Stabilizing Attitude Control For Mobility Of Wing In Ground (WIG) Craft - A Review

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Abstract. Wing in ground crafts development have been rapidly advancing in recent years. The current paper reviews the researches and developments of existing stability control system technology’s development and enhancement for wing in ground effect crafts. The review is critically intended for the development of the control system for two-seater Dragonfly 2, a hoverwing type craft. The current review will commence with the introduction on the theory behind the in ground effect phenomenon on the crafts, its regulations and the types of wing in ground crafts, their advantages and disadvantages, and their stability and control issues. This paper also discusses the available attitude control sys-tems types of wing-in-ground craft (WIG), its experiments, simulations and computational methods done especially on both the longitudinal and lateral motion stability.

Keywords: 2-Seater Hoverwing, Attitude Control, Flight Control, Wing in Ground Craft

1. Introduction

The study of the ground effect phenomenon and the construction of wing –in-ground (WIG) crafts have been going on for over half of a century since the Soviets/Russians proved the concept so dramatically through the Ekranoplan programs of the 1960 – 80’s. A lot of researches are progressing while the present review is being written, which mostly deal with ground effect aerodynamics, maneuverability and hydrodynamics of the WIG crafts. Not until recently, only a few WIG crafts have been certified by International Maritime Organization (IMO) that the said crafts are a ground effect worthy.

Mentioned herewith are two of them, Airfish 8 and WSH-500. In 2010, Lloyd’s Register has certified the 8-seater Airfish 8 (Figure 1-a.) refurbished by Wigetworks Pte. Ltd. of Singapore as the world’s first WIG effect craft to fully surveyed to IMO Rules which the craft is manufactured in Germany and refurbished in Singapore [1]. Wing Ship Technology (WST) of Korea later claimed that their 50-seater WSH-500 (Figure 1-b.) is an A-type WIG which has been fully surveyed during the design and manufactured by Lloyd’s Register and is certified to operate only in ground effect [2-3].

![Fig. 1-a. Airfish 8][4]  ![Fig. 1-b. WSH-500][5]

These highlighted certifications proved that the interests in WIG crafts development are increasing at a very rapid pace and dramatic. These certifications prove that the long outstanding issues and limitations highlighted by The Aeronautical and Maritime Re-search Laboratory such as stability and control, aerodynamics analysis and...
systems, operation of aircraft structures in marine environments, and a relatively high maintenance cost engines and load bearing structures being exposed to corrosion by seawater mist [6] can be resolved with the emerging new researches, developments and technological advancement.

The new millennium witnessed many researches are being studied and papers are being published in the aerodynamic [7] and hydrodynamic [8] stability of WIG crafts, especially during the take-off, heave, pitch and surge motion compared to the transverse and lateral stability that includes the axis roll, yaw and sway attitudes [9]. In addition to dominant wind within the ground effect area of sea level, the ever unstable effect of the wave current [10] is another concern for the instability caused by the aerodynamics of the wing of a smaller sized WIG crafts.

Moving from that point, Department of Aerospace Engineering of Universiti Putra Malaysia (UPM), together with the Centre of Defense Research and Technology (CODRAT) of Universiti Pertahanan Nasional Malaysia (UPNM) are collaborating on an investigation of developing the first ever in Malaysia a 2-seater hover-wing, a Type-A WIG effect craft namely Dragonfly DF-2, a WIG craft that is able to reduce the aerodynamic instability issues during take-off, in-flight, and landing motion. As a part of this investigation, the stability and maneuverability of the WIG craft are going to be the major focus and consideration of this review.

2. The Ground Effect Phenomenon

IMO defines ground effect as “a phenomenon of increase of a lift force and reduction of inductive resistance of a wing approaching a surface” [11]. The boundary of this ground proximity phenomenon is not fixed and it depends on the size, depth and span designs of the WIG craft. Typically, it occurs when a craft is at “an altitude less than the mean chord length of the wing” from sea surface or half of the wing span. Rozhdestvensky [12] defines that ground effect as “an increase of the lift-to-drag ratio of a lifting system at small relative distances from an underlying surface”. Halloran & O’Meara [6] addressed that “in terms of the total pressure of the flow, the additional lift is due to a rise in static pressure under the wing and causes a change to many of the other aerodynamic characteristics of the wing” and this is illustrated in Figure 2. Yun et. al. [13] defines that ground effect is “the enhanced lift force acting on a wing that is travelling close to the ground or water surface, commonly less than one wing chord height” due to higher slow-down of the air trapped between the ground and under wing surfaces which generates greater increase in pressure on the under wing surface.

