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Studies on Race Car Aerodynamics at Wing in Ground Effect

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Abstract**—**Numerical studies on race car aerodynamics at wing in ground effect have been carried out using a steady 3d, double precision, pressure-based, and standard k-epsilon turbulence model. Through various parametric analytical studies we have observed that at a particular speed and ground clearance of the wings a favorable negative lift was found high at a particular angle of attack for all the physical models considered in this paper. The fact is that if the ground clearance height to chord length (h/c) is too small, the developing boundary layers from either side (the ground and the lower surface of the wing) can interact, leading to an altered variation of the aerodynamic characteristics at wing in ground effect. Therefore a suitable ground clearance must be predicted throughout the racing for a better performance of the race car, which obviously depends upon the coupled effects of the topography, wing orientation with respect to the ground, the incoming flow features and/or the race car speed. We have concluded that for the design of high performance and high speed race cars the adjustable wings capable to alter the ground clearance and the angles of attack is the best design option for any race car for racing safely with variable speeds.

Keywords**—**External aerodynamics, External Flow Choking, Race car aerodynamics, Wing in Ground Effect.

I. Introduction

THE motion of air around a moving vehicle affects all of its components in one form or another. Of late, race car aerodynamics gained increased attention, mainly due to the utilization of the negative lift (down-force) principle, yielding several important performance improvements. In all forms of racing, however, aerodynamics eventually surfaced as a significant design parameter. Although the foundations of aerodynamics were formulated over the years, not all principles were immediately utilized for race car design [1]-[4]. In an attempt to resolve some of the external aerodynamics problems of race car and in the light of new findings of wing in ground effect by Sanal Kumar et al. [5], a substantial revision of the existing idea is required for the design of high performance and high speed race cars. Wings in ground effect possess many aerodynamic features of both practical and fundamental importance. In general, the lift and drag forces of a wing will considerably change near the ground. When an airfoil moves near the ground, flow around the airfoil is viscous and has many viscous interactions with the ground. In the analysis of ground effect on the aerodynamic properties of the airfoils, the boundary layer on the airfoil must be considered. On the other hand, prediction of location of the onset of the transition phenomenon, as an example of boundary layer characteristics, is also necessary in order to predict the drag because the skin friction related to a laminar boundary layer is lower than that of a turbulent one [1].

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Von Doenhoff [4] investigated boundary layer around the symmetrical NACA airfoil in zero lift condition. His surveys were made considering different Reynolds number based on airfoil’s chord. In that work, drag of airfoil, distribution of skin friction over the surface of the airfoil and onset of the transition point were found. Lian and Shyy [2] investigated performance of arigid airfoil and a flexible airfoil by numerical method. All the cited works were focused on the investigations of airfoils at distance far from the ground surface, but limited work has been performed or reported for the airfoil that moves near the ground.

