Chapter 18
Ground Effect Aerodynamics

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1 INTRODUCTION

1.1 Definition

The ‘ground effect’ is the enhanced force performance of a lifting surface in comparison to the freestream result, which is evident while operating in close proximity to the ground. The study of ground effect aerodynamics of an aircraft is mainly concerned with changes to the three-dimensional flow field introduced by the presence of the ground plane and their consequent impact upon overall performance. A prominent feature of the aerodynamics is a desirable increase in the lift-to-drag ratio. A review of various types of ground effect aircraft can be found in Rozhdestvensky (2006) and Cui (1998). For ground effect race cars, the aerodynamics is concerned mainly with the generation of lower pressures on the surfaces nearest to the ground for the least possible increase in drag. A review can be found in Zhang, Toet and Zerihan (2006).

The phenomenon has led to the design of dedicated ‘wing-in-ground’ craft (WIG) that can operate with greater efficiency than conventional aircraft. Angle of attack (α) and height above the ground (h) define the WIG geometric configuration (Figure 1). For ground effect aircraft, the positive lift is directed upward and away from the ground. For ground effect vehicles, convention defines that the ‘lift’ is generally directed downward toward the ground and is termed ‘downforce’.

1.2 Historical background: ground effect aircraft

For an aircraft flying close to the earth’s surface, over either ground or water, the phenomenon becomes appreciable when operating within a distance of one wingspan from the boundary. The ground plane alters the flow field around the wing, resulting in a reduction in induced drag and an increase in lift. It is known that the lift-to-drag ratio (C_L/C_D) is generally around 3 for helicopters, 8 for hydro-airplanes, and around 12 for light aircraft. In contrast, this ratio can be as high as 20 or more for WIG flying vehicles if the ground clearance is less than or equal to one-fifth of the wing chord length. The so-called WIG craft exploits this behavior creating a unique class of high-speed, low-altitude transport vehicles.

The ground effect was first investigated seriously around 1920. Wiesesberger (1921) treated the problem with an extension of the Lanchester–Prandtl theory and utilized the basic concept of the induced drag of multiplanes. Tsiolkovsky (1927) described the ground effect and provided a theoretical solution for air cushion vehicles in his chapter entitled

Encyclopedia of Aerospace Engineering.
Edited by Richard Blockley and Wei Shyy
ISBN: 978-0-470-75440-5

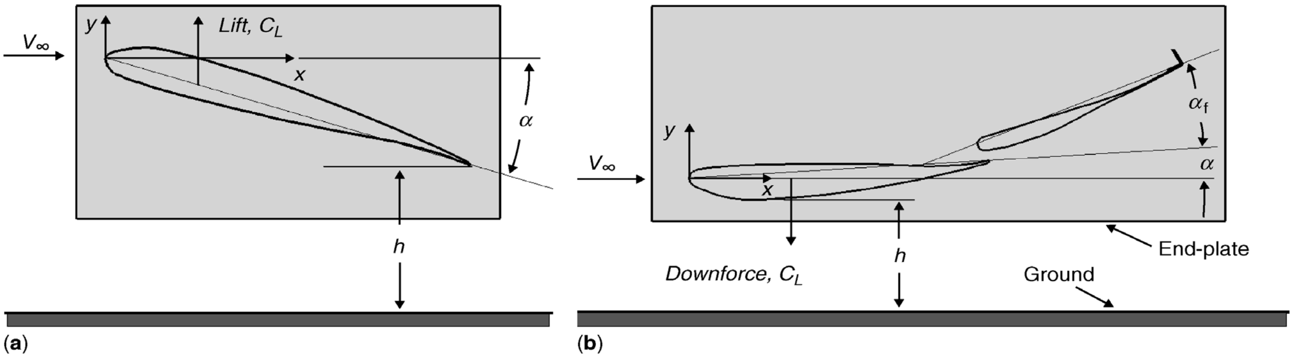

Figure 1. Schematics of wing-in-ground effect settings. (a) Wing of a WIG aircraft; (b) front wing of a racing car.

'Air Resistance and the Express Train'. Since then, a large quantity of related research has been carried out, and a better understanding of this phenomenon has been gradually achieved. Many types of ground effect aircraft have been built around the world.

The use of Power Augmented Ram (PAR) is important for the take-off of WIG vehicles. The exhaust gases from jet engines, or the air displaced by propellers, are directed or ducted, so that they pass underneath the wing to enhance the effect of the air cushion and to create additional lift. Following the incorporation of the PAR principal by the American, Stewart Warner, in the design of his 1928 'compressor' airplane, many subsequent WIG vehicles also adopted the concept.

The economic benefits and practical applications of ground effect were observed in 1932 when the German, Claude Dornier, discovered that his DO-X seaplane could only complete the trans-Atlantic crossing when it flew just above the surface of the ocean. In the mid-1930s, the Finnish engineer, Toivio Kaairo, was the first person to design an aircraft, known as the 'Aerosedge No. 8', to deliberately fly using ground effect.

The study of ground effect aerodynamics for a wing with split or slotted flaps was performed by NACA in 1939. The effort helped to direct the research work of WIG vehicles toward more practical applications. The introduction of the compound wing concept, consisting of a small aspect ratio inboard wing in conjunction with a large aspect ratio outboard wing, into WIG vehicle design had a significant impact since it was found to maximize the benefits of ground effect. An overview of WIG vehicles and their history can be found in Rozhdestvensky (2006).

Since the early 1960s, practical applications of WIG vehicles have been actively researched and developed. The most famous being the Soviet 'Ekranoplan', also known as the 'Caspian Sea Monster'. Rapid progress has been made in the numerical and experimental study of aerodynamic characteristics of vehicle configurations incorporating complex geometry and components. Figure 2 shows a typical WIG aircraft flying over water and illustrates some major characteristic design features, for example a small aspect ratio main wing, a raised horizontal tail-plane (stabilizer), end plates (floats), and a fuselage incorporating a hull with 'planing' surfaces.

1.3 Historical background: ground effect race car

The effect of an inverted wing placed in close proximity to a wall was first observed in the 1920s. In a wind tunnel study, Zahm and Bear (1921) observed that:

> "a complete set of readings also were taken with the ground plane 'above' the aerofoil, that is, opposite to the cambered surface. The most striking features of these readings are the great increase of lift . . . and the considerable increase of drag with proximity of the ground-plane . . ."

