A CFD Analysis of a Race Car Front Wing in Ground Effect

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Aerodynamics is one of the most important factors in racing sports. Open wheel race car series such as Formula 1 or IndyCar highly depend on the aerodynamics of their cars to improve race performance. A crucial part is the front wing which generates about a third of the cars downforce. This study analyses the aerodynamic forces of the high lift airfoil S1223 in ground effect. A symmetric single element wing is used with the overall dimensions close to a Formula 1 front wing. The wing is tested at different level of ground clearance. While moving the wing closure to the ground, the downforce increases. At a ground clearance level H/c=0.22 of the leading edge (height normalized by chord length), the wing reaches its maximum downforce. Smaller ground clearance level show a significant loss of downforce compared to the maximum. The drag force is increasing while decreasing the ground clearance over the whole span of the study. The analysis showed that the skin-friction drag and the induced drag have a significant influence. The wake of a wing in freestream shows two wing tip vortices. While decreasing the ground clearance multiple mid-span vortices are developed and gain on strength while moving closer to the ground. The study is performed using CD Adapco's CFD package STAR CCM+.

Introduction

The principle of using race car wings to improve the downforce on a race car goes back to the 1920s where they first appeared at the Opel's experimental rocket-powered cars RAK 1 and RAK 2 [1]. Since the 1970s the race car wing is a common aerodynamic tool in Formula 1 and later in other race series too. The simplest description of the function of a race car wing is to improve the car's performance. The desired function of a wing is the principle of minimizing the drag while maximizing the downforce for increasing cornering speeds [2].

Since the mid-1990s, the aerodynamics of race car wing has become a research topic all over and several experimental and numerical studies exists. However, there are many different factors which define the aerodynamic behavior of such a race car wing. Despite the wing profile itself, Katz [3] highlighted that a race car front wing operates in strong ground effect which influence the aerodynamic forces significantly. The existing literature can be mainly divided into numerical and experimental studies. As example, numerical studies for single wing airfoils in ground effect are Ranzenbach and Barlow [4] using Reynolds Averaged Navier Stokes to study the NACA0015 profile, which showed that the downforce is a function of ground clearance. Mokhtar [5] studied the influence of ground effect on S1223, E423, LNV109A and NACA9315 profiles and showed that the downforce increases with decreasing ground clearance, and the downforce remains more or less constant for a ground clearance bigger than height to chord ratio H/c = 0.6. Further, Mokhtar studied the behavior of NACA0012 [6] and the influence of endplates on the S1223 [7] profile. A

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lot of experimental studies were carried out by Zhang and Zerihan [8] [9] on the Thyrell026 wing profile. Their research shows that with decreasing ground clearance, the downforce increases. Very small ground clearance has a negative impact on the downforce. Further, the relative velocity of the ground to the wing as a significant impact on the downforce production of the wing. Further, the influence of transition free versus transition fixed wings. Transition fixed refers to a fixed point to trip the boundary layer from laminar to turbulent flow. Both, transition fixed and fixed ground have a significant negative impact on the downforce of the wing.

Present Work

The present study is a computational fluid dynamic (CFD) study of a high lift airfoil in ground effect. The chosen wing profile is the S1223 designed by Michael Selig [10]. This is a high lift wing profile, which means a single element wing, with no flaps or slats can obtain an extremely high lift coefficient. The behavior of the aerodynamic forces on the wing is studied in ground effect with one changing parameter, the ground clearance H/c. The ground clearance is measured between ground and leading edge point and is normalized by the chord length. The speed, 30 m/s, is chosen corresponding to cornering speeds existing in Formula 1. A six degree angle of attack (AOA) is chosen. Literature review shows that race car front wings operate with small angles of attack, depending on wing profile.

