

EFFECT OF WINGLET CONFIGURATIONS ON AERODYNAMIC PERFORMANCE OF WING-IN-GROUND CRAFT

Article history

Received: 2 May 2023

Received in revised form:
25 May 2022

Accepted: 28 June 2023

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Published online: 30 June
2023

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ABSTRACT

Wing-in-ground (WIG) craft is a marine vehicle designed to fly over the sea using the interaction between the wings and ground, known as ground effect. WIG has the benefits in terms of cost and operations. However, in spite of these benefits, WIG has weaknesses including the large vortex formed at the wing tip that affect the overall drag and fuel consumption. To compensate these drawback, this study was conducted to investigate a variation of winglet design to increase the performance of the WIG in terms of Lift-to-Drag Ratio (C_L/C_D). Experiments were carried out in the subsonic wind tunnel, Longwin LW-9300R located at Wind Tunnel Lab, Faculty of Engineering UPM. The winglet was investigated using different dihedral angles, which were 30°, 45°, 60°, 85° and 90°. The model was tested in two conditions; without ground as the baseline case and with Ground Effect (GE) condition. In addition, three different winglet heights were also tested. From the results, it was found that the best winglet configuration was $h/c = 0.09$, dihedral angle of $\delta=90^\circ$ and winglet height of $s/c = 0.09$, with an improvement of nearly 65% from the baseline case.

Keywords: *Wing-in-Ground, Winglet, Ground Effect (GE), Aerodynamics Performance, Subsonic Wind Tunnel.*

1.0 INTRODUCTION

WIG craft gives an exchange result to advanced rapidity of ships [1]. WIG is the combination of aircraft and marine craft technologies that provides transportations over water with certain height

limit. WIG has the combined characteristics of aircraft and marine craft. It can fly close to the surface of water at high speed compared to the speed boat.

The ground effect (GE) is a phenomenon in which an object is traveling near to the surface ground and water that causes the lift-to-drag ratio of body to increase. This phenomenon will cause additional lift and reduction of drag due to increase in compression at the bottom of the wing [2]. The bottom pressure of the wing increases, while the pressure on the top decreases. The differential pressure flow difference within high and low surfaces merges together at the the end of the wing, which then forms a vortex that affects the lift-induced-drag. As the wing is stimulated near to the ground, the wingtip vortices are repressed due to the occurrence of the boundary, thus blocking it to fully develop. This boundary forms an amount of downwash, thus reducing induced drag. Additionally, the wing tip vortices are pushed outwards leading to an effective rise in the wing span [3]. Since the ground clearance is diminished, an air cushion starts to grow under the wings due to the rise in static pressure under it, which is known as a ram effect [4]. The high pressure permits the wing to produce more lift while requiring a small angle of attack.

A study on improvising the aerodynamics of WIG craft by employing flow control on hull-fuselage of the craft has been conducted by Said et. al [5]. The study conducted three different configurations on micro-vortex generator as its flow control and successfully showed 25% improvement in drag reduction. However, in another part of its airframe, the winglet was attached to the design of Airfish 8 wing to improve its aerodynamics performance. To avoid any unforeseen accident, it is very important to understand the component and stabilities of WIG craft. A study on the lateral stability of wing in ground effect craft has been done by Amir et al. [6]. From the investigation, it was found that WIG craft in lateral stability has a natural aerodynamic balance of roll angle in flight close to the shield, which can be sustained without any external input from the pilot. As the WIG cruises closer to the the ground, it becomes more longitudinal stable. This is because the pitch down moment coefficient tends to become more negative for both medium movement of ground effect [7]. In addition, theres is an enhanced presence of lift force is due to the different pressure between the top and bottom wing. This cause a resultant upward force produced, which is called lift. Along the wingtip, the relatively high pressure on the bottom is pushed upwards to escape with the lower pressure at the top and forms the vortices.