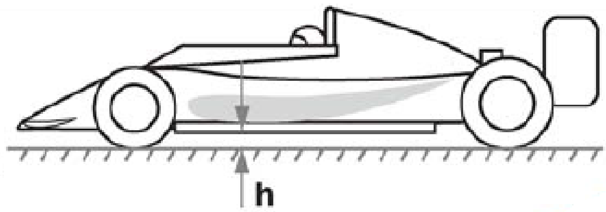


Fig. 1 Race car wings at close proximity of the ground

Wing in ground (WIG) effects is an important phenomenon as it affects the performance of race cars. Fig 1 shows a typical race car with front and rear wings close to ground proximity. Literature review reveals that studies on ground effect on the aerodynamics of a lifting body can be dated as far back as the 1920s but the propulsion aspect of wings in ground effect not yet reported in any open literature. It is generally believed that the presence of ground effect will enhance lift (L) and reduce the drag (D) acting on a lifting body (for example, a wing). However, it is not always true in the light of the findings of Sanal Kumar V. R. et al. [5]. Note that there are a lot of detailed questions which include the details of the relevant flow physics that have yet to be clearly addressed when a race car wings are fixed close proximity to the ground (see Fig. 1). Literature review further reveals that Wing-in-ground effect vehicles operate close to the ground surface by utilizing the air cushion of relatively highly pressurized air created between the airfoil and the surface. The aircushion augments lift and reduces drag considerably compared to an out-of-ground effect vehicle; these phenomena further enhance the lift-to-drag ratio, and have been observed during takeoff and landing of aircraft by a number of researchers since the1900s [6-14]. We believe that this may not be true in close proximity of the race car wings with the ground at high speed and certain angles of attack owing to the fact that there is a possibility of change of flow physics due to convergent-divergent channel effect. Earlier studies have shown that the ground has a significant influence on the pressure distributions along the wing surface. As a WIG effect vehicle moves forward, the speed of the oncoming air gradually decreases under the lower wing surface, and dynamic pressure changes to static pressure. This increased pressure is called an air cushion or a ram effect. Sanal Kumar et al. [5] observed that there are possibilities of external flow choking while aircraft flies in close proximity of the ground. The fact is that if the ground clearance height to the chord length of the aircraft is too small, the developing boundary layers from either side of the surface (ground and wing) can interact and develop a transient *fluid-throat*, leading to a choked flow. The results of this study lead to say that one should ensure a safe combination of the dominating parameters for the external flow choking such as vehicle speed, topography and ground clearance, angle of attack, and incoming flow features and coupled geometry of ground and the wing leading to catastrophic failures of race car wing in ground effect. This study is a pointer to the designers of high speed race car with low wings for the safe racing. Note that in most forms of racing it is desirable to create the fastest vehicle in a particular category. In the light of the aforesaid findings one can comprehend that aircushion or ram effect is only in certain combination of the parameters such as ground clearance (h/c), speed and angle of attack.

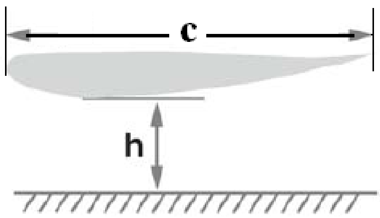


Fig. 2 Physical model of a race car wing

Traditionally, the effects of external aerodynamics are summarized in terms of drag, lift, and stability. Usually the side force (due to aerodynamic side slip) was not examined carefully because race cars go much faster than the prevailing winds, and, instead of lift, the generation of efficient down force became the main issue. The three aerodynamic moments came to light when designers realized that vehicle stability (and handling) can be improved by properly balancing the down force (e.g., front/rear) on the tires. Such desirable aerodynamic down force can be generated by adding lifting surfaces onto, or by modifying, the vehicle's body. When a vehicle moves fast, lateral instability may become uncomfortable from the driver's point of view.

The objective of the present investigation is to carry out parametric analytical studies to better understand the flow physics of WIG effects of race car at different ground clearance, speed and the angles of attack of the race car wings. Fig. 2 shows the physical model of a typical race car wing. The ground clearance h/c (where h is the distance between the lifting body and the ground, and c is the chord of the airfoil cross-section of the wing), and the race car speed, baseline values, are selected based on typical values from literature pertaining to a Formula Mazda car [11]. Vignesh et al. [15] reported that every single surface of a modern Formula One car, from the shape of the suspension links to that of the driver's helmet - has its aerodynamic effects considered. The authors further conjectured that the prudent selection and fixing of a flap at the trailing edge of the race car wing with suitable orientation for increasing the downward force is a meaningful objective for redesigning the race cars for high performance applications. Authors concluded that the maximum design speed of any race car can be increased further by 20 % without any lift penalty by fixing a gurney flap, of size 1% of chord length, fixed vertical to the chord at the trailing edge of the rear wing. Although this paper is of topical interest the authors did not consider the wing in ground effect phenomena. However in this connected paper detailed numerical studies on race car aerodynamics at wing in ground effects have been carried out using the 3d standard k-epsilon turbulence model.

