Wing in Ground (WIG) Effect Vehicles

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>b</td>
<td>Wing Span</td>
</tr>
<tr>
<td>$C_L$</td>
<td>Coefficient of Lift</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Coefficient of Drag</td>
</tr>
<tr>
<td>$C_m$</td>
<td>Coefficient of Moment</td>
</tr>
<tr>
<td>c</td>
<td>Chord Length</td>
</tr>
<tr>
<td>h</td>
<td>Height</td>
</tr>
<tr>
<td>i</td>
<td>Angle of Incidence</td>
</tr>
<tr>
<td>$I_y$</td>
<td>Moment of Inertia about the y-axis</td>
</tr>
<tr>
<td>$i_y$</td>
<td>Coefficient of Moment of Inertia about the y-axis</td>
</tr>
<tr>
<td>M</td>
<td>mass of craft</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds Number</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Angle of Attack</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle of Pitch</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Relative Density</td>
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Abstract

In this paper, the Wing-In-Ground (WIG) Effect on a small scaled vehicle is being studied. Existing WIG crafts as well as those developed in the pasts by the Russians are quite huge in size. The objective of this project is to design and build a small scale WIG crafts in order to investigate ground effect on small scale vehicles.

1. Introduction

Ground Effect is a phenomenon when a lift generating device, like a wing, moves very close to the ground surface which increases the lift-to-drag ratio. Huge airplane like the
747 often experience the plane ‘bounces’ off the runway in the presence of ground effect just before touch down. This phenomenon that resulted in the aerodynamic efficiency of the vehicles was first exploited by the Russians whom designed and build the first WIG craft during the cold war.

Recently, a local spin-off company, Wigetworks Pte Ltd, is trying to market a commercialize Lippisch design WIG craft known as WG-8 (Fig 1). This project was initiated by Wigetworks Pte Ltd to perform further studies and research to gain a better insight of Ground Effect.

![Fig 1. WG-8 in flight (With courtesy of Wigetworks Pte Ltd.)](image)

2. Ground Effect Aerodynamics

When a wing approaches the ground, an increase in lift as well as a reduction in drag is observed which results in an overall increase in the lift-to-drag ratio. This is a result of the chord dominated ground effect (CDGE) and the span dominated ground effect (SPGE) which causes an increase in lift and a decrease in induced drag respectively.

In the study of CDGE, the main causes for the increased in lift is due to a ramming effect whereby the static pressure on the bottom surface of the wing is increased. Theoretically,
as the height approaches 0, the air will become stagnant hence resulting in the highest possible static pressure with a unity value of coefficient of pressure.

Fig. 2 shows the difference between an airfoil without ground effect (a) and with ground effect (b).

![Fig.2](image)

**Fig.2.** Contour plot of static pressure on an airfoil; a. Out of ground effect. b. With ground effect

On the other hand, the induced drag occurs in finite wings where there is a ‘leakage’ at the wing tip which creates the vortices that decreases the efficiency of the wing is now bounded by the ground. As a result the strength of the vortex decreases, the wing now seems to have a higher effective aspect ratio as compared to its geometric aspect ratio therefore a reduction in the amount of induced drag. This is known as the span dominated ground effect.

In the presence of ground effect, the force and moment acting on the body changes with height. Hence for a WIG craft, there are two aerodynamic centers: the center of pitch, which is the same as the aircraft aerodynamic center and the center of height where the
moment is independent of height. These two centers can be calculated by the following given relationship\textsuperscript{[1]}:

\[ x_a = \frac{C_{ma}}{C_{La}} \quad (1) \]

\[ x_h = \frac{C_{m}}{C_{Lh}} \quad (2) \]

where \(x_a\) and \(x_h\) are the center of pitch and the center of height, respectively. In this paper, the sub-subscript means the differential.

3. \textbf{Longitudinal Stability}

Stability is a very important criterion in the design of aircraft. For aircraft, two conditions must be met for longitudinal stability\textsuperscript{[2]}:

\[ C_{ma} < 0 \text{ and } C_{m} > 0 . \quad (3) \]

For WIG craft, as mention in Section 2, the aerodynamic forces and moments vary with Ground Effect. Besides the need for pitch stability, there is also a need for height stability.

