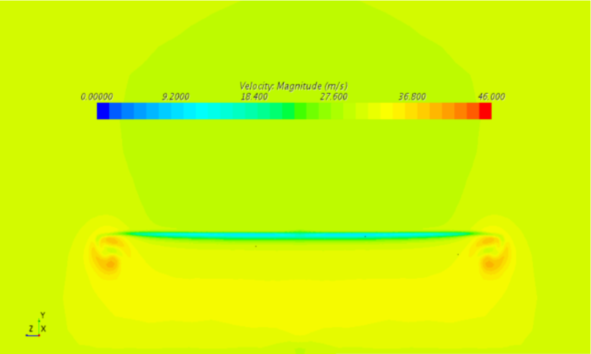

Fig 6: Wake generated by the wing in free stream

2. Phase II: Ground effect analysis

To study the effect of varying ground clearances, the flow characteristics of the double-element wing was investigated at 10 different ride heights of H/c=0.5, 0.3, 0.25, 0.224, 0.211, 0.15, 0.11, 0.09, 0.079 and 0.05 at a constant overall angle of attack of 0degrees and a moving ground simulation. As mentioned earlier a reference velocity of 30m/s was used for the three-dimensional analysis. Figures 7 to 10 show the velocity distribution plots of the mentioned wing at ground clearance of 0.5H/c, 0.224H/c, 0.09H/c and 0.05H/c respectively.