![Fig. 2: Ground Effect on a Wing](image)

Aircraft pilots generally experience the similar ground effect during the landing mode, where extra lift is gained onto the wing prior to the lower part of the carriage reaches the ground. This phenomenon leads the aircrafts to glide above the runway until the cushion decays after sufficient loss of their speed. This is because the airflow between the aircrafts’ lower part and the ground has been blocked such that the pressure on the under surface of the wing and the lift increases [13]. Furthermore, for a wing operating in ground effect zone, the downwash velocity will be reduced by wing tip vortices, and the induced drag reduced by the wing tip vortex-induced velocity [13] as shown in Figure 3. The ground effect reduces the downwash velocity which causes an increase in the lift and reduces the drag, in conjunction with increasing the effective aspect ratio of the wing. These are the two most important features of WIG crafts.

![Fig. 3: Wingtip vortex difference without (a) and with (b) ground effect](image)
3. WIG Craft Definition, Classifications Regulations and Advantages

Wing in Ground Effect (WIG) term has been officially adopted by the “United Nations’ International Civil Aviation Organization” (ICAO) and the “International Maritime Organization” (IMO) for a marine craft using ground effect as a means of lift [14]. According to IMO, “WIG craft have much in common with aircraft characteristics that in their ground effect zone they are supported only by aerodynamic forces of the wing which enable them to operate at low altitude above the sea water surface without any contact” [11].

Both IMO and ICAO have agreed that for any WIG craft that is capable of sustaining its flight outside of the ground effect zone shall be subjected to the rules and regulations of ICAO [11]. On the other hand, for other crafts which includes the limited “fly-over” capability crafts shall be subjected to the rules and regulations of IMO.

The IMO has categorised WIG craft types as follows in Table 1.

| WIG Category | Crafts Certified Operation                                                                 | Regulatory Authority |
|--------------|-------------------------------------------------------------------------------------------|----------------------|
| Type A       | Within crafts’ ground effect zone of the sea surface                                       | IMO                  |
| Type B       | Momentarily increase crafts’ height beyond ground effect zone but below 150 m above the sea surface | Both IMO and ICAO    |
| Type C       | Beyond crafts’ ground effect zone and surpassing height of 150m above the sea surface     | ICAO                 |

Figure 4 below depicts an interpretation of the classification of a WIG craft.

Fig. 4: The Regulatory Authority of Craft Types [15]

Rozhdestvensky [12] outlined that aerodynamically, WIG craft can be classified with the different configurations depending on the method used to satisfy the requirements of longitudinal stability. Table 2 shows the details of each configuration.

The Safety Committee of IMO in its 76th session has approved the Interim Guidelines of a WIG Craft in 2002 under MSC/Cir. 1054 [11]. The configuration of WIG craft falls between the maritime and aviation regulatory regimes in view of which the Interim Guidelines of a WIG craft were developed. These guidelines were intended for “proper engineering analysis, design and developmental testing to achieve an adherently safe WIG craft to operate within the ground effect”. It is essential to note that WIG craft have much alike with aircraft characteristics, but it operates within the other waterborne vessels’ zone as such the Interim Guidelines of a WIG Craft stated that its operation must comply and use the equivalent “collision avoidance rules” as of the typical shipping rules.