II. Numerical Method of Solution

Numerical simulations have been carried out with the help of a steady 3d, double precision, pressure-based, standard k-epsilon turbulence model. This model uses a control-volume based technique to convert the governing equations to algebraic equations. The viscosity is determined from the Sutherland formula. The airfoil geometric variables and material properties are known *a priori*. Initial wall temperature and inlet temperature are specified. At the exit, far field boundary condition is prescribed. At the solid walls no-slip boundary condition is imposed. The Courant-Friedrichs-Lewy number is chosen as 5.0 in all of the computations. The turbulent kinetic energy and the specific dissipation rate are taken as 0.8. Ideal gas was selected as the working fluid.

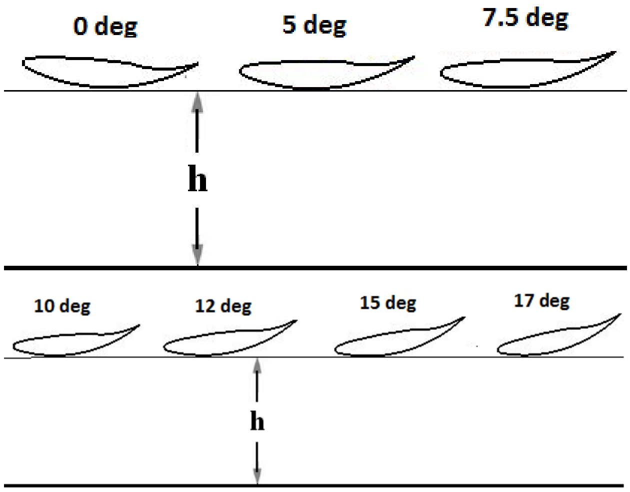
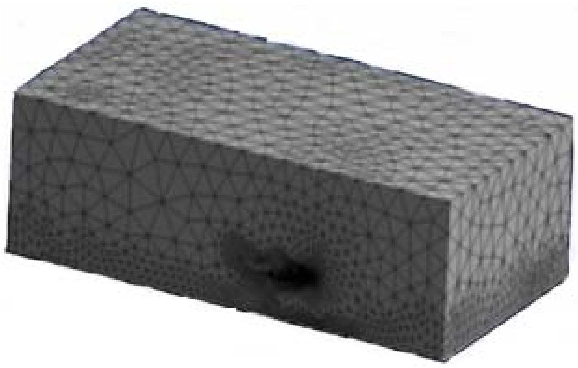
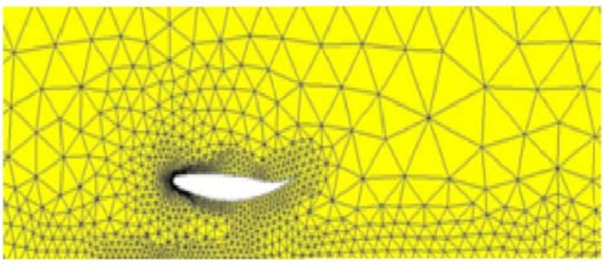


Fig. 3 Race car wing at different angles of attack

Fig. 3 shows the cross sectional view of the race car wing at different angles of attack. Figs. 4 (a), (b) show the typical grid system in the computational domain. The grids are clustered near the solid walls using suitable stretching functions for capturing the boundary layer effect.



(a) Grid system in 3d computational domain



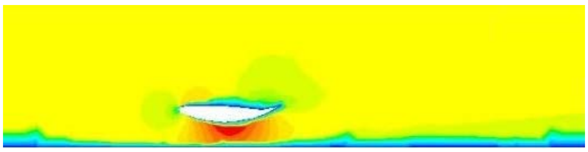
(b) Grid system in 2d plane

Fig. 4 (a), (b) Grid system in the computational domain

III. Results and Discussion

In the parametric analytical studies a typical airfoil has been used to understand the propulsion and the aerodynamics aspects of wing in ground effects (ground effects or surface effects). It occurs typically when the wing of an aircraft flies in close proximity of the ground (approximately one quarter the height of the wing span depending on the aspect ratio of the wing). There are a number of changes in the flow characteristics around the wing due to this effect. In the light of the non-cataloged failures of aircraft and race cars in the ground effect region; detailed numerical studies have been carried out to examine the flow features at wing in ground effect of a typical race car. In this paper using a steady three-dimensional k–epsilon turbulence model, detailed parametric studies have been carried out to examine the external flow features of a race car wing with different angles of attack, ground clearance (h/c), and speed. In the numerical study, a fully implicit finite volume scheme of the compressible, Reynolds-averaged, Navier–Stokes equations is employed. Through detailed parametric analytical studies we have observed different aerodynamic flow features of the race car wings in close proximity of the ground (see Figs. 5-9).

