Computational analysis of aerodynamic characteristics for wing in ground effect craft in lateral stability

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Abstract. Wing in-ground effect (WIG) crafts are becoming promising transportation over the last decade. However, stability and control problems faced by the WIG in earlier development are still unresolved. This paper objectively investigates the lateral stability of wing in ground effect craft. The wing encompasses a winglet at the end of the wingtip. Lift, drag and pressure were measured with the respect of the heeling angle of 10°, 15° and 20°, respectively, with the h/c of 0.3. Initial results from the computational studies show that the ground effect pressure distributions provide a natural righting moment when the WIG craft heels near ground. This initial result provides an insight to understand the current state of knowledge of stability for WIG, particularly on transverse or lateral stability of WIG where it plays important roles in the safety aspect. It is crucial to understand the stability and its component in order to avoid any unforeseen accident. This paper discusses the results obtained from the numerical studies.

1. Introduction
The dynamic behaviour of the wing in ground (GIGD) effect is formed significantly by its stability and control properties. Today, WIG tends to be more concerned with wider issues of flying and handling qualities rather than the conventional, which are more on stability and control. WIG craft design faces many challenges in the aspect of aerodynamics. Many studies deal specifically with the ground effect aerodynamics, stability and control, and hydrodynamics. Until this moment, very few researchers have done studies on the lateral stability of WIG [1, 2, 3]. To date, surprisingly this topic has not yet been comprehensively studied and there is very little (or none) available scientific publication in any readily referenced form.

In recent years, there has been increasing interest in WIG, with the pace of development quickened and the progress evolves dramatically [4]. Nevertheless, the stability and control problems that faced by WIG in earlier development still continue until now. Many researchers study the dynamic stability of WIG during take-off, heave, pitch and surge motions (longitudinal stability) but very few researches conducted on roll, yaw and sway especially during cross wing (transverse and lateral stability). This is very important since WIG is commonly operated over the surface of seawater and in the air. These axes (i.e. roll, yaw and sway) are more common to WIG during the cruise compared to heave, pitch, and surge motion because the wind on the sea surface is more dominant compared to higher altitude.
The effect of lateral stability is still unresolved to date. Lateral-directional stability must be put into consideration in WIG development to ensure that roll of the WIG remains at wings level and the yaw tends to weathercock into the wind when the ailerons and rudder are at their zero or datum position. This way the WIG will naturally seek lateral-directional equilibrium without interference by the pilot and this is crucial because the distance between the WIG and the surface is very narrow, which will result with catastrophic incident if the wing or the body get caught with the surface due to roll.

In lateral condition when a WIG craft is heeled or rolled, the pressure on its lifting surfaces changes and redistributed. At one point, the lifting elements approach the ground while on the other, deviate from it. The coefficient of lift increases for the wing that approaches the ground and decreases for the portion that leaves the ground. This situation causes a generation of recovering transverse moment. Therefore, a WIG craft in lateral aspects has a natural aerodynamic stabilization of roll angle in flight close to the shield, which is an extremely important aspect in flight safety [5]. However, this theory never been studied for WIG in a proper scientific way.

2. Background of the study
A research team has been established in Universiti Teknologi Malaysia (UTM) on the WIG study. The aim of this research is to further investigate WIG at higher speed. Recent studies are focusing on the aerodynamic characteristics and stability during take-off, cruise and landing. This includes various variables such as angle of attack, with or without endplate, with or without wing tip, single hull and multi hull. Lift and drag data has been discussed in detail in previous studies [6, 7, 8, 9]. The previous studies are focusing only on the longitudinal stability. Hence, there is a need to extend the study on the transverse or lateral stability because its consequences is important and the fact that it is understudied is indeed a cause for concern.

3. Model
A numerical calculation on longitudinal analysis of a single hull WIG, equipped with the endplate, is performed on available UTM model. Several modifications have been done to the model. The profile for the wing root is changed to NACA 4415. It has been decided also to set the profile of the wing tip with NACA 6409 and, at the wing tip, the aerofoil's anhedral angle is set to be 13 degrees as shown in Figure 1. The wings tip is using NACA 6409. The overall design is adopted from previous model [6, 7, 9]. The detailed dimensions of the model are tabulated in Table 1.