Table 1: Phase 3 study parameters

Parameter	Min	Max
Ground clearance (H/c)	0.15	0.5
Angle of Attack (AOA)	6°	
Chord length (c)	300 mm	
Wing span (s)	1600 mm	
Reynolds number	600,000	

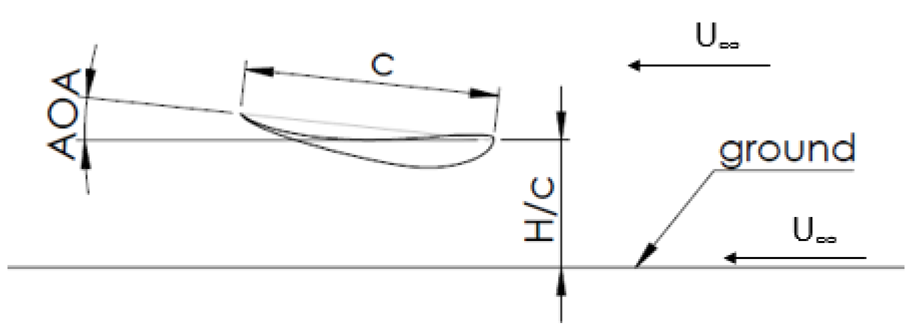

Figure 1: Schematic of the S1223 wing profile operating in ground effect

Computational Method

This presented study is performed using CFD package STAR CCM+, a finite volume method code for structured and unstructured meshes developed by CD-Adapco Inc. Segregated flow model is used to solve the three dimensional Reynolds-Averaged Navier-Stokes Equation (RANS). The AMG linear solver with the Gauss-Seidel relaxation scheme is used to solve the velocity and the pressure. Further, the k-ω two equation turbulence model is used.

The computational domain consists of the wing model placed into a far field. The wing has the dimension of 300 mm chord length and 1500 mm span. The wing is placed in a far field with a length of 2000 mm, a width of 4000 mm, and a height of 1000 mm. To safe computational resources, the model is cut in half and the vertical plane at mid span defined as a symmetry plane. The wing is placed 600 mm downstream within the far field. A polyhedral unstructured mesh is used throughout the study. Two refinement blocks are placed around the wing which allows more grid clustering around the wing. One of the refinement is used for immediate surrounding whereas the other refinement is used to have enough clustering within the wake region. Depending on the ground clearance, the number of cells is 6 to 10 million.

In addition to the symmetry boundary condition on the center plane, both the wing and the ground are defined as a wall boundary. On the wing itself, no-slip condition is applied where U=V=0 exists. The ground is defined as no-slip condition too. However, since the ground moves with a relative velocity to the wing and zero relative velocity to the air, a moving component in x-direction is applied with the velocity of the air, 30 m/s.

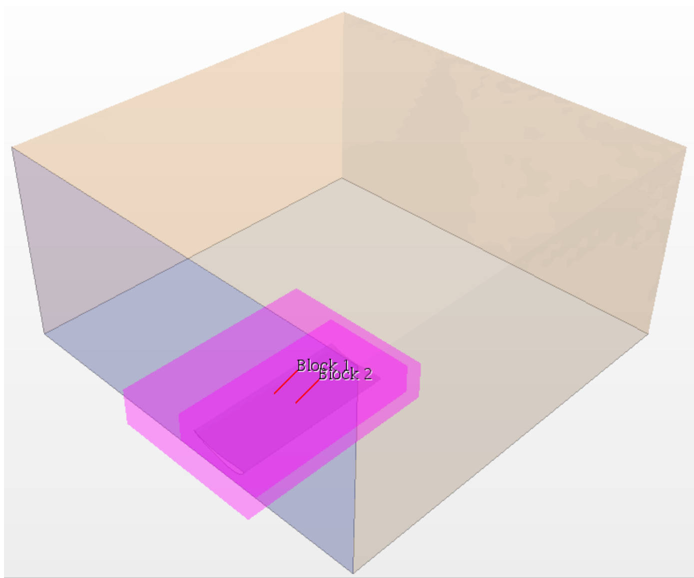

Figure 2: A sample model with the refinement blocks shown

Results and Discussion

The present study focus on the influence of the ground effect on a single element high lift airfoil without any additional add-ons such as endplates or gurney wing flaps. First, the wing model is studied in freestream condition with no ground effect to benchmark the behavior of the wing and validate the profile. Second, the effect of the ground clearance on the aerodynamic forces is studied.

Freestream with no ground effect – The inverted high lift airfoil S1223 generates lift by accelerating the air underneath the wing. Factors such as wing thickness, camber, and angle of attack affect the lift production of a wing. The effective range of angle of attack is limited by the stall condition where large separation occurs on the lower or suction surface. Selig designed the S1223 airfoil for low speed and high lift application and therefore to recover the pressure underneath the wing without separation. Therefore, the S1223 profile generates high lift even at small angle of attacks [11].