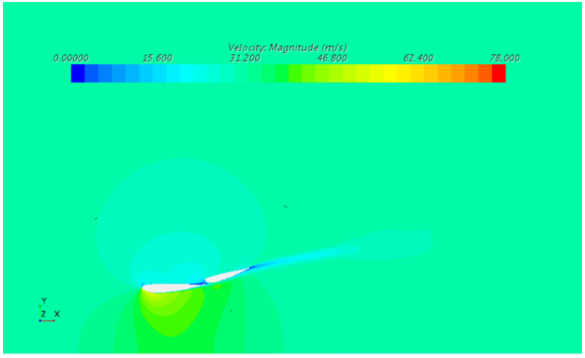

Fig 7: Velocity distribution of a double-element wing at 0.5H/c

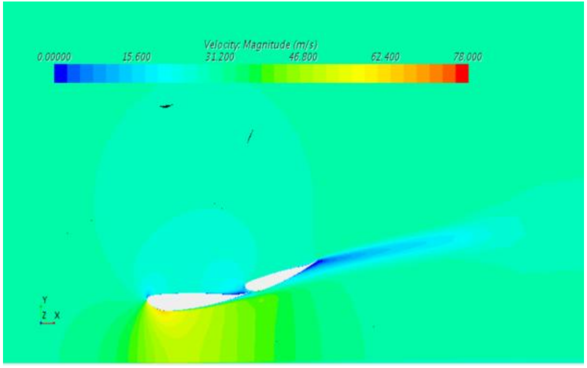

Fig 8: Velocity distribution of a double-element wing at 0.224H/c

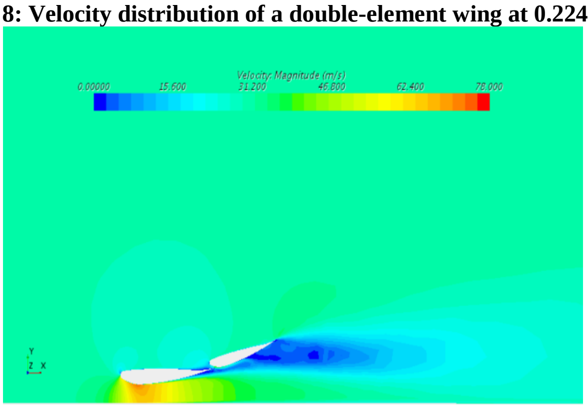

Fig 9: Velocity distribution of a double-element wing at 0.09H/c

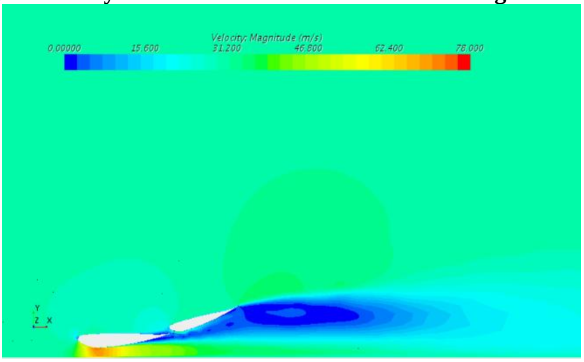

Fig10: Velocity distribution of a double-element wing at 0.05H/c

By observing the figures 7 to 10 it can be clearly seen that as the ground clearance decreases, the flow between the suction surface and ground is accelerated further and it achieves higher values of velocity. This accelerated flow thus results in a lower pressure values at the suction surface leading to a higher pressure difference between two surfaces. This pressure difference can be clearly seen in figures 11 to 14 which show the pressure distribution of the wing at these ground clearances as shown below.