Figure 2. A WIG aircraft flying over water (courtesy of WIG Vehicle Development Center of Chinese Academy of Science & Technology Development).

Following the Second World War, the growth in popularity of open-wheeled racing on the newly abandoned military airfields saw the beginning of the modern closed-circuit motor racing culture. It soon became apparent that competitive advantage lies in the optimization of high-speed maneuverability and control, enabling a greater capacity for lateral acceleration and consequent turning performance. Driving, braking, and cornering forces are created at the contact patch between the tires and the road, and the magnitudes of these frictional forces are proportional to the vertical force applied through the tire itself. Aerodynamic downforce provided by an inverted wing can be used to supplement the low mechanical downforce of a lightweight vehicle and increase the tire load without incurring any weight penalties that could adversely affect both lateral and longitudinal performance. The maximum longitudinal acceleration of a race car can be approximated using the simple expression derived from Newton's second law:

$$a = g \times \mu_{\max} + \frac{(1/2)\rho_\infty V_\infty^2 A C_L \mu_{\max}}{m} \tag{1}$$

where a is the acceleration, ρ_∞ the density, V_∞ the speed, A the reference area, C_L the downforce coefficient, g the gravitational acceleration, m the mass of the car, and $\mu_{\max}$ the coefficient of friction between the tires and the ground. The downforce coefficient is clearly related to wing performance and can be enhanced through ground effect.

Until 1966, aerodynamic considerations were limited to providing a streamlined design that sought to minimize drag, but in this year, the first downforce-generating wings appeared on the Chaparral Can-Am car; they were initially mounted out-of-ground effect on struts. The following year, they made their first appearance on a Formula One vehicle. By 1970, the configuration had evolved to include a wing located at the back of the car, behind, and above the rear wheels, together with a second lower wing ahead of the front wheels, which operated in ground effect.

However, the true potential of ground effect aerodynamics was not realized until 1977 when Lotus introduced the revolutionary type 78 racing car. The vehicle possessed a sculpted underside with side-sealing skirts designed to create rapid flow accelerations beneath the car, manipulating the Venturi effect to generate low (negative) pressure. This enabled the car to be 'sucked' downward toward the ground at high speed, further enhancing downforce and traction. The skirts were subsequently banned by the sports governing body, the FIA, and a flat bottom was introduced. Another important ground effect device, the underbody diffuser, was introduced in the 1980s.

2 THEORETICAL EXPLANATION

2.1 Ground effect aerodynamics of aircraft

In order to explain the ground effect, it is necessary to first define the aerodynamic forces on a wing. The aerodynamic force can be decomposed into two components: lift normal to the freestream and drag parallel to the freestream. A wing generates lift due to the pressure differences between the pressure (lower) and suction (upper) surfaces as it moves through the air. At the wing tip, the higher-pressure flow beneath the wing attempts to flow around the wing tip toward the low-pressure area above the wing, leading to the formation of trailing wing tip vortices. The primary effect of the vortices is to create a spanwise distribution of 'downwash' that acts to deflect the freestream flow around the wing in a downward direction leading to a reduction in local flow incidence. Consequently, the overall lift generated by the wing reduces. Furthermore, since the lift vector remains perpendicular to the local freestream, there is an increase in the drag equal to the product of the lift force and the angle through which it is deflected. Since the deflection itself is a function of the lift, the additional drag becomes proportional to the square of the lift. This additional drag contribution is known as induced drag or lift-dependent drag, since it is a consequence of lift generation. Figure 3a illustrates a schematic of the wing tip vortices and the downwash, which they induce.

There are two aerodynamic changes associated with the ground effect: (i) a reduction of induced drag and (ii) the presence of an effective air cushion. When an aircraft is flying close to the ground surface within a distance of one wingspan, the induced drag experienced by the aircraft is reduced because the vertical component of the airflow around the wing tip is limited, and the trailing wing tip vortices are disrupted by the ground (see Figure 3b). The downwash intensity is therefore reduced leading to a beneficial effect on lift and drag. If the aircraft is flying extremely close to the ground, within roughly 1/4 of the wingspan, the air flow between the wing and the ground is compressed to form an air cushion. The pressure on the lower surface of the wing is increased creating additional lift. Both of these effects lead to an increase in the lift-to-drag ratio (Figure 4).

In ground effect, the lift curve slope is seen to be enhanced. The reduced downwash generated by the wing tip vortices is shown to increase the effective angle of attack and therefore the lift. The two effects are sometimes classified to be span-dominated (due to the loss of induced drag) and chord-dominated (due to the increase of lift).

The ground effect becomes more pronounced the closer the wing is to the ground. The performance of a wing-in-ground effect is dependent upon many factors (Figure 5)