Interestingly, these vortices can help in improving flow behaviour. For example, Saad et al. [8,9] investigated the shockwave boundary layer interaction effect that was able to be suppressed by bringing the high momentum flow on the vortices from the outer regions towards the wall surface on boundary layer. However, vortex can influence the efficiency of a moving objects as it causes induced drag due to the physical presence. This will increase the fuel consumption of WIG craft when the size of vortex becomes larger. The presence of winglet at the wingtip affects the size of vortices to become smaller, which contributes to the lift force and reduces the induced drag. The presence of winglet also creates a side force, which has a forward component due to the side wash produced from the wing tip circulation. A recent study on the angle of dihedral winglet demonstrated that maximum C_L of 90° dihedral angle, delivers 22% higher compared to the baseline wing [10]. The benefits of modifying dihedral angle was also applied to Unmanned Air Vehicle aircraft on various types of wing performance. A study conducted by Wang achieves a slight reduction in C_D at a dihedral angle of 10° on a NACA2412 type airfoil [11]. In another planform, Sharma modifies the dihedral twist and managed to increase the lift by 10% at the same

time reduces the induced drag by 11% on a Selig 1223 airfoil [12]. On a military perspectives, an optimum dihedral angle of 20° was found proper for low speed cruise mode. Effectively, by decreasing the dihedral to a -90° shape around the horizontal axis plane, high speed mode was able to be achieved [13]. This is more suitable when conducting a mission such as package delivery, and search and rescue applications where weather might be a concern. This shows that the increase in demand on airfoil winglet dihedral design research has been taken a step further to suit the appropriate purposes. [14-17].

From the review of WIG in terms of state of current stability knowledge, there are common agreements on the benefits of winglet. Winglet provides a better performance on canopy lift at upstream, which will give higher nose up moment, lift and aerodynamics efficiency [18]. From this phenomenon, it is justified that the forward component of the lift acts as a thrust force that reduces the induced drag of aircraft by 40% of the total drag in cruise situations and 80-90% total drag in the second climb part situations [19]. Other than aerodynamics performance, winglet configurations has proven to have a increase in fuel efficiency. A study by Kolappan et al. shows a better mile distance benefited by the winglet design attached to variable wing incidence angle. On the highest winglet angle of attack of 75° , the aircraft performs better due to lesser drag especially on the lower incidence angle [20]. These contributed by a partial studies, showing that around 7% of reduction on the wing drag has been achieved when using the winglet formations with 2% reduction in fuel weight in the presence of winglet. Although the reduction in fuel consumption was not huge, the aircraft with configuration of winglet will result in about \$2.25 million reduction in fuel cost within a 15 years life cycle of that aircraft (assuming an aircraft utilisation of 3750 hours/year) [21].

However, based on the reviewed studies, none of the work was done on improving aerodynamics flow by investigating the effect of winglet dimensions on the aerodynamic performance of WIG craft. Therefore, this study was carried out to find the best configuration of the winglet to obtain the best result of lift-to-drag coefficient ratio for the wing of WIG craft. The finding in this study will help to improve the efficiency of WIG craft in the future.

2.0 METHODOLOGY

2.1 Wing and Winglet

Solidworks was used to design the CAD model of WIG's wing and winglet. The assembly model is depicted in Figure 1. The compound wings consisted of rectangular wing and reverse taper wings with various anhedral angles at the side. The NACA 6409 airfoil section was selected as the section of the compound's wings. The NACA 6409 airfoil section of wing and winglet was fabricated by 3D printer technology. 3D printer consume less material compared to the traditional manufacturing process, which saves material cost. Polylactic Acid (PLA) was selected as a filament since it has a high melting point from 190 to 200 °C and is a common filament used in 3D printing that is available in the market. The principal dimensions of the WIG wing are summarised in Table 1. The fabrication of 3D printed model was achieved using the concept of Fused Deposition Modelling (FDM). The model was fabricated by laying down successive layers of materials until the model was completely finished, which occurred in the additive process. In order to avoid any flow disturbance on the surface of the model, post-processing of fabricated

model was done. To get the smoothest surface, few types of sandpaper were used together with filler to cover to remove uneven and roughness of the surface, which can affect the result output.



Figure 1: Part assembly model of wing and winglet

Table 1: Dimensions of WIG wing

Details	Dimension
Scale Factor	1 : 5
Wing Span	0.11 m
Wing Root Chord, c	0.22 m
Aspect Ratio	0.52

2.2 Ground Plate

The wind tunnel was modified by placing an adjustable flat plate to represent GE in this study. Two ground boundary conditions, which were moving boundary and fixed boundary, have been analysed by Chun and Chang [22] on turbulent flow around two-dimensional WIG. The lift force and moment in their study were not affected by the variety of bottom conditions, while moving bottom would make the drag force simulated greater than that by the fixed one. Therefore, in this study, fixed ground boundary conditions was used by the fabricated plate to create the GE phenomenon. The ground plate was made of polypropylene (PP) plate with the dimensions of $0.29 \text{ m} \times 0.27 \text{ m} \times 0.08 \text{ m}$ as depicted in Figure 2.