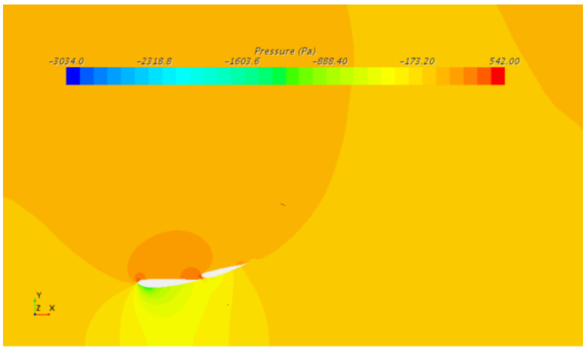

Fig 11: Pressure distribution of a double-element wing at 0.5H/c

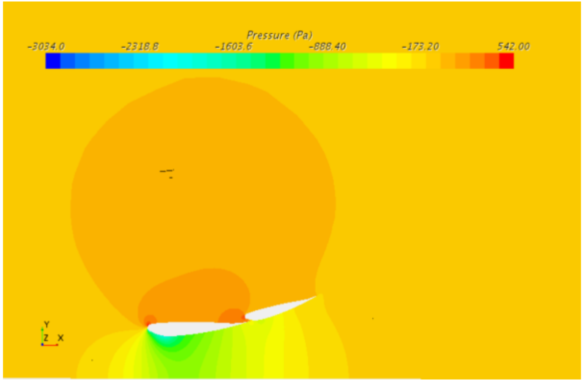

Fig 12: Pressure distribution of a double-element wing at 0.224H/c

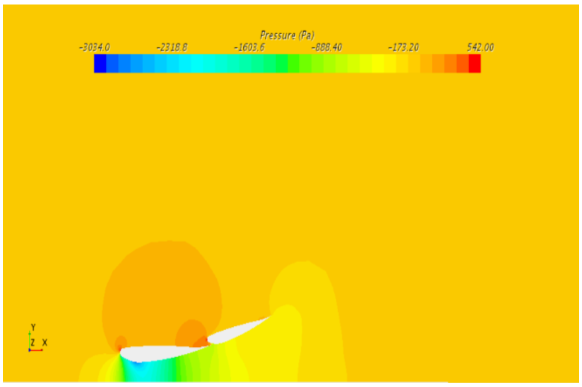

Fig 13: Pressure distribution of a double-element wing at 0.09H/c

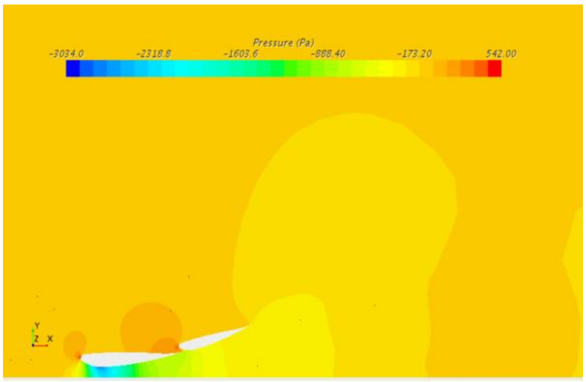

Fig 14: Pressure distribution of a double-element wing at 0.05H/c

Thus by observing the velocity and pressure distribution plots it can be inferred that, the decreasing ground clearance creates a nozzle effect where air flows at an accelerated velocity with decreasing ride heights. By Bernoulli’s principle, this accelerated airflow then leads to lower suction pressure value at the suction surface resulting in a higher pressure difference. Furthermore, this higher pressure difference between two surfaces eventually results in a higher value of negative lift force (or downforce) being generated by the wing. In addition, by observing the wake characteristics of wing at decreasing ground clearances, it can be seen that the ground plane assists in eliminating the end tip vortices. The figures 15 to 18 show the wake characteristics of wing at decreasing ground clearances.

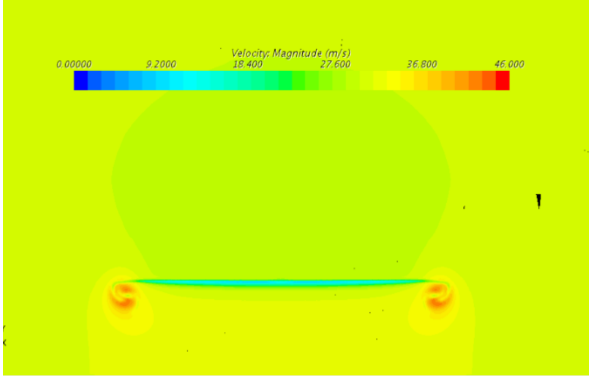

Fig 15: Wake characteristics of a double-element wing at 0.5H/c

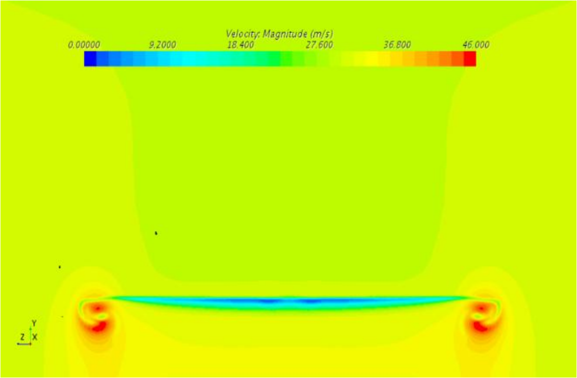

Fig 16: Wake characteristics of a double-element wing at 0.224H/c

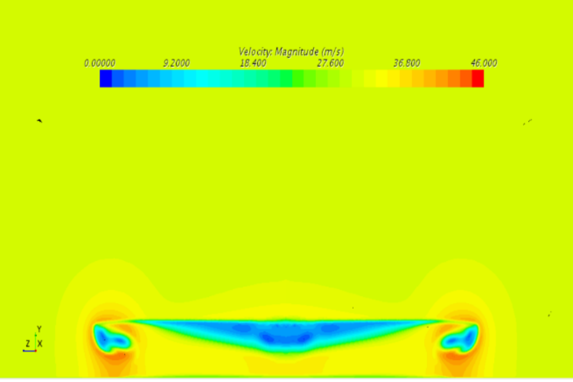

Fig 17: Wake characteristics of a double-element wing at 0.09H/c

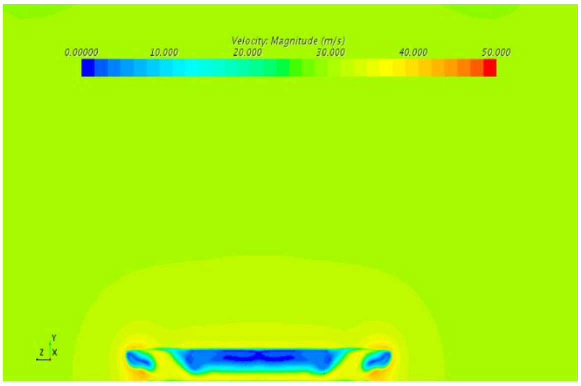

Fig 18: Wake characteristics of a double-element wing at 0.05H/c

Furthermore, a plot of decreasing ground clearance to the coefficient of lift and drag was plotted and is as shown in figure 19.