3.1 \textbf{Linearized longitudinal equations of motion}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{axes_system.png}
\caption{Definition of axes system.}
\end{figure}
With the assumption of the cruise speed remains unchanged, the linearized longitudinal equations of motion for a WIG craft with reference to the C.G are written in a dimensionless form as \(^{(4)}\):

\[
\mu \frac{d^2 \tilde{h}}{dt^2} - C_{\lambda k} \frac{d\tilde{h}}{dt} - C_{\lambda k} \tilde{h} = C_{\lambda o} \frac{d\tilde{\theta}}{dt} + C_{\lambda o} \tilde{\theta} \tag{4}
\]

\[
\mu i_y \frac{d^2 \tilde{\theta}}{dt^2} - C_{m_k} \frac{d\tilde{\theta}}{dt} - C_{m_k} \tilde{\theta} = C_{m_o} \frac{d\tilde{h}}{dt} + C_{m_o} \tilde{h} \tag{5}
\]

In equation (4) and (5), \(\tilde{h}\) and \(\tilde{\theta}\) is the perturbed height and pitch respectively, the over dot means differential with respect to time, \(\mu\) is the relative density of craft and \(i_y\) is the Coefficient of Moment of Inertia about the y-axis which are define as:

\[
\mu = \frac{2M}{\rho Sc} \tag{6}
\]

\[
i_y = \frac{I_y}{Mc^2} \tag{7}
\]

3.2 Stability criterion

For a WIG to attain stable states of motion, the following criterion has to be fulfilled based upon Routh – Hurwitz (See Rozhdestvensky\(^{(4)}\) for details):

\[
x_b - x_o > 0 \tag{8}
\]

To achieve height stability of a WIG craft, one must select a configuration such that the center of height is located upstream of the center of pitch in addition to the condition stated in equation (3) to ensure the static longitudinal stability of a WIG craft. Hence to ensure the WIG craft is longitudinally stable, both equation (8) and (3) must be satisfied.
4. **Design Optimization**

The design of a WIG craft is much more involve than designing an aircraft or a ship alone as there is only a limited amount of published literature and data on the design of WIG crafts. Therefore during the design phases, certain guidelines and rules are taken from aircraft and ship designs.

4.1 **Conceptual Design**

In the conceptual design phase, the overall shape, dimensions and weight of the WIG craft is determined. The size of the craft is limited by the availability and the constraints of off the shelves components like servos, electrical engines and propellers in order to reduce the cost and fabrication time. Being a heavier than air vehicle, the weight of the craft will be an important consideration in the design. Also, the craft must be able to float on water as well, therefore a material that is less dense than water is also a requirement.

4.2 **Preliminary Design**

During the preliminary phase, extensive Computational Fluid Dynamics (CFD) analysis is being carried out to determine the aerodynamic characteristics of the WIG. From the estimated weight, the required lift to take off and cruise is optimized by running the simulation of the wings of different sizes. Simulation for various angle of attack and height are run in order to determine $x_a$ and $x_h$ from the relationship given in Equation (1) and (2).
4.3 Configuration Layout

As a rule of thumb, the cruising altitude of a WIG craft is to be kept at \( h/c < 0.25 \). Hence to ensure the craft will operate at an altitude higher than the wave height, a relatively large wing with a long chord is used. The airfoil use for the wing is the Gottingen 436 as it has a flat suction (bottom) surface which reduces the suction effect as the wing approaches the ground.

To provide stability and controllability of the craft, the tail is needed. The horizontal tail, normally mounted high out of ground effect provides the longitudinal trim, stability and pitch control with the aid of the elevator. Directional control is achieved with a rudder to provide yaw and is attached to the vertical tail which provides lateral stability.