The guidelines were later amended in 2005 for the Wing-in-ground Craft Safety Certificate and Record of Equipment document [16]. In addition to the guidelines, the “Sub-Committee on Standards of Training and Watchkeeping” of IMO has also approved the “General Principles and Recommendations for Knowledge, Skills and Training for Officers On Wing-In-Ground (WIG) Craft Operating in Both Displacement and Ground Effect Modes” in MSC/Cir.1162, focusing to “primarily assist Member governments in developing their national requirements for qualification and certification of officers on a WIG craft operating in both displacement and ground-effect modes” [17].
Table 2: The Configuration of WIG Craft [12]

| WIG Configuration | Main Design Feature | Advantages | Disadvantages | Models Built |
|-------------------|---------------------|------------|---------------|--------------|
| Tandem            | - Adjusted pitch angles design  
                   - Adjusted wing elements design (fore and aft) geometry | - Construction: simple  
                   - Configuration for static stability margin tuning: simple  
                   - Control: throttle (one channel), effective  
                   - Span: small | - Operation mode: ground effect zone (GEZ) only  
                   - Marginal static stability: very sensitive to pitch angle and ground gap combinations | SM-1, Tandem Aerofoil Boat (TAB) |
| Airplane-type wing-tail | - Lower main wing (closer to ground)  
                         - Mounted tail plane (horizontal type) on vertical stabilizer  
                         - Height is stabilizer outside ground effect zone | - Stable craft flight sustainability: good  
                         - Heights and height-pitch combinations range: large  
                         - Power enhancement at take-off: possible to efficient  
                         - High speed (wing loadings are large)  
                         - Turning manoeuvres: efficient (use ‘’hop’’ and banking ability)  
                         - Lift-Drag (L/D) ratio: high  
                         - Stable flight heights and pitch angle range: large  
                         - Capable to do ‘’dynamic jump’’ manoeuvre  
                         - Turning manoeuvres: efficient | - Weight fraction (empty): large  
                         - Weight penalty: very large  
                         - Structural weight: large  
                         Note: (structurally large craft and have large tail unit highly mounted) | Kaspian Monster, Orlyonok, Loon, Strizh, |
| Airplane-type wing-tail (Reverse Delta Planform) | - Used reverse delta planform type for main wing  
                                                  - Tail unit is quite small relative to wing | - Maximum advantage of ground effect (GE) utilisation: efficient  
                                                  - Weight fraction (empty): low | - Power augmentation: absent  
                                                  - Take-off aids: Inefficient  
                                                  - Overpowering | Lippisch-type craft (X-112, X-113, X-114) Airfish craft family, Eska, XTW |
| Flying wing | - Reduced components (not related to increase lift)  
             - Smaller tail (horizontal type) or no tail | - L/D ratio: Higher  
             - Efficiency and range: Higher  
             - Efficiency of the power-augmented take-off: Maximized | - Height-pitch combinations range: low  
             - Flaps control: inefficient | Amphistar Aqua glide WISE KAG-3 |
| Composite wing | - Centro plan wing type with endplates (aspect ratio: small), and side wings (aspect ratio: high)  
                   - Under-wing (profiled to make tail unit smaller) | - | - | Ekranoplan (MPE) |
Many studies have addressed that there are advantages and yet dis-advantages to the operation of a WIG craft. Foremost were its range and payload capabilities. Since the WIG crafts are designed to fly a few meters above water by making use of the ground-effect, they have the technical advantages above traditional airplanes and vessels because they are more energy efficient in their speed range. Compared to conventional marine craft vessels, WIG is significantly faster [6].

Considering the fact that WIG crafts exploit the ground effect zone during their cruise mode rather than cruising on the seawater, it can be easily understood that they have higher lift to drag ratio giving them the potential for greater efficiencies than even aircraft [18,12]. The WIG crafts will achieve an increase in its maximum speed and optimal cruise speed with reduction in drag or increase in lift to drag ratio [6]. According to Yun et. al. [19] the increased lift to drag ratio of WIG crafts due to the sea surface effect may result in they are being more economical compared with aircraft. The ekranoplanes have the ability to carry the payload of a very large weight and overall dimensions at a farther range [18], have better operational cost efficiency than aircraft [6,8,12-13] and offer their passengers better quality services [8] as such the comfort level is as close as to vessels standard once they cruise in the air [18].

Operationally, the WIG crafts have good potential to serve as military crafts for their ability to operate below radar detect ability and near coastal areas [6,12]. Nebylov [18] outlined that WIG crafts have the upper hand on their nonessential of special aerodromes since passengers boarding can be implemented directly in a central part of a seaport and they are also exploitation-safe crafts due to their capability of cruising at a very low altitude and landing on water. Park et. al. [8] stated that WIG crafts consume fewer fuel than other high speed vessels including hydro-foil craft effect and they do not require expensive infrastructure because of their ground effect principle exploit. Rozhdestvensky [12] outlined the classification of WIG crafts highlighting its advantages and disadvantages as in Table 2.