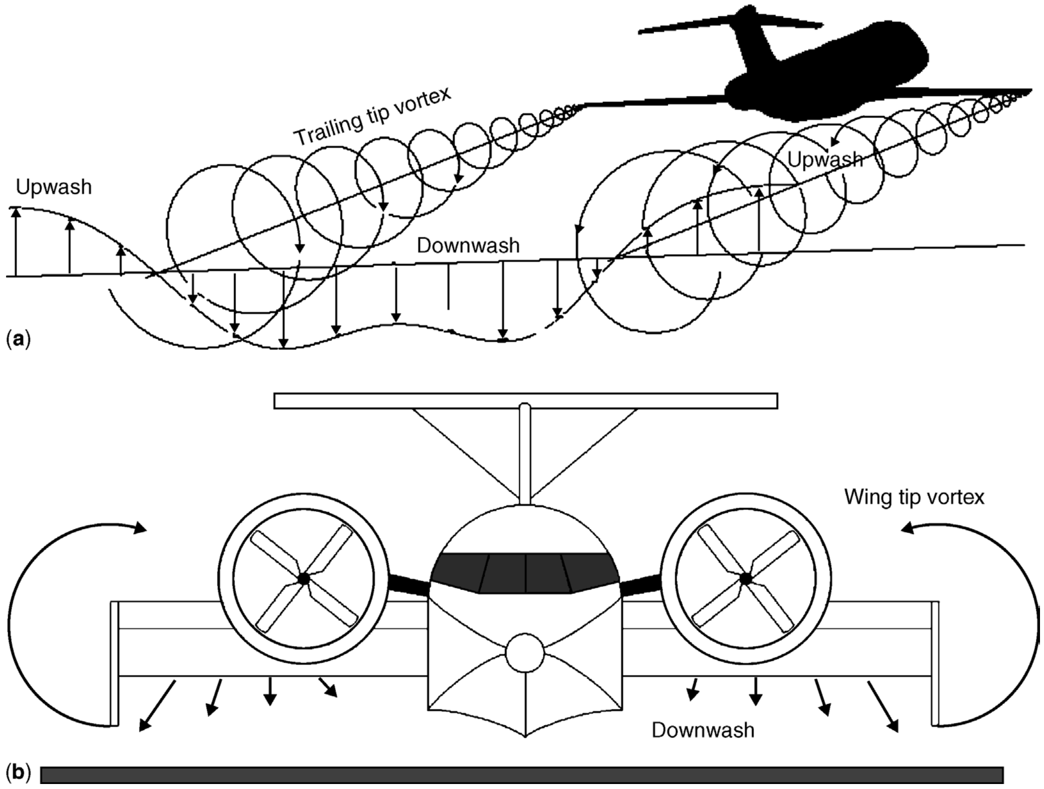

Figure 3. Illustration of wing tip vortices and induced downwash of a WIG aircraft. (a) Illustration of the wing tip vortices and induced downwash; (b) reduction of downwash in ground effect.

such as wingspan, chord length, angle of attack, flying speed, and wing loading factor (aircraft weight per unit area of wing). For aircraft with complex geometries, the interaction between wing, fuselage, tail, and rudders cannot be neglected (Han, Cui and Yu, 1999). It has therefore become popular within ground effect aerodynamic research to investigate the configuration by means of optimization that yields the maximum lift-to-drag ratio with the best stability and control.

2.2 Ground effect aerodynamics of race cars

For a high-speed vehicle such as an open-wheeled race car, the flow around a number of components including the front wings, diffuser, and wheels is subject to the direct influence of ground effect. The enhanced aerodynamic response can have a significant effect on the overall force performance. For example, the overall downforce can amount to three times the weight of the car, of which one-third comes from the front wing, one-third from the undertray and the rear diffuser, and the remainder from the rear wing. The rear wing is placed out of ground effect, but its performance is directly influenced by the flow exiting the diffuser and so is indirectly in ground effect. A number of fluid flow phenomena are evident. These include:

1. Venturi-type downforce enhancement mechanisms with reduction in ground height.
2. Downforce-enhancing edge vortices attached to the end plates of wings and diffusers.
3. Separation as a normal fluid flow feature.
4. Suspension motion leading to unsteady flow.
5. Turbulent wake and ground boundary layer interaction.
6. Wall jet, shear layer instability, vortex meandering, and breakdown.
7. Compressibility effects.

A typical wing assembly generally consists of an inverted wing of multi-element configuration, end plates, and often high-lift devices such as Gurney flaps (see Figure 1). When the airfoil is set at a positive angle of attack, the gap between the suction surface (underside) and the ground forms a channel through which the flow initially accelerates. Negative pressure is produced, rather similar to that in a ‘Venturi’ type of pipe. The pressure then gradually recovers toward the trailing edge of the section as the channel passage expands,

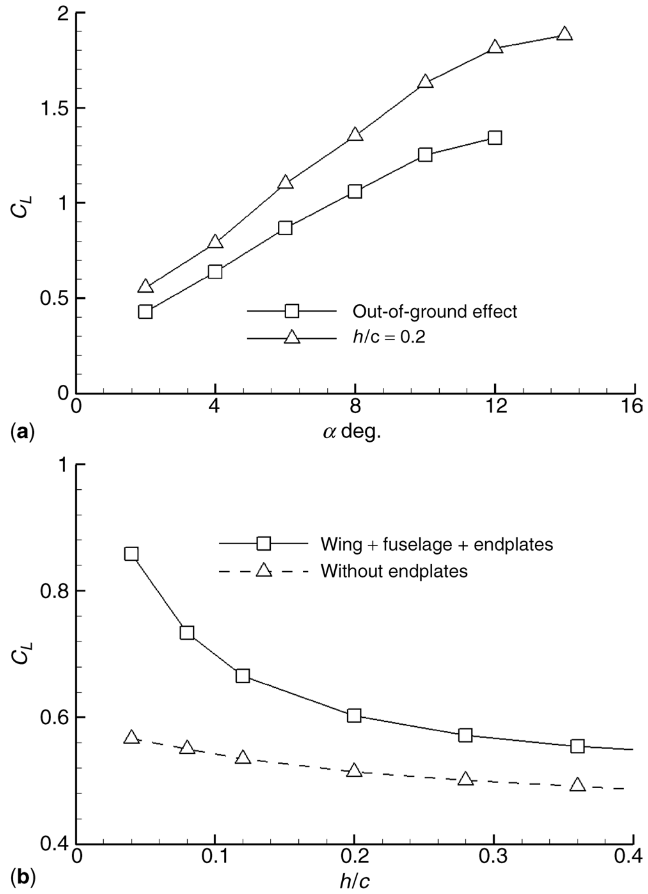

Figure 4. Lift coefficient of wing and components in ground effect for a WIG aircraft. (a) Lift coefficient varying with angle of attack; (b) lift coefficient of components varying with *h*/*c* (*c*, wing chord).