The wing in freestream sustain velocity and pressure changes compare to the freestream around the airfoil. Figure 3 shows the velocity distribution on a streamwise plane located at the wing mid span for an angle of attack of 6 degrees. The main areas show that there is a velocity increase underneath the wing, a stagnation area around the leading edge, and a low velocity/separation region, the wake, behind the wing. The velocity increase underneath the wing due to the cambering and thickness of the wing is approximately 72.7 % compared to the freestream velocity. It can be seen that the maximum velocity is located at the maximum camber of the wing. Revised to the velocity increase underneath the wing, a velocity decrease can be seen on the upper surface as well as in the separation or wake region near the trailing edge.

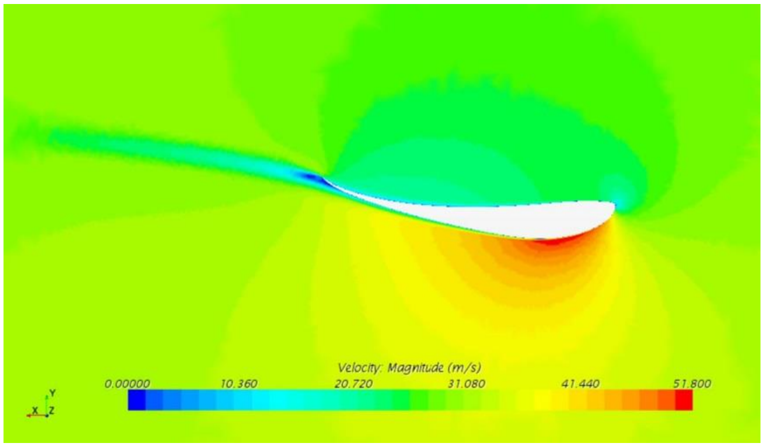

Figure 3: Velocity distribution on center plane for AOA=6° in freestream

The pressure distribution in Figure 4 is an illustration of the velocity distribution. Low velocities generate high pressure whereas high velocity generate low pressure or as seen in this case suction. Similar to the velocity distribution, the pressure distribution shows three main areas: the stagnation pressure at the leading edge, a high pressure region above the wing, and a low pressure or suction region underneath the wing.

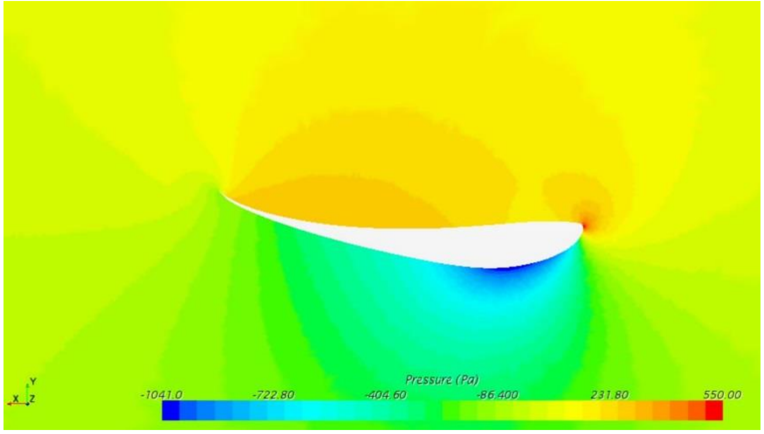

Figure 4: Pressure distribution on center plane for AOA=6° in freestream

The wake characteristic shown in Figure 5 shows that the wing creates a low velocity region along the span of the wing. This low velocity span is the illustration of the velocity decrease within the wake. This wake thickness stays constant along the wing span. Further, as it is very common for wing, the wing tip vortices can be seen clearly. The rotating air results in a local velocity magnitude increase since a rotating component is added. The two large wing tip trailing vortices shown in Figure 6 create an upwing which has a negative effect on the downforce. These wing tip trailing vortices arise from the high and low pressure region. The air starts flowing from high pressure, the upper surface towards the low pressure, lower surface, and creates the rotating effect. This has not only a negative effect on the lift or downforce coefficient, it also increases the induced drag of the wing.