![Figure 1. Initial wing design](Image)

| Parameter     | Units   |
|---------------|---------|
| Wing span     | 166.8 mm|
| Wing root chord | 112.35 mm|
| Middle wing span | 83.4 mm|
| Aspect ratio | 1.48    |
| Anhedral angle      | 13 degree|

4. Validation
There are two main parts in this study. The first is a CFD simulation and it is followed by wind tunnel experiment. For the simulation, the data was verified with the experimental data obtained previously. The results showed a consistent trend between the simulation and the experiment. The slope of lift and drag coefficients are presented in Figure 2 and Figure 3, respectively. The comparison showed that both lift and drag coefficients obtained from the simulation are higher than those from the wind tunnel experiments.
Figure 2. Lift coefficient vs h/s

Figure 3. Drag coefficient vs h/s
5. Numerical

The analysis is carried out by solving the incompressible Reynolds average Navier Stokes equations and realizable k-ε turbulence model using FLUENT. The Reynolds number is 1.2 x 10^6 (based on the chord length, c) with the given velocity is 25 m/s. For incompressible flow, the governing equations (continuity and momentum) are solved by coupling method of two variables, which are pressure and velocity. The Semi-Implicit Method for Pressure Linked Equations (SIMPLE) will be used to achieve the objective. The governing equations are written as:

\[
\rho \left( \frac{\partial u_i}{\partial x_i} + u_i \frac{\partial u_i}{\partial x_i} \right) = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial}{\partial x_i} \left( \frac{\partial u_i}{\partial x_i} + \frac{\partial u_j}{\partial x_j} \right) + S_M
\]

Equation 1 is known as the Navier-Stokes equation for incompressible fluid flow, where \( S_M \) is a source term that is used to include the smaller contributions to the viscous stress term by the second viscosity coefficient as well as the body force. The derivation of energy equation involves the balance calculations such as those performed for the momentum equation. The internal energy equation of incompressible fluid flow is given as:

\[
\rho \left( \frac{\partial l}{\partial t} + (V.N)l \right) = -p \nabla V + k(\nabla \nabla T) + \Phi + S_l
\]

The left hand side of Equation 2 is the rate of change of energy embodied by the local and convective derivatives of internal energy, \( l = h - \frac{P}{\rho} \). At the right hand side, it consists of the rate of work done on the fluid element by pressure forces, net rate of heat transfer to the fluid element, viscous dissipation term and source term, respectively.

6. Boundary condition

In this case, it is assumed zero relative velocity between the surface and the fluid. Thus the non-slip condition is applied on the model surface. The velocity perpendicular to the wall is zero because it is finite and tangent to the wall. In any case, if there is no friction between the surfaces, then the slip condition will apply. The boundary conditions that are set are:

- **Velocity inlet.** The inlet velocity is specified directly. However, the program will extrapolate the pressure from the adjacent cells using reconstruction gradients.
- **Pressure outlet.** The boundary pressure is specified but the boundary face velocity is extrapolated from the interior cells using reconstruction gradient.
- **Wall.** The surface of the wing profile is considered no-slip wall. The pressure is extrapolated from the adjacent cell using reconstruction gradients. The roughness of the wall is set as smooth.
- At inlet, the velocity is prescribed to be a uniform velocity. The ground is considered to be rigid and has same velocity as inlet.

7. Grid sensitivity validation and mesh quality

Table 2 shows the specifications of different grids used in grid sensitivity. The qualities of meshes are in good condition as they have a lower number of skewness and high number of orthogonal quality. Figure 4 shows the pressure coefficient distribution on the lower surfaces of the airfoil as computed by the three grids. Grid B and C have the same result and good agreement but the latter one required less time. Therefore, Grid C has been chosen to conduct the analysis presented hereafter.

| Grid | No. of cells | Growth rate | Aspect ratio | Skewness | Orthogonal quality |
|------|--------------|-------------|--------------|----------|-------------------|
| A    | 2038301      | 1.1         | 1.8225       | 0.2188   | 0.8645            |
| B    | 2746814      | 1.1         | 1.8232       | 0.2187   | 0.8644            |
| C    | 3403968      | 1.1         | 1.8235       | 0.2187   | 0.8643            |
8. Results and discussions
Pressure coefficient distributions obtained from simulation studies on the upper and lower surfaces are shown in Figure 5 and Figure 6, respectively. Essentially, the results showed that the wing produced significantly higher lift and lower drag. The ground effect was evenly distributed along the wing span and wing chord. The lift was higher at the middle of the wing and decreased at the end of span.