Apart from the Interim Regulation by IMO in 2002, there is no consensus for longitudinal stability control [7]. By the time the study was made by [20], they indicated that WIG crafts have never reached a satisfactory reception as mainstream marine transport crafts. According to [21], the commercial competitiveness of WIG craft has been weakened by tremendous impact of the maximum price of WIG craft onto its direct operating costs. Aforementioned licenced crafts may not wholly have accepted by the investors for that particular reason, but others are still intended for hobbyist, demonstrators or test flight crafts. Wiriadidjaja et. al. [7] claimed that system life cycle model of WIG craft is stagnant at the infant development, still has not evolved to its crawling stage, but rather a mere conceptual development stage.

4. The Importance of WIG Stability and Attitude Control and Issues

Many studies have been focusing on the WIG craft stability in specific areas during its take-off, cruising in ground effect and landing onto the sea surface recently. The interim guide from the IMO requires that; any due certified WIG craft should have at least controller of suitable design for lateral, longitudinal, and attitude control of the WIG craft [11]. These WIG craft stability controls can be achieved by using “air or water rudders, foils, flaps, propellers or jets which may be steerable, yaw control ports or side thrusters, differential propulsive thrust, variable geometry of the craft or its lift-system components or by a combination of these devices” [11].

In addition to the recommendations, IMO has also outlined that the on-board officers of a WIG craft must be qualified and certified with adequate training in maritime and aviation knowledge and skills of handling the unique complexity of a WIG craft [17]. These requirements are somewhat general for WIG manufacturers and operators as a pre-requisite safety front for commercial operation to make sure that there is no fatalities and subsequently impair or cap-size the craft [8].

The flights of WIG crafts and their stability control are very challenging as such these issues are the most likely why WIG craft stability-related safety issues is still being studied by many scientists and engineers to solve for in the wake of commercial operation of WIG crafts. Unlike seaplanes, WIG crafts take-off from the sea surface and cruise at a constant gap just a few meters from the sea surface, and of course the significant landing on the sea surface.
The state of sea surfaces is naturally propagating waves in the presence of wind. However, dominant and strong wind may cause significant and rough wave condition on the sea surface [9]. This rough wave condition causes disturbances to the operation of WIG craft, may it be during take-off, cruising flight or landing mode. With the presence of these disturbances, stability problems arise that make safety issues of operating WIG crafts become more delicate to handle. Thus, the operation of the WIG crafts that are close to the sea surface at high speed requires a good stability in both longitudinal and lateral directions [22].

Staufenbiel & Schlichtingt [23] analysed the stability of an aircraft in longitudinal motion during its flight in ground effect and observed that the ground proximity has caused variations in the aircraft’s longitudinal stability that were responsible for significant changes in the landing course, particularly whilst the flare-out manoeuvres. As aforementioned in Table 1 [12] Rozhdestvensky has aerodynamically classified WIG crafts as the different configurations depending on the method used to satisfy the requirements of longitudinal stability. These classification of WIG crafts have their own advantages and disadvantages that affected the longitudinal stability of the crafts.

Disturbances affect the longitudinal stability such that establishing a control system that can stabilize the WIG craft is essential [10]. WIG crafts are concluded to be safely operated when cruising flight is at maximum reliability, as such the trailing edge of the wing do not touch the water surface [24], or the disturbances. The disturbance issues are the non-linear aspects of the aerodynamics of ground effect zone, thus Hahn et. al. [24] considered that advanced control system concepts are highly demanded for to overcome the WIG crafts hindrance for actuators and states.

The hydrodynamic drag during take-off the most significant drag that contributes the problem on resolving the power demand and distance for take-off and landing [25]. Power Augmented Ram (PAR) is one of the devised and tested lifting power scheme that enhances the air cushion under the wing by blowing high pressure air which can give the WIG craft the high lift at low speed they require during take-off and landing. Another essential approach to improve WIG craft performance is using hydrofoil which has similar shape and principle to aerofoil used by aircrafts, particularly to reduce the hydrodynamic drag during the planning mode of the WIG craft and substantially gains speed and lift during take-off [25].