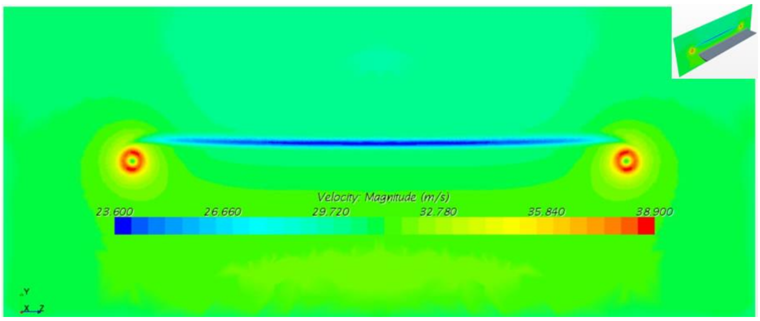

Figure 5: Velocity distribution on a plane 2/3 of a chord length downstream in freestream at AOA=6°

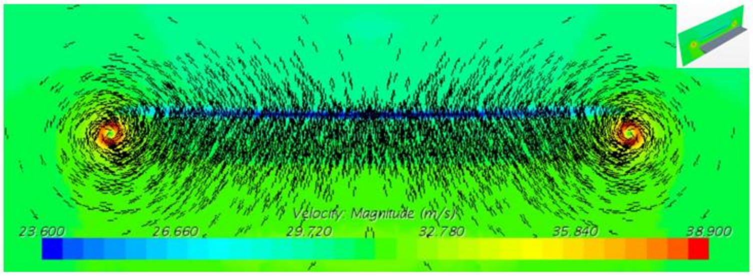

Figure 6: Wake vortices on a plane 2/3 of a chord length downstream in freestream at AOA=6°

A wing operating in ground effect - The lift or downforce coefficient is calculated for all the different ground clearance values. The overall expected behavior is to have an increase in downforce while decreasing the ground clearance H/c up to a certain point. If the wing gets too close to the ground, the boundary layers start to merge, which has a negative impact since the boundary layer have lower velocities. Therefore, if boundary layers merge, the velocity underneath the wing gets slowed down.

The velocity and pressure distribution shows an increase of the maximum velocity underneath the wing can be seen while analyzing the velocity distribution in Figure 7 to Figure 10. It can also be seen that by decreasing the ground clearance, the wake is not steady anymore. The ground has a huge impact on the wake and its vortices. The velocity increases by decreasing the ground clearance up to H/c = 0.22. The velocity increases between a ground clearance of H/c = 0.3 and 0.22 by 6.8%. The velocity distribution shows that the smaller the ground clearance, the more unsteady the wake becomes. At a ground clearance of H/c = 0.3, the wake has only small vertical fluctuations, whereas at H/c = 0.17 the wake covers a significant larger area and growth in vertical size. This growth can be seen clearly at the wake analysis.