One of the main problems encounter by WIG craft during the take off phase is the large hydrodynamic drag which requires a lot of power to overcome. One of the solutions to solve this problem is to blow air underneath the wing causing a large deceleration of air that resulted in a larger increase in static pressure thus more lift (Fig. 4). This is known as the Power Augmentation Ram effect or PAR\(^4\). Hence propellers are placed in front of the wing to generate PAR effect.
5. Results and Analysis

Existing analytical solution for airfoils and wings that are developed were based on the assumption of inviscous flow \[^5\]. Those methods are fairly accurate if the operating Re base on the free stream velocity and the chord length is very high (in the order of $10^7$ and above). Based on the Thin Airfoil Theory, the coefficient of lift is proportional to the angle of attack and independent of the free stream velocity. This is however not true for lower Re flow lesser than $4 \times 10^6$. The coefficient of lift is highly dependent on the Re for flow within this region as shown in Fig. 5. Similar observations are also obtained by Hsiun and Chen \[^6\].

Based on the dimensions and operating speed of our WIG craft, the Re is expected to be in the order of $10^5$. Therefore the classical methods of analysis will not be applicable here as theoretical solution for flow at Re of this range is not available at this moment.
Analysis will then have to be carried out using commercial CFD package, Fluent, where the viscous effect of the flow will be taken into account during computation.

**Fig. 5.** Effect of Reynolds number on the Lift of a Gottingen 436 at 0 deg angle of attack and $h/c = 0.05$.

Lift, drag and moment coefficients of a rectangular wing with respect to angle of attack and height are presented in Fig 6a to 6f. The results obtain are in agreement with experimental studies carry out by Ahmed and Sharma [7] and the theoretical results from Rozhdestvensky [4] even though they are only applicable to symmetrical airfoil and 2D flat plate respectively.

CFD analysis is further applied to the WIG craft with both wing and fuselage integrated. The aerodynamic characteristic curves, Fig. 7a to 7f, are also obtain in this case which will be use to determine the C.G position for static stability requirement which is
discussed in section 5. Although some similar trends is observed here, slight deviation from the curves obtain by the wing alone is due to two reasons. One is the interference of the flow between the fuselage and the wing. Second is the wing is position at the middle of the fuselage which makes the relative height between the wing to the ground higher.

Fig. 8 shows an increased in aerodynamic efficiency in the presence of ground effect. This is however much due to the SDGE. From Fig. 6a and Fig. 7a, although there is an increment in lift as the wing approaches the ground at 0 degrees angle of attack, it is however not as significant as compared a large WIG craft. This is most likely due to the relatively small wing area and lower operating velocity of our craft hence the ramming effect is much lesser than a large craft which can cause a higher amount of flow deceleration under the wing. However, it is interesting to note that once the angle of attack is increased slightly, the ramming effect will become significant and the increment of lift force can be up to twice the initial value at 0 degrees angle of attack.

On the other hand, flow separation is observed beyond angle of attack beyond 5 degrees. For ground effect, the stall angle seems to be smaller than without ground effect (up to 8 degrees). This is due to the pressure difference at the trailing edge cause by the ramming effect. Fig. 9a and 9b shows the comparison of the flow at a high Reynolds number (for big WIG craft) and low Reynolds number (for small scale WIG craft). Under low Reynolds number, the flow is circulated from the bottom surface of the wing to the top results in a retardation of the flow on the upper surface, causing flow to separates much earlier than in the absence of ground effect.
Fig. 6. Aerodynamic characteristics of a wing with 0.4m chord, AR = 5, Free stream velocity $V = 12.5\text{m/s}$. 
Fig. 7. Aerodynamic characteristics of Wing-Fuselage configuration of wing with 0.4m chord, AR = 2.5, Free stream velocity $V = 15\text{m/s}$. 
Fig. 8. Lift to Drag ratio with respect to ground clearance

Fig. 9. Vector plot of velocity at trailing edge. a. Re = 10^7. b. Re = 2 \times 10^5

Table 1. Aerodynamic centers of pitch and height with x directed upstream with reference to the leading edge of the wing of chord length \( c = 0.4 \text{m} \).

<table>
<thead>
<tr>
<th></th>
<th>( x_\alpha )</th>
<th>( x_h )</th>
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<tbody>
<tr>
<td>Wing</td>
<td>-28.55%</td>
<td>-32.112%</td>
</tr>
<tr>
<td>Wing-Fuselage</td>
<td>-29.2%</td>
<td>-34.1%</td>
</tr>
</tbody>
</table>
From the results shown in Table 1, a wing alone design will not be stable as the center of height will always be at the aft of center of pitch hence violating condition (8).