During the unstable or heel condition of the WIG craft, the pressure distribution changed across the wing section. As the wing was located closer to the ground, the effect was higher on the wing (in this case, it was lift coefficient). The effect of in ground was more prominent on the descending section of the wing that was approaching the ground. This pressure generated a natural righting moment on the WIG craft as depicted in Figure 5 and Figure 6. Nonlinear pressure distribution on the wing between the rise and descending sides basically cancelled and balanced each other until it was in equilibrium condition since the righting moment react with the increases of lift due the heeling angle.

![Figure 4. Pressure distribution on the wing during heeling angle](image)

![Figure 5. Pressure distribution top wingspan, the negative Z referring to the descending side](image)
The anhedral increases lift pressure and forbids flow from escaping under the wing section easily to keep the pressure high. The effect of anhedral is quite similar to endplate as discussed scientifically [3, 10, 11]. The comparison on anhedral lift distribution during descending side at different heeling angle is shown in Figure 7. The vertical lift is increased with increment of heeling angle. It can be observed also that the anhedral angle and winglet further improved the lift increment. Furthermore, the righting moment was induced due to the lift pressure during descending side of the wing. In midsection area, not much different on the pressure distribution as shown in Figure 8, except at heeling angle 20°. At this test condition, the pressure shows a slight increase in lift pressure. Several important observations can be seen in Figure 9. Simulation results show that the winglet has reduced vortex formation on the upper surface and increase the lift coefficient.
Figure 8. Midsection pressure distribution comparison for different heel angle

Figure 9. Winglet pressure distribution comparison for different heel angle

Pressure distributions of the upper and lower surfaces are shown in Figure 10. The results show that the descending side induced more pressure, particularly at 20° heel (close to the ground). WIG experienced an increase in vertical lift when heeling in ground effect. The situation is different from aircraft stability where heeling will decrease the vertical lift of the plane in air. Therefore, this means it requires less control to overcome the righting motion because of the existing natural righting moment. Another observation from the results shows the side force may be induced on the WIG craft. The pressure distribution on the descending side was higher compared to that on the rising side. It also had a tendency from a leak of high pressure downwash to the lower pressure on the outer surface pressure that will further increase a side force. More experimental data from the wing tunnel testing is required to verify this hypothesis.
The operation of the WIG craft that is close to the ground at high speed requires a good stability in both longitudinal and lateral directions. In some cases, the stability of the WIG is improved by using a complex automatic height control system [12]. However, the design of this system is complicated as it requires information on environmental conditions that varies and uncertain. On the other hand, if such system is not available onboard the craft, the pilots must maintain the stability of the craft manually, and that will put extra cautions that will lead to their fatigue for a long flight duration. Thus, with the improvement of the design, the safety of the WIG can be assured with the natural righting moment can be an advantage of the in ground effect.
9. Conclusion
The research is driven by the importance of understanding the lateral stability of WIG. The simulation has been carried out to study the effect of heeling angle on lateral stability. The results show that the ground effect increases vertical lift when heeling on the craft's descending side. Thus a natural righting moment is introduced when the WIG approximately close to the ground, where pressure distribution on its lifting surfaces changes and redistributed. Coefficient of lift increases at wing that approaches the ground and decreases for the portion that leaves the ground. This situation causes a generation of recovering transverse moment. Therefore, WIG craft in lateral has a natural aerodynamic stabilization of roll angle in flight close to the shield. Because WIG naturally seek lateral-directional equilibrium, the stability can be sustained without interference by the pilot. On the other hand, side force occurs from the effect of different pressure distribution during heeling angle on the surface. To proceed with this study, a model of wind tunnel experiments will be designed and fabricated in the near future. The model will be tested in low-speed wind tunnel at UTM for several testing conditions. Data from this experiment will be compared with the simulation work that has been carried out.

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