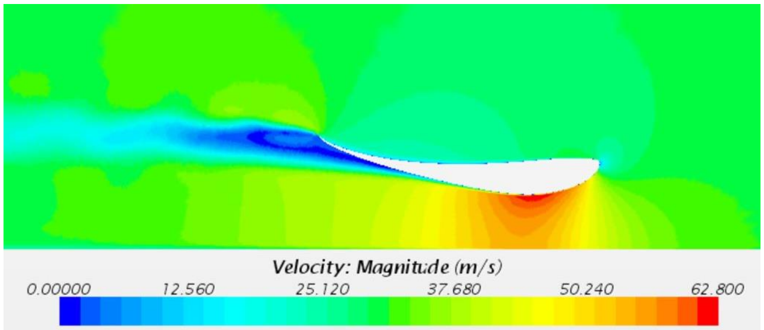

Figure 7: Velocity distribution on center plane at H/c=0.3 in ground effect

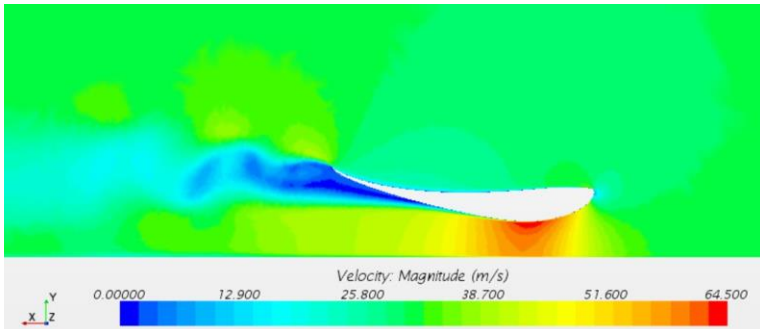

Figure 8: Velocity distribution on center plane at H/c=0.24 in ground effect

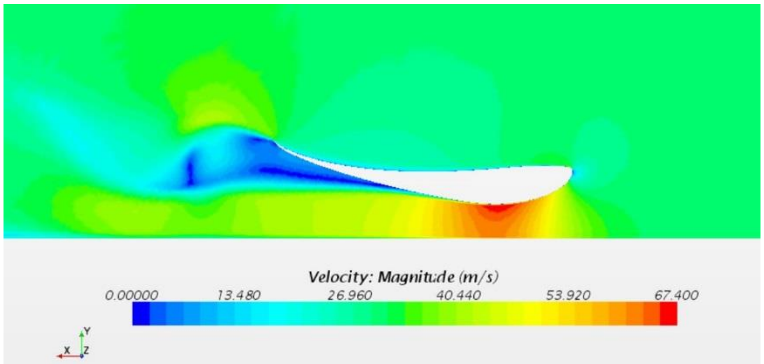

Figure 9: Velocity distribution on center plane at H/c=0.22 in ground effect

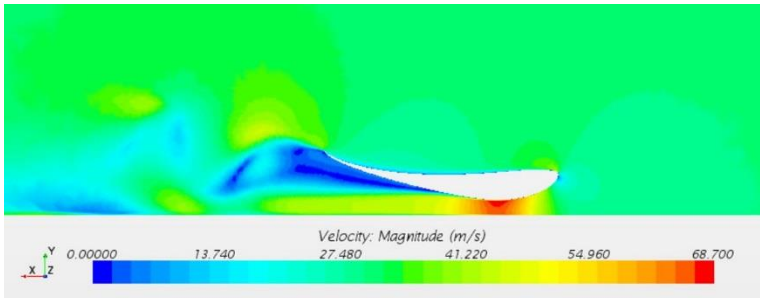

Figure 10: Velocity distribution on center plane at H/c=0.17 in ground effect

The presented different ground clearance cases in Figure 11 to Figure 14 show only a small fluctuation on the stagnation pressure, which is also the highest acting pressure on the wing, producing a fair amount of the total drag. The low pressure region underneath the wing, which is a negative pressure, behaves correspondent to the velocity. The velocity distribution showed that the flow is accelerating underneath the wing which causes a decrease of pressure. Where the velocity increases by 6.8% between a ground clearance of H/c = 0.3 and 0.22, the pressure decreases by 18.6%. Further, it can be seen that the low pressure region extends beyond the trailing edge of the wing. This shows that low or even negative pressure exists in the wake region.