We have conjectured that at a particular speed and ground clearance (h/c) of the wing, the downward force (negative lift) was found high at a particular angle of attack. Note that the flow development and the boundary layer thickness over the lower surface of the wing and the ground are the unique features of each race car at different speed conditions and topography. These are discernible in Figs. 5, 6. Having known this flow physics the next step will be to design a race car wing with flexible and/or adjustable wings capable to alter h/c and the angles of attack for getting the high performance at variable speeds. We have comprehended that any inappropriate combination of speed, ground clearance and angle of attack the possibility of altering the benign aerodynamics characteristics of a race car including the lift (upward force) will be high (see Figs. 7-9). As stated in the introduction external aerodynamic choking (i.e., flow choking between the ground and the wing) will create supersonic flow due to the formation of a transient convergent – divergent (CD) nozzle effect, which can lead to the formation of shock waves. The fact is that if the ground clearance height to the chord length of the aircraft is too small, the developing boundary layers from either side of the surface (ground and wing) can interact and develop a transient *fluid-throat*, leading to a choked flow. Note that due to the choking phenomena the flow passing over the lower surface of the wing will be get accelerated due to the transient formation of a CD nozzle shaped geometry effect between the ground and the lower surface of the wing and consequently a sudden drop in downward force will be the consequent effect. This is an area that needs to be examined carefully, which however not attempted in this paper.



(a) h/c = 0.26

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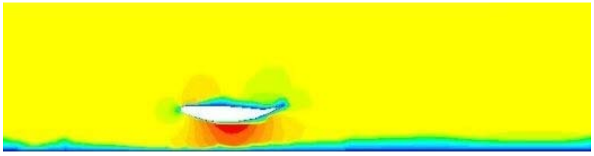

(b) h/c = 0.29

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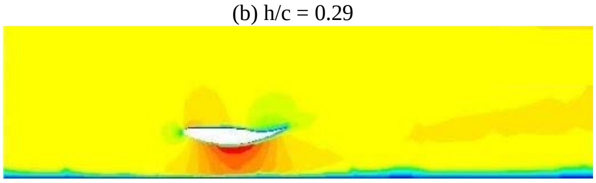
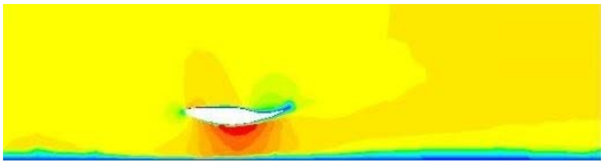


(c) h/c = 0.31



(d) h/c = 0.34

(e) h/c = 0.36

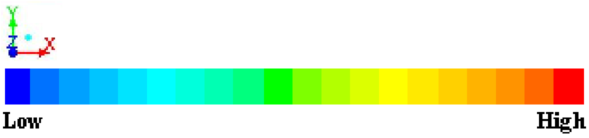
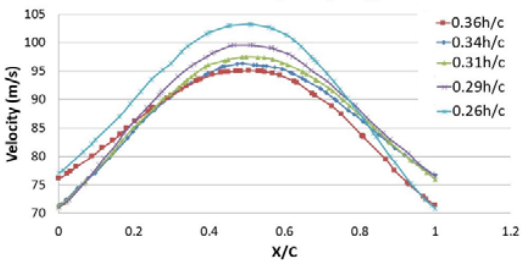
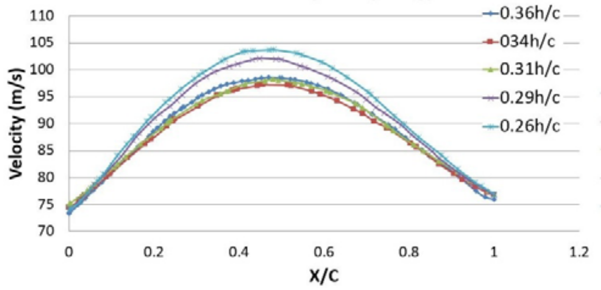