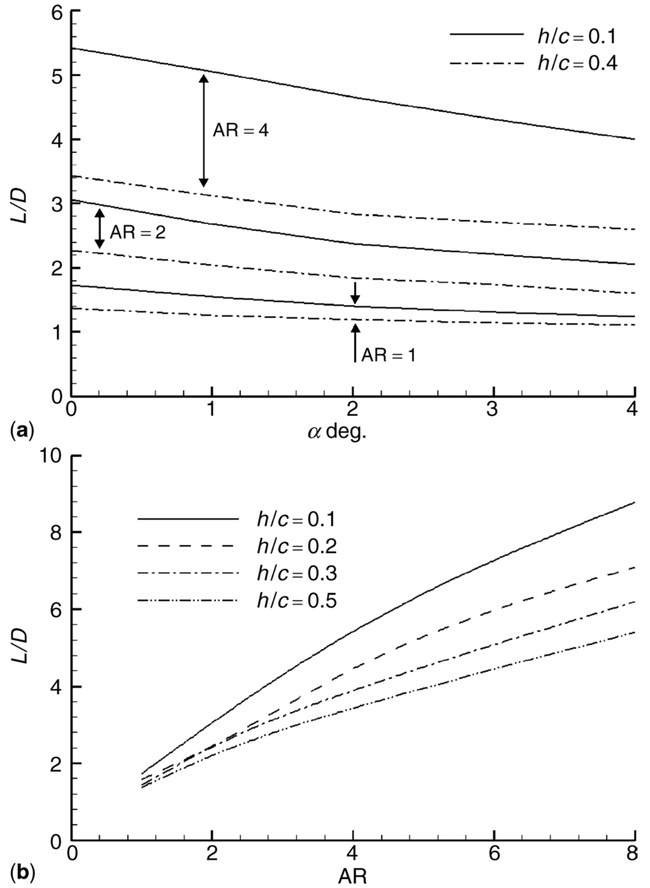

Figure 5. Effect of aspect ratio, ground clearance, and angle of attack on lift-to-drag ratio for a rectangular planform. (a) Lift-to-drag ratio varying with angle of attack; (b) lift-to-drag ratio of components varying with aspect ratio.

similar to that encountered in diffuser-type flow (Zhang and Zerihan, 2003a, 2003b). When the end plates are installed, edge vortices are formed through separation around the lower edge of the plate. The presence of these edge vortices is beneficial for force performance, in contrast to the ‘wing tip vortices’ found on aircraft. The edge vortices lead to additional suction near the junctions between the wing and the end plates. They also induce an upwash that reduces local effective angle of attack, leading to a delay in the appearance of trailing edge separation over the surface of the wing.

The force behavior is subject to the influence of many factors such as airfoil shape, wing planform, geometric settings, ground height, and end plate design. Prominent among them is the ground height (*h*). This is illustrated in Figure 6a. The force response curve can be divided into three distinct force regimes: force enhancement, force slow down/maximum, and force reduction. The force enhancement regime begins at about one chord length from the ground; as the ground height is reduced, C_L increases in a nonlinear manner. The Venturi effect becomes stronger and the edge vortices strengthen. The exponential response is attributed to the extra suction generated by the edge vortices. At a certain ground height, the edge vortices break down due to the strong adverse pressure gradient developing in the channel between the wing and the ground; the rate of force increase is then reduced until the maximum downforce is reached. The wing then stalls synonymous with the force reduction.

For a diffuser-in-ground effect, the physical mechanisms described above still apply. Owing to the narrow span width of the diffuser, the effect of the edge vortices can be stronger and the force regimes are much more clearly defined in the C_L vs h curve (see Figure 6b). The figure also highlights the presence of hysteresis in the force response between the maximum downforce and force reduction regimes due to the boundary layer separation on the suction surface. When the device is placed very close to the ground, the supply of air is choked off and the downforce is lost.

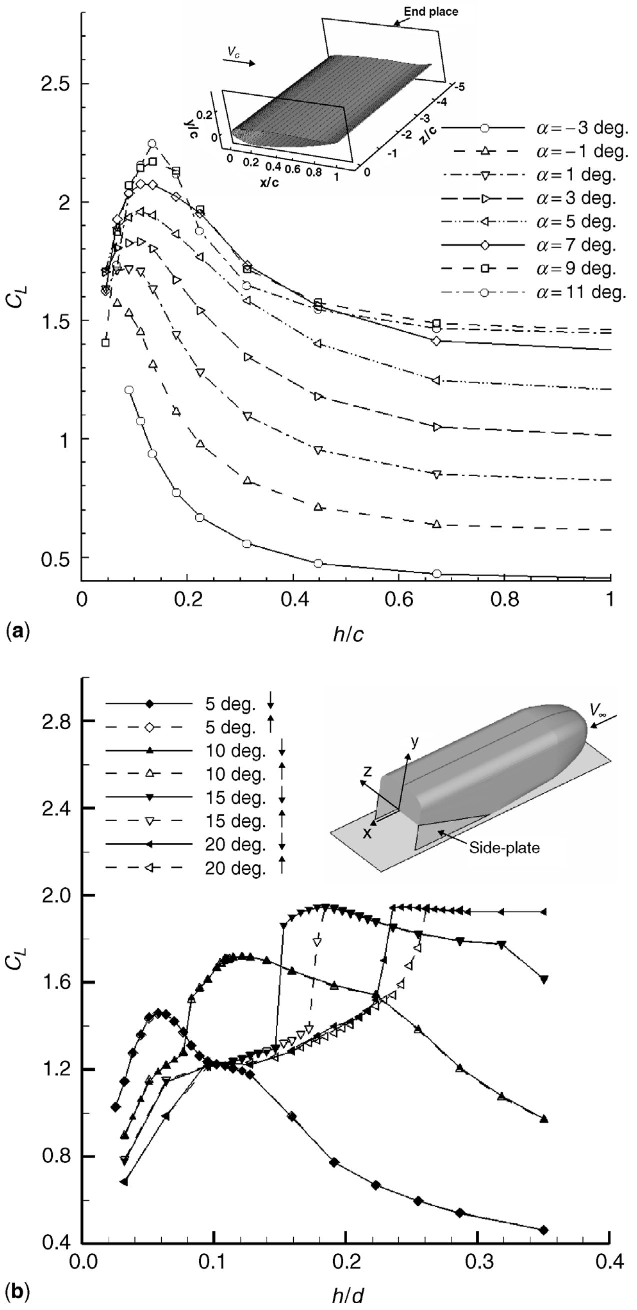

Figure 6. Downforce behavior in ground effect for a racing car. (a) Effect of angle of attack on wing downforce (c, wing chord); (b) diffuser angle effect on downforce.(d, model half-width).

3 PREDICTION OF GROUND EFFECT

Methods exist to assess the performance of vehicles utilizing ground effect aerodynamics; these include empirical approximations for preliminary estimations, asymptotic approach schemes, analytical methods, numerical simulation, and experimental testing. Relevant discussions on this topic can be found in Cui (1998), Rozhdestvensky (2006), and Zhang, Toet and Zerihan (2006).

The configuration of aircraft and high-performance cars, involving wings, fuselage, tail planes, end plates, and control surfaces, is usually highly complex and presents a great challenge when applying direct numerical simulations and analytical methods. For many years, performance analysis and designs have had to rely mainly on simplified theories, for example, two-dimensional models or experimental data with appropriate empirical corrections. Nowadays, the situation has improved greatly with significant progress being made in aerodynamic theory and computational techniques supported by the availability of more powerful computers.