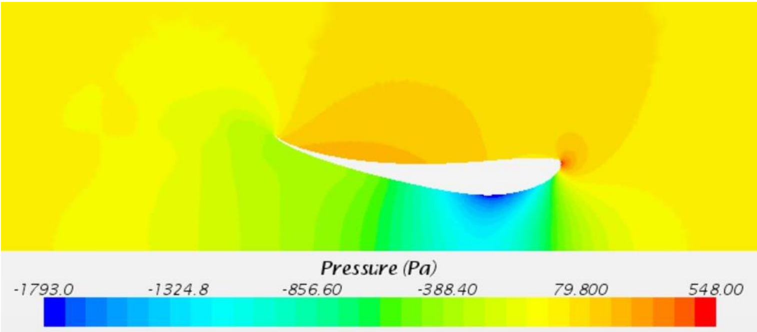

Figure 11: Pressure distribution on center plane at H/c=0.3 in ground effect

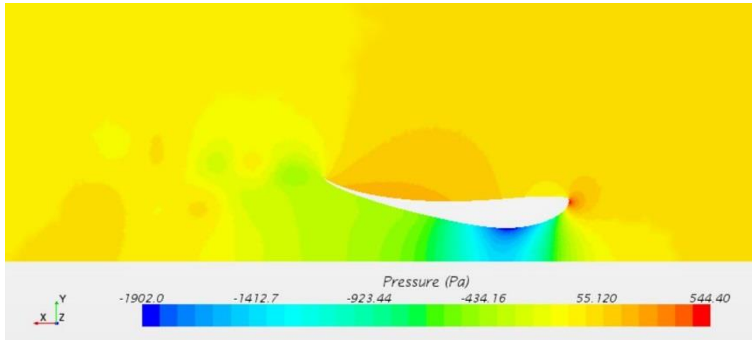

Figure 12: Pressure distribution on center plane at H/c=0.24 in ground effect

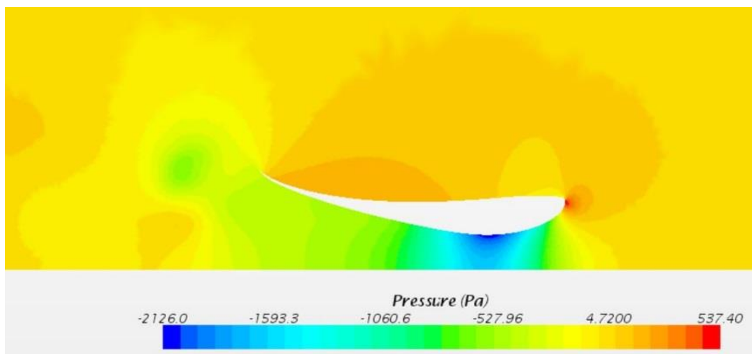

Figure 13: Pressure distribution on center plane at H/c=0.22 in ground effect

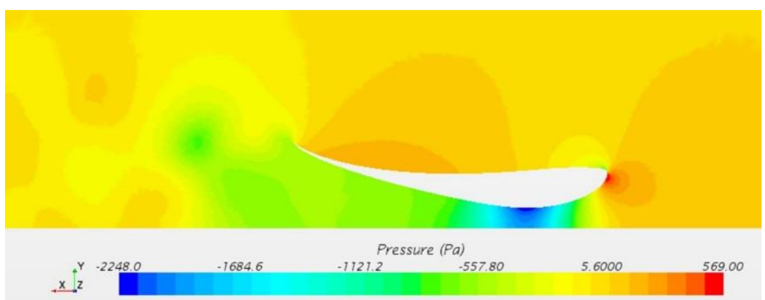

Figure 14: Pressure distribution on center plane at H/c=0.17 in ground effect

The phenomena of increasing downforce while decreasing the ground clearance can be explained through the theory of a duct. The wing and the ground build a duct together. By decreasing the ground clearance, the air gets accelerated underneath the wing. The closer to the ground it gets, the more the air gets increased which causes negative pressure. This negative pressure acts as a suction region which pulls the wing towards the ground.

Viewing the velocity distribution within the wake on a plane 2/3 of a chord length downstream shows how the wake does change by changing the ground clearance. In Figure 15 to Figure 17, it can be seen that by decreasing the ground clearance, vortices start to develop across the wing span. The more the ground clearance gets reduced, the more and stronger these mid-span vortices get. These vortices have direct influence on the induced drag and, therefore, have a negative influence on the aerodynamic forces. The low velocity area, which started as a constant wake in freestream, gets more and more shattered the smaller the ground clearance gets. At a ground clearance H/c =

0.22, the wake which looked like a beam became a kind of wave through all the existing span-wise vortices. While more vortices start to occur, the wing tip vortices get slowed down at smaller ground clearance.

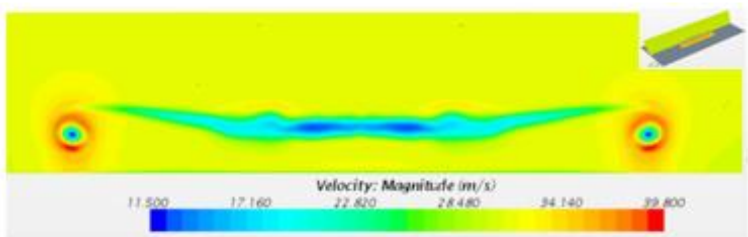

Figure 15: Wake velocity distribution on a plane 2/3 of a chord downstream at a ground clearance H/c=0.3