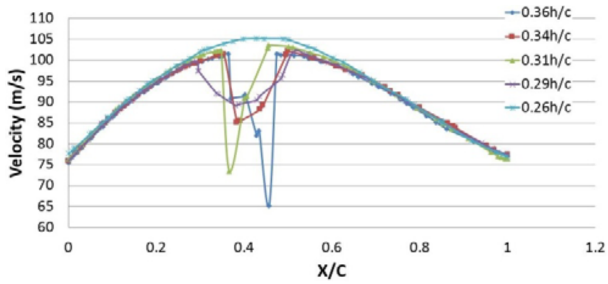
Fig. 5 (a)-(e) Velocity contours at different ground clearance (h/c) at zero angle of attack



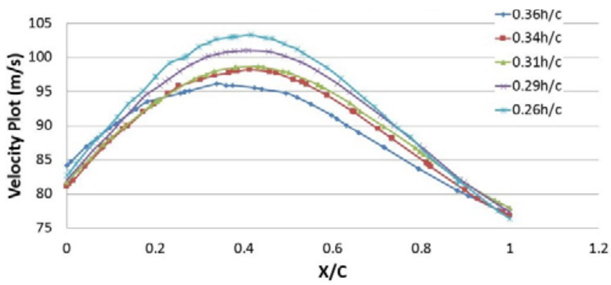
(a) Velocity variations at zero angle of attack



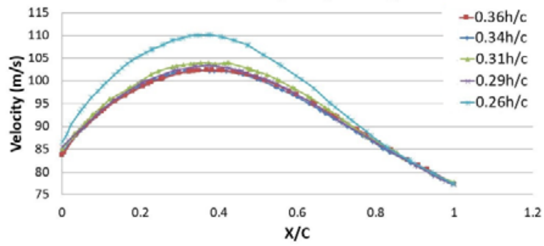
(b) Velocity variations at 5^0 angle of attack



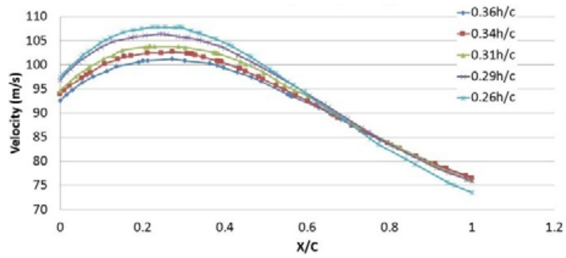
(c) Velocity variations at 7.5^0 angle of attack



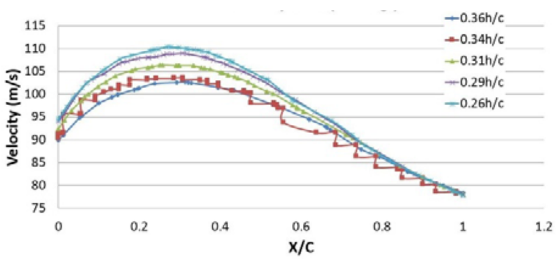
(d) Velocity variations at 10^0 angle of attack



(e) Velocity variations at 12.5^0 angle of attack



(f) Velocity variations at 15^0 angle of attack



(g) Velocity variations at 17^0 angle of attack

Fig. 6 (a)-(g) Comparison of the velocity variations at different ground clearance at different angles of attack