3.1 Simplified calculation methods for 2D flow

It is well known that for a thin flat-plate airfoil, operating out of ground effect, the lift-curve slope is 2π. On the basis of two-dimensional flow theory, the approximate lift coefficient C_L for a thin flat-plate airfoil within ground effect was given by Barrow, Mangoubi and Curtiss (1995) as

$$C_L = (1+\delta^2)(1-2\zeta)\times 2\pi\alpha \tag{2}$$

where α is the angle of attack and δ and ζ are both nondimensional parameters defined as

$$\zeta = \frac{\sin\alpha}{4(h/c)}$$

$$\delta = \frac{\cos\alpha}{4(h/c)} \tag{3}$$

where h is the height of the airfoil above the ground surface and c the chord of the airfoil.

Barrow, Widnall, and Richardson (1970) derived another lift coefficient as

$$\frac{C_L}{C_{L|\mathrm{OGE}}} = \frac{1}{2\pi(h/c)}\left(\frac{1}{1+2\zeta}\right) + \frac{1+2\ln(\pi\sqrt{h})}{\pi^2} \tag{4}$$

where the subscript OGE denotes the out of ground effect regime. This formula can be used for a wing operating closer to the ground.

3.2 Analytical methods

For two-dimensional airfoils, with or without flaps and ailerons, numerous analytical methods based on potential theory are available. Comprehensive reviews of previous work, using analytical methods to study ground effect aerodynamics, can be found in Cui (1998) and Rozhdestvensky (2006).

Early analytical treatment of the ground effect problem used Prandtl's lifting-line theory and image model to satisfy the tangential flow boundary condition on the ground surface (Wiesesberger, 1921). In the Wiesesberger model, the height from the wing position to the ground has the same order as the wingspan, and the wing chord is treated as a much smaller parameter for an aircraft with a large aspect ratio wing. The theory is limited to large aspect ratio wings with small angle of attack at a relatively high position above the ground (Tomotika, Nagamiya and Takenouti, 1933).

The method of matched asymptotic expansion (MAE) has been used successfully to study ground effect aerodynamics. This method is a common approach employed to find an accurate approximation to a problem's solution, particularly when solving singularly perturbed differential equations. It is suitable for the investigation of physical problems involving multiple regions with differing characteristics. In the analysis, the problem domain may be divided into two subdomains. One of the domains can be treated as a regular perturbation problem, and its solution is approximated by an asymptotic series of perturbation parameters. But for the other domain that contains small interior areas, its solution is inaccurate since the perturbation terms are not negligible. The asymptotic series for these smaller areas can only be obtained by treating each area as a separate perturbation problem, and this approximation is called the 'inner solution'. The solution for the former domain is called the 'outer solution'. The solution for the whole domain can only be obtained by combining these two solutions through a matching process. For wing-in-ground effect aerodynamic problems, the whole flow field is usually divided into regions above and below the wing surface at the wing edges. Different small perturbation parameters such as dimensionless flight height h/c (c is the chord length), or its reciprocal, c/h, and other combinative parameters have been used to obtain different forms of expansion for different problems. Widnall and Barrows (1970) first introduced the MAE approach to study ground effect aerodynamics for two- and three-dimensional flat wings. Plotkin and Dodbele (1988) used the MAE approach to solve the ground effect aerodynamics problem of flow around a wing with large span. In their approach, the relative height (flight height/chord length) was considered as a small parameter. Rozhdestvensky (1992) extended the MAE approach to a linear unsteady flow around a wing with flaps and took compressibility effects into account.

Analytical methods have been used to study ground effect aerodynamics successfully. Since analytical solutions exist only for cases with simple geometry and small angles of attack, they are best applied to preliminary design and configuration optimization. Caution must be exercised when using these approaches to study complex problems.

3.3 Computational fluid dynamics (CFD)

In addition to experimental model tests (see below), computer modeling is another important tool used widely in ground effect aerodynamic study. Computational fluid dynamics techniques have been applied to various problems involving ground effect vehicle simulation. The governing equations solved range from potential equations to Euler equations and Navier–Stokes equations of various forms.

Among the various existing simulation methods, panel and vortex lattice methods are widely used (Cui, 1998; Hiemcke, 1997; Rozhdestvensky, 2006). These methods are commonly used for solving linear, incompressible, potential flows neglecting viscous effects. By utilizing boundary layer correction, the viscous effect and the skin friction can be predicted. It is well known that the solution of a linear differential equation can be represented in terms of a linear combination of some elementary solutions such as sources, sinks, dipoles, and vortices. In the vortex lattice method, the airfoil and wing surface is divided into small segments (for two-dimensional geometry), or panels (for three-dimensional geometry) and one may place the vortices on each segment or panel. Vortices are usually placed at the 1/4 chord point of each panel, and the 3/4 chord points are used as downwash velocity control points where the kinematic flow condition has to be satisfied. The nonpenetration boundary condition on the ground and the Kutta condition at the trailing edge must also be satisfied in order for the flows from the upper and lower edges to leave the trailing edge in the same direction. After determining the strength of vortices, the circulation around the airfoil or wing, and consequently the lift, can be obtained. These methods have been utilized to solve the ground effect aerodynamic problems of airfoils with flaps or jet-flaps, the nonlinear effects due to large angle of attack or large flap angle, the complications associated with three-dimensional aircraft, and the unsteady effects of the wake deformation and vortex shedding into the wake.

Simulation methods based on the solutions of Euler or Reynolds-averaged Navier–Stokes (RANS) equations such as the finite element method (FEM), finite difference method (FDM), and finite volume method (FVM) have been used to study aerodynamic performance of two-dimensional airfoils, three-dimensional wings with or without end plates as well as the integrated configurations of the vehicle to obtain results with differing accuracies both in and out of the ground effect area. In unsteady ground effect aerodynamic fields, these simulation methods are mainly used to predict the wake behind an airfoil, the interference effects of the vortex system, and the effects of waves on the aerodynamic performance of the wing and vehicle flying over the sea surface. In recent years, progress has been made in using large eddy simulation (LES) and detached eddy simulation (DES) to study ground effect aerodynamics.