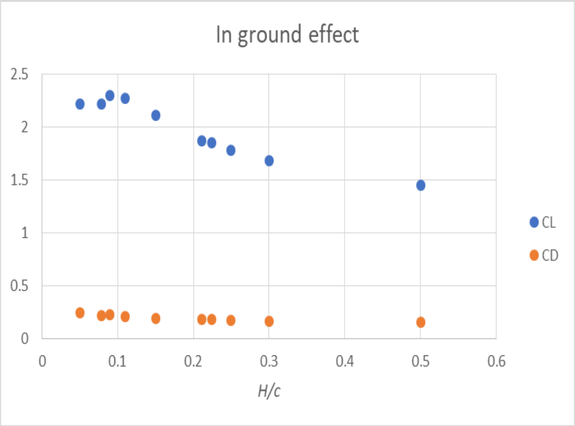

Fig 19: **Graph of lift and drag co-efficient v/s decreasing ground clearances.**

By observing the graph of lift co-efficient above it can be seen that there exist two distinct regions. The first region exist roughly between 0.3H/c to 0.1H/c where for every decrease in ground clearance the dowforce generated increases exponentially for a relatively less increase in drag. This is also known was a force enhancement region where downforce behaves as a function of ground clearance. The downforce generated reaches a maximum at 0.09H/c then it starts to decrease for any further decrease in ground clearance. This region is known as a force reduction region which roughly exists for values less than 0.1H/c. The reason for the downforce reduction is due to the separation of boundary layers at the trailing edge of wing. This separation of boundary layers is a result of boundary layers at trailing edge not capable of withstanding the adverse pressure gradient associated with accelerated flow at very low ground clearances.

3. Phase III: Varying angle of attack

In the present study, the effect of varying overall angle f attack with decreasing ground clearance was investigated. The overall angle of attack was varied from 0 degree to 13 degrees with a simultaneous decrease in ground clearance from 0.11H/c to 0.015H/c. Furthermore, by studying the lift and drag forces generated the plot of co-efficient of lift and drag was plotted against overall angle of attack and is as shown in figure 20 below.

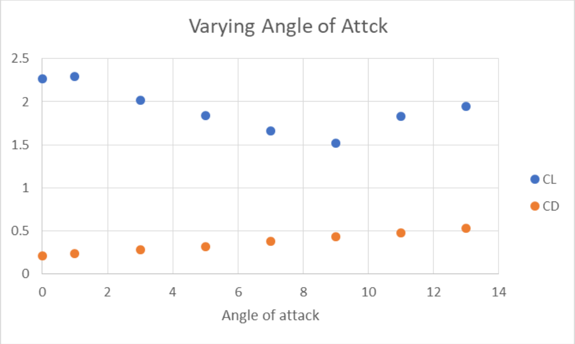

Fig 20: Graph of lift and drag co-efficient v/s overall angle of attack.

It can be seen from the graph of lift co-efficient above that there exist three regions. In the first region there is an immediate increase in downforce generated as increasing angle of attack increases camber and decreasing the ground clearance also facilitates in enhancing downforce generated as there is no separation of boundary layers yet. For the second region, for angle of attack from 1 degree to 9 degrees and corresponding ground clearance from 0.1H/c to 0.044H/c, the downforce generated decreases. It can be stated that the flow characteristics of the wing are affected strongly by the changes in ground clearances than the changes in angle of attack. Thus, even though there is an increase in overall angle of attack, the downforce generated decreases as the ground clearance decreases below 0.1H/c. This can be also seen from the velocity and pressure distribution of wing at 1 degree and 5 degrees as shown in figures 21to 24 below.