As a result, a horizontal tail needs to be designed to provide the condition of longitudinal stability by shifting the center of pitch downstream such that condition (8) will be met. Also, by placing the horizontal tail high up such that it is out of ground effect, the value of $C_{mh}$ and $CL_h$ is theoretically unmodified as a result $x_h$ remains in the same position. Therefore to achieve condition (8), the $C_{m\alpha}$ value will have to be modified.

**Table. 2.** Aerodynamic centers of pitch with x directed upstream of wing of chord length $c = 0.4m$.

<table>
<thead>
<tr>
<th></th>
<th>$C_{m\alpha}$ at x/c = 0.3</th>
<th>$x_{n}$ with ref to x/c = 0.3</th>
<th>$x_{n}$ with ref to leading edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing-Fuselage</td>
<td>0.1854</td>
<td>1.90%</td>
<td>-28.10%</td>
</tr>
<tr>
<td>Wing-Fuselage-Tail</td>
<td>-1.1579</td>
<td>-30%</td>
<td>-50%</td>
</tr>
</tbody>
</table>

Based on the condition given by equation (3), the horizontal tail has to be design to ensure the pitching moment characteristic of the whole craft meet the requirements given in (3). Therefore by fixing the C.G, the required moment characteristic for the tail can be chosen. With the C.G position slightly aft (30% of wing chord) of the center of pitch, the moment characteristic curve of the wings-fuselage configuration, $C_{mwf}$, is plotted (Fig. 9). From equation (1), the center of pitch is dependent on the value of $C_{m\alpha}$ hence in order to shift the center of pitch further downstream until condition (8) is met, the $C_{m\alpha}$ of the entire craft is then chosen to meet the condition as shown in Table 2. From Lift curve obtained in Fig. 7b, the trimmed condition chosen at 3 degrees of angle of attack as flow separates beyond 5 degrees. With the trimmed angle fixed, $C_{m0}$ of the entire craft will
also be determined. Therefore with the moment characteristic curve of the entire craft, $C_{\text{mwf}}$, known, the tail moment characteristic curve can be simply obtain by the following relation \(^2\):

$$C_{\text{mwf}} + C_{\text{mt}} = C_{\text{mwt}}$$  \hspace{1cm} (9)

The moment characteristic curves of $C_{\text{mwf}}$, $C_{\text{mt}}$ & $C_{\text{mwt}}$ are all plotted in Fig. 10.

\textbf{Fig. 10.} Moment characteristic curves.

5.3 Preliminary Flight Test Results

From the first flight test (Fig. 11), the craft was unable to take off due to insufficient lift and speed. The large gap between the wing and the water surface has made the PAR ineffective which results in loss of lift. The large wetted area due to the submerged fuselage greatly increases the hydrodynamic drag that requires even much more thrust to overcome.
Fig. 11. WIG craft during the first flight test.

Fig. 12. WIG craft skimming above water surface.

Slight modification was made for subsequent tests (Fig. 12). The wing was lowered to reduce the height and the fuselage was raised higher from the water surface. This greatly improves the performance of the craft because the wetted surface was reduced and the thrusts are able to produce sufficient speed for lift off. Simultaneously, with the wings closer the water surface, the ramming effect is now greater since the gap is now minimized which results in higher static pressure generated beneath the wings. Despite
that the only static stability is taken into account in the design, the craft is seems to possess both static and dynamic stability in the longitudinal and lateral direction.

6. Conclusion

In design of small scale flying vehicle, the viscous effect due to the lower operating Reynolds’s number has made the traditional analytical methods inapplicable. However, with the current development in CFD codes, the viscous effect is taken into account during the analysis. As much of the parameters are optimized based on computational results, not much modification is needed and the iterative process in design is greatly reduce. Furthermore, the results from the flight tests has validated the data obtained from simulations as the craft is seen to perform as expected.

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References