Detailed information about the whole flow field, for example, velocity and pressure distributions, as well as the vortex pattern, can be obtained using the simulation methods, which is important for a thorough study of ground effect aerodynamics and the effects of parameter variation. Owing to the limitation of computational resources, it is necessary to impose restrictions on the geometry, kinematics, and dynamics of the aircraft being studied. Success of any given CFD method depends on correct application of the simplified flow model to the physical system concerned; in particular, the selection of an appropriate turbulence model, adequate resolution of the computational domain, and the specification of correct boundary conditions will determine the accuracy of the solution.

3.4 Airfoils and wings over calm and waving water surfaces

The aerodynamic characteristics of a vehicle moving over waves are significantly different from those of a vehicle moving over calm water. The aerodynamic forces are unsteady due to surface fluctuations and the random nature of the waves. Many investigations have been undertaken to study the sinusoidal wave in two dimensions (see the review by Cui, 1998). In those studies, linear theory was used based on the assumptions that the fluid is incompressible and all disturbances are sufficiently small. The results show that the forces acting on an airfoil depend not only on the angle of attack and the height above the surface, but also on the wavelength and amplitude of the water surface variation. The phase angle between the wave and the airfoil motion also has a strong influence on the forces on the airfoil.

Under random wave conditions, the airflow induced by wind–wave interactions also has an influence on aerodynamic forces besides the direct impact of the wavy boundary. Statistical methods can be used to solve this problem (Cui, 1998).

There are currently no feasible computational methods for either a three-dimensional wing or an integrated configuration of a vehicle flying over waves. In most cases, the aircraft design depends on the data obtained through model tests in towing water channels. Model tests (Figure 7) show that the total drag is much higher when waves are present compared to that of calm water for a typical vehicle configuration (Han, Cui and Yu, 1999; Rozhdestvensky, 2006). There is no satisfactory solution for many practical problems under complex sea conditions. Further studies are needed to understand the effect of wave direction, the unsteady and nonlinear aerodynamic effects when in close proximity to a surface, and the changes under high-lift conditions.

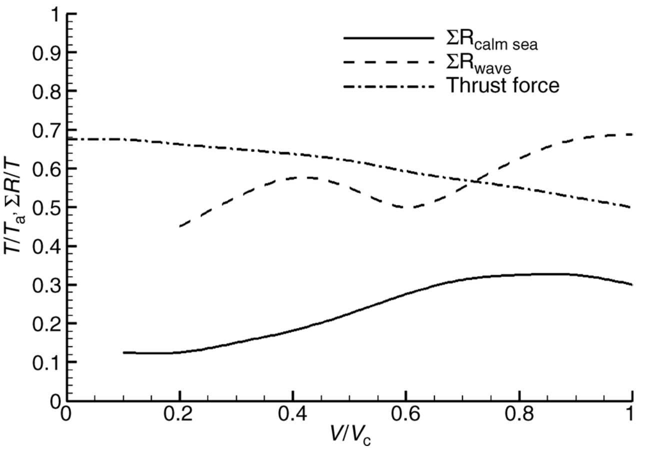

Figure 7. Total resistance ΣR of a WIG vehicle flying over calm and waving water surface, where T is the thrust force provided by the engine, V the flying speed, V_c the cruise speed, and T_a the design allowable thrust.

3.5 Nonlinear phenomenon in extreme near-ground effect region

Both wind tunnel model tests and numerical simulation results reveal that the aerodynamic characteristic of an airfoil becomes nonlinear when the airfoil is operating in extreme ground effect configurations, that is, in very close proximity to the ground surface. As a direct result, the lift-to-drag ratio decreases as the airfoil approaches the ground. It is believed that this is due to the interaction between the boundary layer formed under the airfoil and the airflow in the narrow passage between the airfoil and the ground. In some cases, separation and breakdown of vortices can also contribute to this nonlinear phenomenon.

4 EXPERIMENTAL METHODS

Wind tunnel testing and water tunnel testing are extensively employed in studying the ground effect aerodynamics of WIG vehicles. Detailed reviews of wind and water tunnel testing can be found in Hooker (1989). There are basically four widely used methods to study the ground effect; these include the mirror image model method, the ground plate method, the moving belt method and the towing model method. Wind

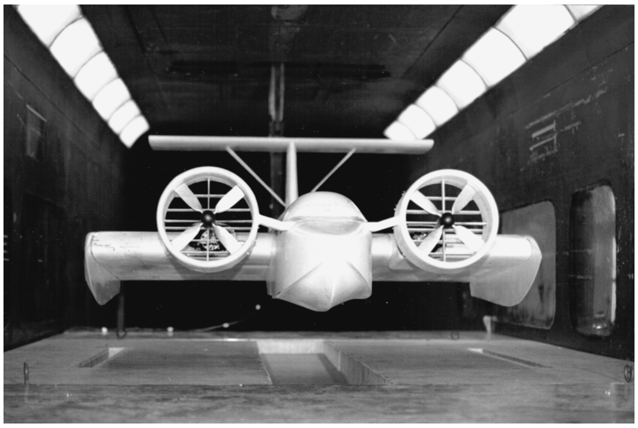

Figure 8. Wind tunnel testing of a WIG aircraft (courtesy of WIG Vehicle Development Center of Chinese Academy of Science & Technology Development).

tunnel testing of WIG aircraft poses some unique challenges since the aircraft operates very close to the ground or water surfaces. The planing surfaces and end plates may even be inside the water. Figure 8 shows a sting-mounted WIG wind tunnel model; the effect of the partially submerged aircraft (its end plates and hull) can also be tested in this arrangement.

Measuring techniques, designed to evaluate both on and off surface flow and model data, have been greatly advanced yielding pressure distributions, aerodynamic forces, moments and dynamic stability derivatives. Analysis is enhanced through sophisticated flow visualization techniques including particle image velocimetry (PIV), laser Doppler anemometry (LDA), and surface oil flow visualization.

4.1 Mirror image model method

The mirror image model method uses a pair of mirror image models (the actual model and the dummy model) mounted inside the wind tunnel with a virtual mirror plane located in between. The virtual mirror plane imposes conditions similar to the ground since the geometric symmetry forces the normal flow velocity at the mirror plane to be zero. This method has limitations since it cannot guarantee the satisfaction of the correct tangential flow velocity at the virtual plane. In addition, it is difficult in practice to set up a perfect pair of image models inside the wind tunnel. Furthermore, the setup is expensive and so now is rarely used.