The side of the test section is purposely designed with two 8 mm diameter slot to mount additional model structure during test run. Thus, this designed was fully utilized by two M8 size bolt exerted from the test section side exterior to the bottom part of the ground plate. Additionally, metal nuts are firmly tightened together with the ground plate to avoid unwanted vibration. This setup allows the ground plate to be adjusted closer or further distance from the airfoil depending on the intended ground clearance while location of the wing leading edge is fixed at $l = 0.15 \text{ c}$ from the ground plate front tip. Here, the ground plate surface layout covers the entire blowing side of the airfoil. This is to have enough high pressure air cushion built up under the airfoil model [4]. Figure 3 shows the top view schematic diagram with adjustable h/c ground plate inside the wind tunnel test section.

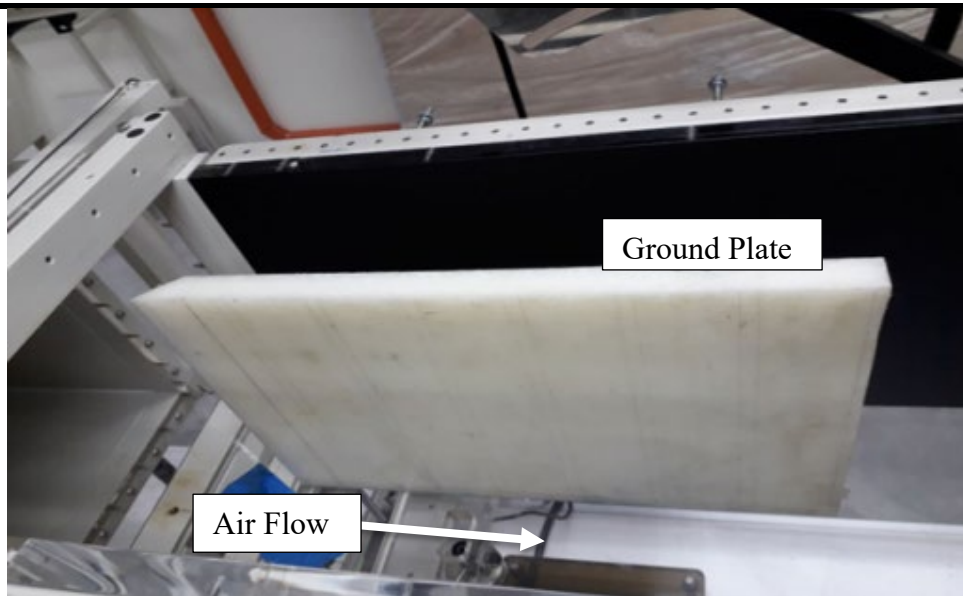


Figure 2: Ground plate in wind tunnel

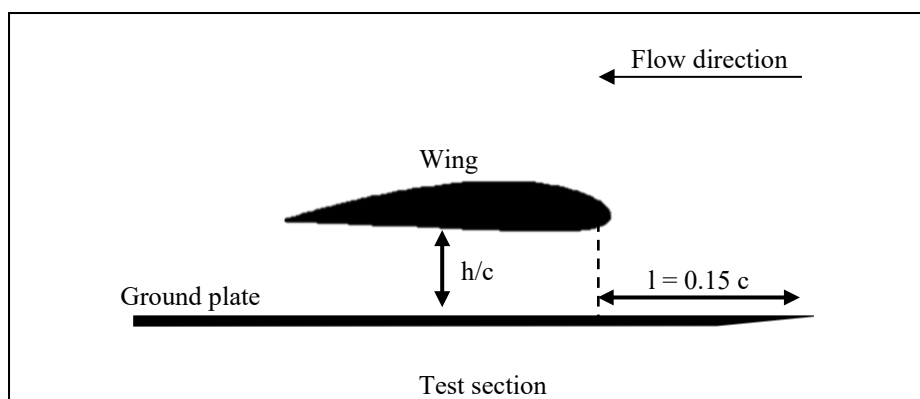


Figure 3: Schematic diagram of wing model setup in the wind tunnel test section (top view)