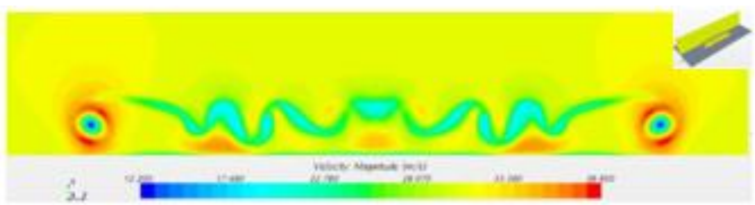

Figure 16: Wake velocity distribution on a plane 2/3 of a chord downstream at a ground clearance H/c=0.22

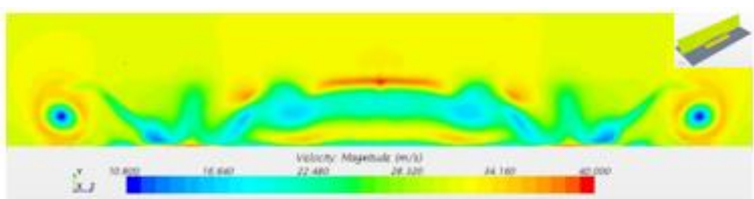

Figure 17: Wake velocity distribution on a plane 2/3 of a chord downstream at a ground clearance H/c=0.17

Placing a constant vector field over the velocity distribution done in Figure 18 to Figure 20 show the behavior of all the vortices. At a ground clearance of H/c = 0.3, the mid-span vortices start to build. The closer to the ground the wing gets moved, the stronger these vortices get. In addition, it can be seen that with decreasing ground clearance, the vortices do not only get stronger, they also increase in their number.

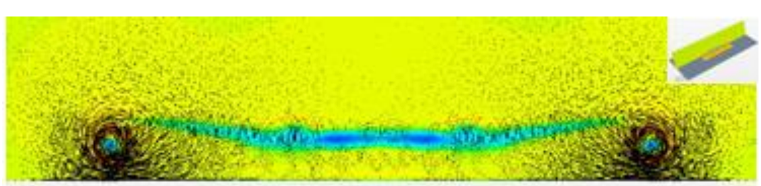

Figure 18: Wake vortices on a plane 2/3 of a chord downstream at ground clearance H/c=0.3

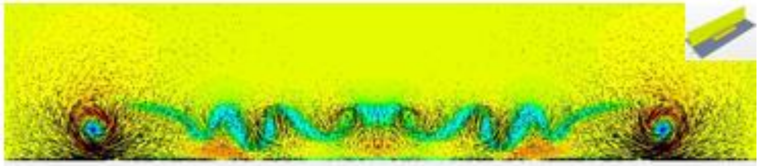

Figure 19: Wake vortices on a plane 2/3 of a chord downstream at ground clearance H/c=0.22

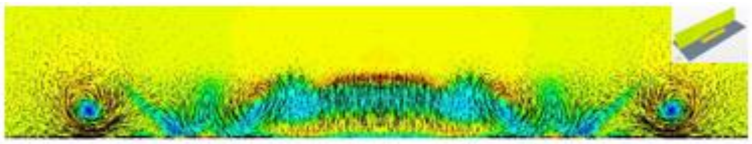

Figure 20: Wake vortices on a plane 2/3 of a chord downstream at ground clearance H/c=0.17

The lift coefficient change shown in Figure 21 for an angle of attack of 6° shows that the wing operating near ground shows that there is continuous increase of the lift coefficient up to a ground clearance H/c = 0.22. The effect of the ground, which is moving with the relative velocity to the wing, can be seen by a maximum increase of 46.4% in lift coefficient. As soon as the lift coefficient reaches its maximum, there is a significant decrease in downforce which was also stated by various other studies [6] [9] [12]. Analyzing the lift coefficient at a very low ground clearance, H/c = 0.15, it actually has a negative impact. The lift coefficient decreased by 16.7% compared to the free steam case whereas all the other tested ground clearances increase the downforce compared to the freestream result.