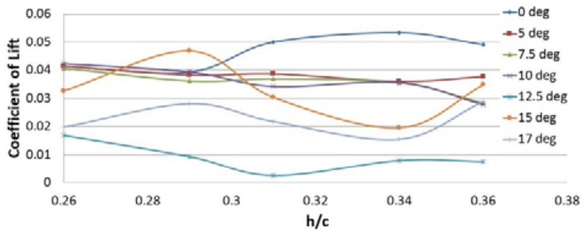


Fig. 7 Comparison of the lift coefficients at different angles of attack and ground clearance

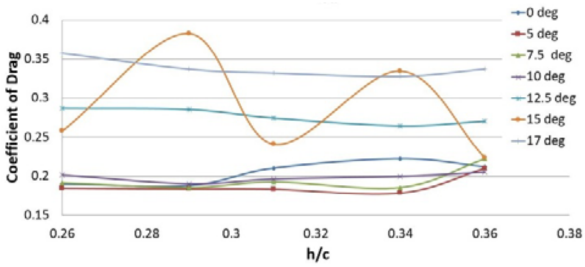


Fig. 8 Comparison of the drag coefficients at different angles of attack and ground clearance

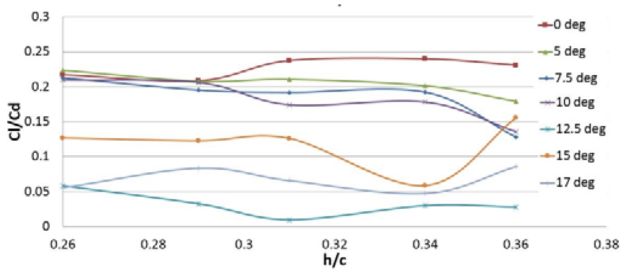


Fig. 9 Comparison of the ratio of lift to drag coefficients at different angles of attack and ground clearance

Furthermore, one should ensure a safe combination of the dominating parameters for the external flow choking such as vehicle speed, topography and ground clearance, angle of attack, and incoming flow features and coupled geometry of ground and the wing leading to possible catastrophic failures of race car wing in ground effect.

It may be recalled here that, owing to the viscous friction, a boundary layer could be formed on the lower walls of the wing and the ground, and their thickness will increase in the downstream direction leading to the formation of a temporary CD nozzle throat at the transition location due to the coupled effects of the port geometry and the area fraction being blocked by the boundary-layer displacement thickness. As a result, in general, at larger distances from the inlet section of the wing the velocity will be high at the transition location and this will lead to high downward force. However, it can lead to the formation of shock waves in the downward region of the wing region having divergent channel effect. This obviously will contribute to the high-pressure spike, which might cause structural failures of race car wing, in addition to the downward force loss. The fact is that if ground clearance height to chord length (h/c) is too small, the developing boundary layers from either side of the port can interact, leading to a choked flow. On the other hand, if the developing boundary layers are far enough apart, then choking does not occur. It may be noted here that most of the available models do not capture the shock wave phenomena encountered in race car at wing in ground effect. Nevertheless, the accurate evaluation of the Mach number contours between the wing and the ground are sufficient to propose the possible occurrence of shock waves at wing in ground effect, which is beyond the scope of this paper. From the point of view of continuum theory, shocks can be treated as localized discontinuities within the flow, which everywhere else satisfies the continuum hypothesis. The authors have inferred that the shock waves at wing in ground effect can generate additional turbulence. The shock waves and the new turbulence level will alter the race car aerodynamics at the wing in ground effect, which merit further investigation.

IV. Concluding Remarks

We have concluded that when the high speed race car wings are at the close proximity of the ground at a particular speed and angle of attack the aerodynamic performance characteristics of the race car, essentially the lower surface, can alter leading to a catastrophic failure. Therefore a safe ground clearance must be ensured throughout the racing, which obviously depends upon the coupled effects of the topography, wing orientation with respect to the ground, the incoming flow features and/or the race car speed. Through these parametric analytical studies we have concluded that for the design of high performance and high speed race cars adjustable wings capable to alter the wing ground clearance (h/c) and the angle of attack is the best design option for racing safely with variable speeds.

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