4.2 Ground plate with boundary layer suction

The use of a fixed ground plate is a simple, yet direct method. A fixed ground plate, often raised above the tunnel floor, is used to simulate the effect of the ground. There is no relative movement between the model and the ground plate during tests. A fresh boundary layer forms on the ground plate. The displacement thickness of the boundary layer alters the effective gap between the model and the ground; therefore, the aerodynamic characteristics of the model are also affected. The impact of the boundary layer can be minimized by utilizing a ground plate with boundary layer control (such as suction or blowing) or by including flow corrections.

4.3 Moving ground method

The moving belt method is the only physically correct method that simulates the effect of the moving ground. The moving belt is a mechanical device that moves at the same speed as the freestream flow in the wind tunnel. In practice, suction is applied in front of the moving belt to form a complete system. A suction box eliminates the retarded air approaching the belt and ensures the physically correct ground flow condition. Figure 9 shows a typical three-roller setup of a moving belt system including front and drive rollers to move the belt and tension and tracking rollers to assist in a correct alignment. A system of suction is also used to suck the belt from below onto a flat surface so that negative pressure fields generated by test models will not cause the belt to rise. This necessitates the employment of a cooling system to remove the heat generated during a test run. More recently, steel belt technology has been developed as an expensive alternative mainly for the race car industry.

4.4 Towing model method

Another approach in the study of ground effect aerodynamics is the towing model method. In a towing facility, the model is moved through still air on a carriage in an enclosed building, correctly simulating the ground boundary conditions. Measuring instruments are installed on the carriage and move with the model, recording various physical quantities such as forces, moments, flow field, etc. Curtiss *et al*. (1983) used this method to study the ground vortex phenomena of a helicopter rotor flying near the ground.

5 GROUND EFFECT ON AERODYNAMIC PERFORMANCE

Ground effect aerodynamics has been widely used in the research and development of various vehicles. A thorough

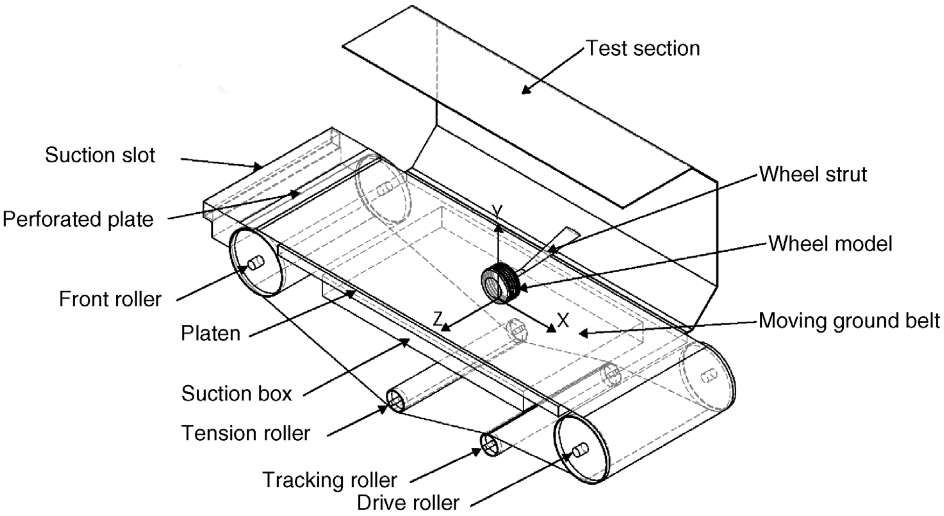

Figure 9. Schematic of a moving ground system.

understanding and meticulous implementation of ground effect aerodynamics can maximize a vehicle's aerodynamic efficiency and improve the safety of the vehicles in operation.

5.1 Aircraft in take-off and landing

Ground effect aerodynamics has an important impact on the take-off and landing performance of an aircraft. For a constant pitch attitude, the lifting surfaces experience a larger angle of attack within ground effect conditions. For a heavily loaded aircraft required to operate on shortened airstrips, a large angle of attack has to be used. When it climbs out of the ground effect area, the loss in incidence may cause the aircraft to 'sink' and potentially stall if the flight speed is inadequate when the pilot corrects the aircraft pitch. This is thought to be the cause of many aircraft accidents. In contrast, when an aircraft descends toward the ground during the landing phase and below a distance of one wing chord, the reduced level of induced drag causes the aircraft to 'float' as the speed of the aircraft refuses to 'wash-off'. Any excess speed will make this float effect stronger leading to increased landing distances and potential pitch oscillations due to excessive control inputs.

The rapid and continuous variation of speed and height with time, encountered during the take-off and landing phases of flight, results in unsteady flow dynamics. As a consequence, the ground effect aerodynamic response must be carefully considered, and any sudden change in flight behavior must be recognized and predicted in order to prevent any risk of crash.

5.2 Rotary wing of a helicopter in near ground configuration

A rotary wing aircraft such as a helicopter is also subject to the influence of ground effect when it hovers at, or under, approximately one blade length above the ground surface. It is essentially an air-cushion effect generated by the rotation of the wing that results in an increase in the lift of the rotor disc. For this reason, hovering in ground effect takes less power than that required in out of ground effect operation.

When a helicopter hovers near the ground, a ground vortex may appear in front of the helicopter. This ground vortex can change the rotor flow field such that very large moments are produced. This can lead to a loss in control and a potential crash.

5.3 Wing-in-ground effect vehicle

In the middle of the twentieth century, many researchers realized that the ground effect phenomenon could be exploited to develop a new class of highly efficient craft known as WIG vehicles that would experience 30–50% less drag than a normal aircraft and could therefore travel further using the same amount of fuel.

Since the 1960s, the former Soviet Union (now Russia) and many other countries have successfully built a number of WIG vehicles. Examples include the Soviet 400 ton Lun and 140 ton Orlyonok (Rozhdestvensky, 2006) as well as the Chinese TY-1 that carried 15 passengers (Cui, 2003). The practical operation of the WIG vehicle still faces some unresolved difficulties such as those of economy, wind and wave resistance capability, sea-worthiness, and stability and maneuverability both inside and out of the ground effect area. These limitations have formed the major barriers to WIG vehicle development and to their successful entry into the commercial market at the present time (Cui, 2003).