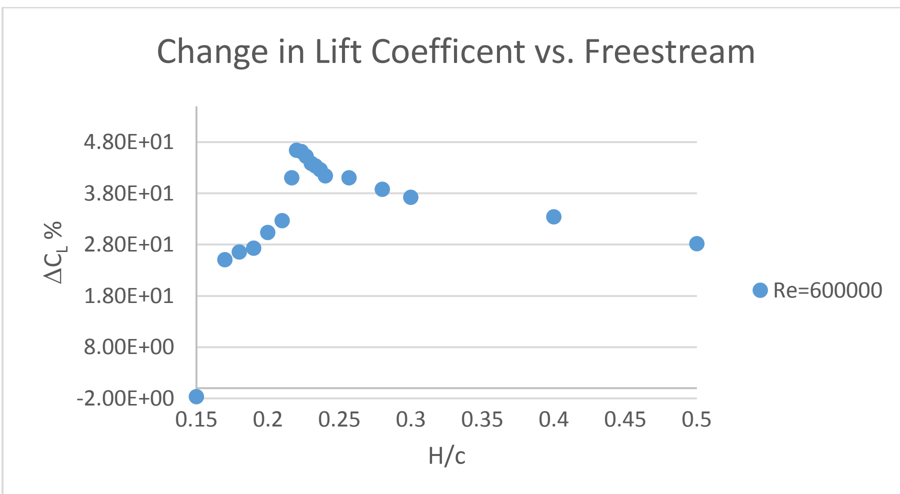

Figure 21: Change in lift coefficient vs. freestream in ground effect

The overall drag can be divided into pressure and skin-friction drag. The pressure drag consists from drag and induced drag, also known as the vortex drag. The induced drag depends mainly on the wake behind the wing. Skin-friction or surface-friction drag is depending on shear stresses acting on the wings surface [13].

The drag coefficient in Figure 22 shows an increase while decreasing the ground clearance H/c. The drag coefficient does not reach its maximum at a ground clearance of H/c = 0.22 such as the lift coefficient. The drag coefficient increases by 63.2 % at the maximum lift coefficient ground clearance. Since the drag keeps increasing at a ground clearance of H/c = 0.15, the drag has increased by 95.6 % compared to the freestream case.

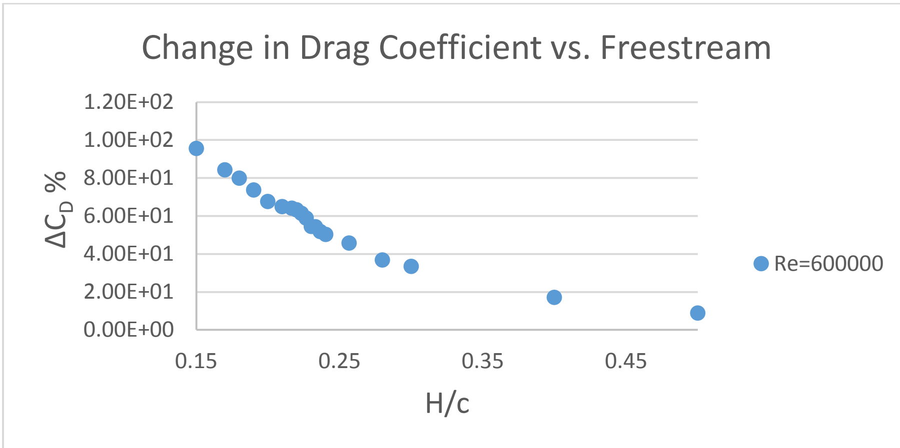

Figure 22: Change in drag coefficient vs. freestream in ground effect

By decreasing the ground clearance, the wing and ground build a duct. This leads to an acceleration of the air. Higher velocity corresponds to higher skin-friction drag. The friction drag is not the only component which affects the overall drag. The induced drag starts to play a bigger impact by decreasing the ground clearance. The induced drag is produced by the wake. The wake gets more disturbed, and multiple vortices are added to it at lower ground clearance. At freestream, the only two vortices which could be seen were the wing tip vortices. The closer the wing gets to the ground, more vortices become visible and have a negative impact, which means increased drag.

Conclusion

In conclusion, the wing behaved as expected. The increase in lift coefficient could be seen up to a maximum point which occurred at a ground clearance of H/c = 0.22. The continuous drag increase showed the effect of increasing skin-friction drag and induced drag through the wake. The flow structure analysis showed the increase of velocity between wing and ground while decreasing the ground clearance which also lead to a stronger suction. The wake showed that in ground effect, multiple span-wise vortices start to build and get stronger with decreasing ground clearance.

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