WIG crafts also experience natural aerodynamics roll angle of stability in lateral aspect which is considered as an remarkably significant aspect for safety of their flight [26-27]. In addition, Amir et. al. [9] highlighted that to avoid unforeseen accidentals, a thorough understanding on the transverse or lateral motion stability is crucial and; roll, yaw and sway are typical dynamics to WIG crafts during their flight cruising phase because of the wind on the sea surface is more dominant compared to an altitude higher than the ground effect zone.

5. Significant WIG Crafts Control System De-velopment Regarding Stability and Attitude Control Issues
Detailed submission guidelines can be found on the journal web pages. There are studies done that investigated regarding WIG crafts stability which are going to be reviewed later in this chapter, and Amir et. al. [22], Kornev & Matveev [26] and Divitiis [28], to name a few, are studies that have been done in term of attitude control of a WIG craft. Successful WIG craft models have been running their trials all over the world for years, yet commercialisation is still at halt. This situation is portraying a somewhat grey impression towards the possibility of the craft could finally accepted by the marine industry players. Safety, among the reasons, is the key factor that needs special attention Park et. al. [8] to convince the marine industry players to invest in its customer attraction.

From a safety viewpoint, it is necessary to avoid accidentals and crashes. While performing a banked turn, the risk of the wingtip of a WIG craft touching the ground surface is very high. Kornev & Matveev [26] highlighted that depending on the roll angle, the WIG craft gains additional aerodynamic forces and moments while per-forming a banked turn at the ground proximity. This manoeuvre must be performed with a limited roll angle at a safe height between the wingtip and the sea surface to avoid the touchdown risk. This limits the manoeuvrability of the WIG craft as it demands a very large turning
radius [26]. This phenomenon has been investigated by Divitiis [28] that the computational analysis for the banked turn explained the behaviour observed in ground effect, while the stability analysis provides clarification about the flying characteristics with appropriate respect to the spiral mode stability and oscillating rolling mode nature.

Wave disturbances are another safety concern which are very hard to predict thus lead to number studies were conducted either experimental or by simulation. Nebylov et. al. [10] in their research have found the effective way of minimising the wave disturbance problem by optimising the landing approach direction of WIG crafts in relation to a general direction of sea waves’ propagation, and have developed technology application which made the operation of WIG crafts on all-weather conditions allowable. Therefore, Nebylov et.al. [10] suggested that during landing, the distinct function of minimising mechanical loadings would accomplish the coordination control of all steering-related structure.

In another paper a year later, Nebylov & Nebylov, [29] discovered “the laws for change of all rudders positions” as such that “the pitch angle and engines thrust should be adhered to the most probable time of landing of the first contact between WIG craft and the disturbed sea surface”. They elaborated that all steering related structures of the WIG craft shall be coordinated by an on board control system as such the information of sea waves properties can be obtained prior to landing as shown in Figure 5. They suggested that all flaps and elevator shall be implemented foremost [29].

![Fig. 5](image)

**Fig. 5:** The proposed “Law of Height Change in The Final Stage of Landing” by [29]

As it been known that the ground effect action is the most significant when the WIG flight is at an altitude of less than the mean of the wing chord as presented in Figure 6. Thus, the possibility of the action at the limited height of sea waves is dependent a particular size of WIG craft. In order to fulfil the safety of flight at a certain permissible height of sea wave’s criterion, it is imperative to select the flight at an extremely low altitude. Daniel [30] suggested that automatic height control system establishment can assure the functional characteristics required for rough sea circumstances even though if the craft has the ability to perform altitude and angle inclination self-positioning naturally, and its necessity to provide good flight stability in the case of overcoming the essential longitudinal plane motion instability of particularly WIG crafts.
To achieve a safe low altitude flight, a particular Lift-to-Drag ratio and stable flight are required. Daniel [30] implemented a control system that has the capability to automatically maintain the WIG craft at an ideal flying altitude as his objective. He adopted the concept of a system that can take control the elevator along with ability to rectify the flying altitude while in the initial take off until the craft reached its mean chord height and maintain it there whilst providing accurate flight altitude data. As compared to aircraft monitoring system, this significant insight sets a new standard for operating WIG craft that requires various hardware components such as actuators and sensors, algorithm control logic programming and the flight motion dynamics understanding as illustrated in Figure 7.