5.4 Stability of aircraft flying in close proximity to the ground

For a WIG vehicle operating at a very low altitude and close to the ground for a significant period of time, ground effects can have a great influence on the stability of the vehicle; this period can include both the take-off and cruise configuration as well as the transition between the two phases of flight. If this problem is not correctly addressed, the instability may have catastrophic repercussions. Numerous experimental results have revealed the different performances of the WIG vehicle in and out of the ground effect regime and confirmed the existence of two distinct aerodynamic centers when a vehicle is flying very close to the ground. Along with the conventional aerodynamic center, Xf_α, which varies with the angle of attack, there is another aerodynamic center, Xf_h, which varies with the height above the surface.

Many factors have a strong influence on the stability of WIG vehicles. These include flying height, h, derivatives of lift coefficient, C_L and pitching moment coefficient, C_M, with respect to angle of attack, α ($C_{L\alpha} = \partial C_l/\partial\alpha$, $C_{M\alpha} = \partial C_M/\partial\,\alpha$) and nondimensional flying height, h/c, ($C_{Lh} = \partial\ C_L/\partial\ (h/c)$, $C_{Mh} = \partial C_M/\partial(h/c)$), and the two aerodynamic centers (Xf_α, Xf). In the transition process from take-off to cruise state, the longitudinal and lateral coupling often has to be taken into account leading to a more complicated problem.

In WIG vehicle design and operation, it is necessary to maintain a static stability both in pitch and height directions, which means that the following requirements must be satisfied in agreement with those for a conventional aircraft:

$$
\begin{aligned}
C_{M\alpha} &< 0 \\
C_{Lh} &< 0 \qquad (5)
\end{aligned}
$$

The position of the center of gravity (X_T) with respect to these two aerodynamic centers is directly related to the stability of the vehicle. Theoretical analysis by Irodov (1970) shows that the following criteria have to be satisfied in order to maintain longitudinal stability

$$\text{Aperiodic stability}: \quad Xf_h - Xf_\alpha < 0 \qquad (6a)$$

$$\text{Oscillatory stability}: \quad X_\text{T} < A_1 \times Xf_h + A_2 \qquad (6b)$$

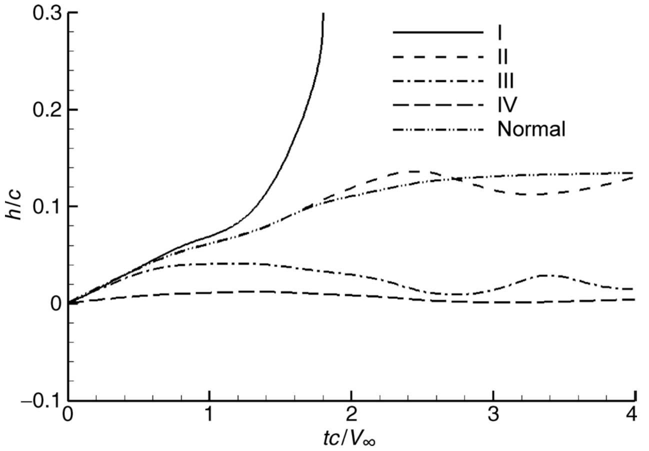

Figure 10. Abnormal flight states during take-off: I – rapid pitch up, II – oscillatory divergence, III – off–on surface contact, and IV – failure to take-off.

where A_1 and A_2 are known functions of aerodynamic and structural parameters for the vehicle. The equation (6a) requires that Xf_h should be ahead of Xf_α and equation (6b) provides a basis for determining the center of gravity location.

Another existing problem is longitudinal trim at the stage of take-off and transition to cruise. If the parameters such as angle of attack, flap and elevator configuration are not correctly controlled, the WIG vehicle may not operate smoothly. Flight simulation and model tests both in water channels and above open water surfaces have shown that during take-off, if the above conditions (5) and (6a) are violated, unexpected results, either rapid pitch up or failure to take-off, will occur. In other cases, if the two aerodynamic centers are not properly positioned and the criterion (6b) is violated, the WIG vehicle can lose its longitudinal stability leading to oscillatory divergence or the vehicle can make ‘off and on’ contact with the water surface as shown in Figure 10.

In order to ensure flight stability both in and out of the ground effect area, maintaining a much larger static stability margin than that of a conventional aircraft should be the primary objective. Another possible method to enhance longitudinal stability is to locate the aerodynamic center (Xf_h) nearer the center of gravity (X_T) and to employ a large horizontal tail unit, positioned far above the boundary of ground effect influence.

6 CONCLUSIONS

Ground effect aerodynamics plays an important role in the take-off and landing phases of various aircraft and in the study of the performance of hydroplanes flying close to the sea surface, high-speed trains, and high-performance cars. It is also the foundation for the research and development of WIG vehicles. The effect is manifest as an increase in the force performance of the lifting surfaces employed due to the flow constraints imposed by the close proximity of the ground plane.

The study of ground effect aerodynamics includes theoretical analysis and experimental observation. For theoretical analysis, engineering approximation and linear potential theory have provided the major means of studying ground effect aerodynamics in the past. Between the 1970s and the 1980s, significant progress was made in achieving numerical solutions of both the Euler and Navier–Stokes equations in their various forms. Since then, computational methods have been used successfully to simulate the response of both airfoils and aircraft with complex geometry and to study their steady and unsteady aerodynamic behavior near solid ground and over water surfaces perturbed by wave motion. Furthermore, investigations have yielded a greater understanding of vehicle flight dynamics, stability and control, aeroelastic phenomena, integrated configurations, and vehicle optimization.

Well-established methods exist for successful wind tunnel testing to study ground effect aerodynamics such as the moving belt and towing model methods. Measuring techniques, designed to evaluate both on and off surface flow and model data, have also been greatly advanced yielding pressure distributions, aerodynamic forces, moments and dynamic stability derivatives. Analysis is enhanced through sophisticated flow visualization techniques including particle image velocimetry, laser Doppler anemometry, and surface oil flow visualization.

Modern perspectives on engineering design are focussed on the pursuit of more efficient technologies with increased performance. The clear benefits apparent with ground effect aerodynamics will ensure that the phenomenon will occupy a dominant role in the future optimization and development of vehicles subject to its influence. The scope of ground effect study will be expanded and deepened. The implications of compressibility effects and the interaction with control systems are likely to receive extensive attention.

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