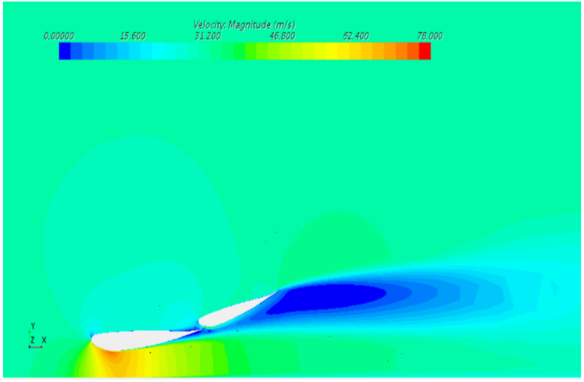

Fig 21: Velocity distribution of a double-element wing at 1 degree and 0.1H/c

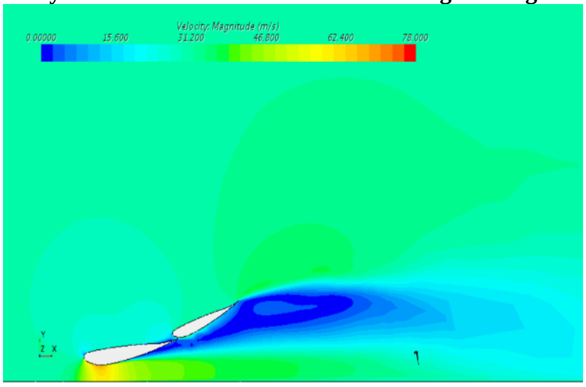

Fig 22: Velocity distribution of a double-element wing at 5 degrees and 0.075H/c

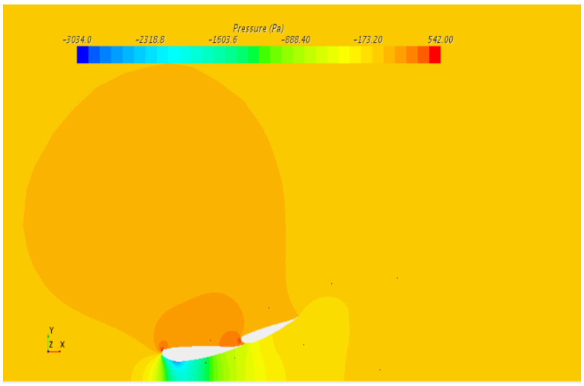

Fig 23: Pressure distribution of a double-element wing at 1 degree and 0.1H/c

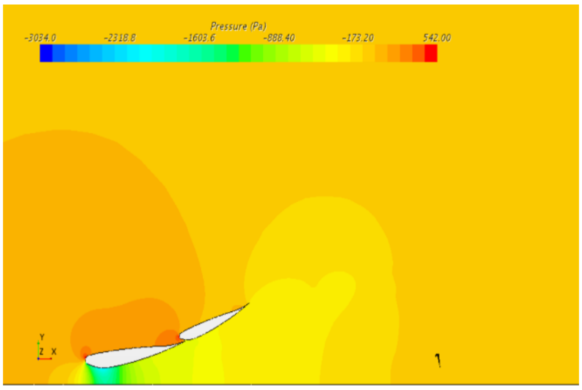

Fig 24: Pressure distribution of a double-element wing at 5 degrees and 0.075H/c

Furthermore, there exists a region from 11 degrees to 13 degrees for corresponding ground clearance of 0.03H/c to 0.015H/c where the downforce generated increases. The reason for this can be stated as the increase in angle of attack above 10 degrees significantly increases the camber of the wing and any further decreases in ground clearances has less impact when compared relatively. On the other hand, the drag coefficient increases linearly throughout.

IV. CONCLUSION

The three dimensional computational analysis of a double element front wing was successfully conducted. By studying the double-element front wing in free stream, it was observed that the double-element front wing behaves as an inverted airfoil in free stream generating downforce with the help of Bernoulli's principle. Also, when subjected to decreasing ground clearance, the wing exhibits two distinct regions of downforce generation. A force enhancement region for medium ground clearances where downforce behaves as a function of ground clearance and a force reduction region for very low ground clearances where the downforce generated reduces. It was observed that the separation of boundary layers is the reason for the force reduction. Furthermore, the flow characteristics for increasing overall angle of attack with simultaneous decrease in ground clearance indicate that ground plane has more impact in determining the downforce generate for lower values of overall angle of attack. However, for very low values of ground clearances and higher values of angle of attack, the downforce generated increase as the overall angle of attack has a significantly more impact.

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