It is worth noted that the aforementioned findings have been updated and there are two concepts established by Nebylov et. al. [31]. Firstly, during its flight, a WIG Craft can be stabilised with respect to the average level of disturbed sea (Figure 8-a) and the craft flies in a straight path above the crests of waves with a clearance margin of $\Delta$. Their insights have the ability to avoid the collision with the wave’s crests even if there are some errors in controlling the motion. They suggested that there is a possibility with a very ideal altitude stabilisation system, reducing the clearance margin can in-crease the craft’s flight efficiency [31].
The stabilisation of altitude of flight in longitudinal plane is slightly easier for the second concept (Figure 8-b). It permits the craft to capture partly the signal from the harmonic disturbance passing through the motion sensor equipped with transfer function capability. The flight is said to be of more effective as the performance of the synchronised phase is much reasonable to acquire from the motion control system of the IWG craft given that it uses the radar powered wave disturbance predictor or estimator [31].

Wang et. al. [32] numerically analysed the design criteria (wing anhedral, winglet, and tail) positioning on a conceptual WIG Craft design. They found out that somehow the aerodynamics efficiency and stability of the craft are effected by the positioning combinations of the design criteria [32]. Therefore, the selection of suitable combination of design criteria would result in compromising the aerodynamic efficiency and stability during the ground effect.

Hydrodynamics and aerodynamics were the major considerations for Yang et. al. [25] whose on their paper proposed the mathematical model for WIG craft in the longitudinal motion. They analysed the equations and criterion for static stability and discovered that the hydrodynamic centre in lift should be located both at the down-stream of the aerodynamic height centre, and the downstream of the WIG craft’s centre of gravity in water. They also suggested that the hydrofoil should be located in front of WIG craft’s centre of gravity to provide the static stability in longitudinal motion during take-off and cruising in ground effect. They also highlighted the aforementioned aerodynamic height centre should be at the upstream of the WIG craft’s aerodynamic pitch centre while cruising in ground proximity region [25]. These insights are very valuable for WIG craft developers as such the knowledge can be useful to analyse as the design phase is concerned.

On the lateral stability of WIG crafts, previous study found that the lateral mode of oscillation for a single wing was stable in both roll and yaw, the latter being subject to fin and endplate configurations [33]. In a computational analysis done by Divitiis [28], the attitude of the flight significantly modifies the lateral stability of the craft. In this lateral state, WIG crafts have natural aerodynamic stability of roll angle in flight ground effect. The effect of heeling angle being subject to NACA 6409 wingtip at 13 degrees anhedral angle resulted that when the WIG craft side heeled over to a precarious angle, the ground effect increases the side’s vertical lift thus pressure distributions provide a natural righting moment when the WIG craft heels near sea water which causes a generation of recovering transverse moment [22].

In compliance with the IMO Interim guidelines, Wiriadidjaja et. al. [7] indicated that the stability augmentation capability features together with an efficient design integrated with an automatic control system of the WIG craft shall result in an inherently safe and reliable aerodynamic features. These
features will also establish accurate flight data for WIG craft navigation management while reducing the pilot's workload.

6. Conclusion
Wing-in-ground and hoverwing crafts development have been rapidly advancing in recent years in terms of stability, mostly longitudinal. The current paper has reviewed the theory for the in-ground effect (IGE) phenomenon on the crafts, regulations and types of WIG crafts, their advantages and disadvantages, previous and recent researches and developments of existing altitude and attitude control technology enhancement for wing-in-ground effect and hoverwing crafts. There are many configurations that can be considered for the WIG effect craft Dragonfly DF2, as such the WIG craft that is able to reduce the aerodynamic instability issues during take-off, in-flight, and landing motion. The insights from the re-viewed paper will be based on the inventing the latest control system suitable for a small WIG especially on the longitudinal and lateral motion stability.

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