2.3 Wind Tunnel

The aerodynamics performance in terms of drag coefficient (C_D) and lift coefficient (C_L) of wing WIG craft was investigated in a wind tunnel at Universiti Pertahanan Nasional Malaysia (UPNM) as shown in Figure 4. It is categorised as an open loop suction type wind tunnel. The wind tunnel is able to operate at a maximum speed of 101 m/s. The dimension of the test section is 0.3 m wide, 0.3 m height and 1.0 m long. The test section is made of transparent acrylic material, which allows it to be visible from all sides. Data acquisition system was used to conduct the experiments of lift and drag force measurements, pressure distribution and flow visualisation. The flow inside the wind tunnel covers over 80% of cross section area, flow uniformity of more than 98% and turbulence intensity less than 0.05%.



Figure 4: LW-9300 Wind Tunnel

2.4 Wind Tunnel

In this study, the range of the dihedral angle (δ) and wing configurations without winglet (baseline) were carried out for measuring aerodynamics force. The dihedral angles of 30° , 45° , 60° , 85° and 90° and baseline wing were used in this study as shown in Figure 5. The winglet height was the main parameter investigated measured between span of the wing, s divided by root chord length, c . The height of the winglet was tested at $s/c = 0.05$, 0.07 and 0.09 as shown in Figure 6. The angle of attack, α was fixed in this experiment, which was at 0° . Ground clearance (h/c) is defined as the distance between wing trailing edge centre and ground surface (h) divided by root chord length (c) of the wing. Ground clearance (h/c) for this experiment was used with and without the ground plate. The ground clearance ratio, h/c with the ground plate tested in this study was $h/c = 0.09$, $h/c = 0.14$ and $h/c = 0.18$. Meanwhile, the ground clearance (h/c) without the ground plate in this experiment was 0.5 at a fixed angle of attack (α) of 0° . The α refers to the incoming freestream incoming air flow velocity from the wind tunnel to the reference line on the wing model.

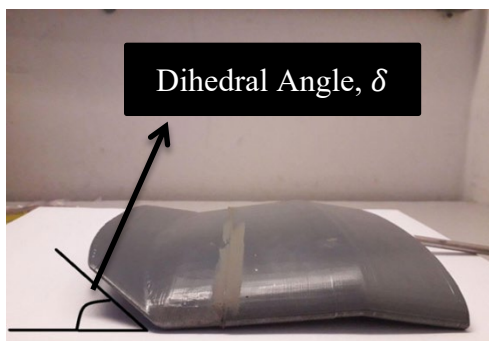


Figure 5: Various dihedral angle, δ

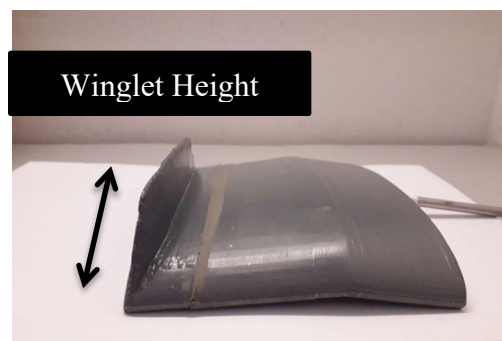


Figure 6: Various winglet height

3.0 RESULTS AND DISCUSSION

This study covers the effects of ground plate, ground height, dihedral angle, δ and winglet height toward aerodynamics performance. The performance was evaluated in terms of C_L , C_D and lift-to-drag coefficient C_L/C_D in various winglet and dihedral angle configurations. The flow velocity was set from 5 m/s to 30 m/s.

The comparison of the lift-to-drag ratio was conducted for the wing WIG with and without GE. For lower ground clearance, which was with GE, the C_L/C_D was enhanced to 17.5% at the maximum speed of 30 m/s. This means that the effective speed was 30 m/s in the GE case. The C_L/C_D of the GE case showed an upward trend when the speed (m/s) increases. The trend proved that C_L/C_D increased when the ground clearance became smaller in the presence of GE as shown in Figure 7. The h/c used for the experiment with ground plate was 0.14, whereas 0.50 without the ground plate. The low C_L/C_D result at the beginning of the experiment, which was -12.39%, was then improved up to 18% at the end of experiment with 30 m/s velocity.

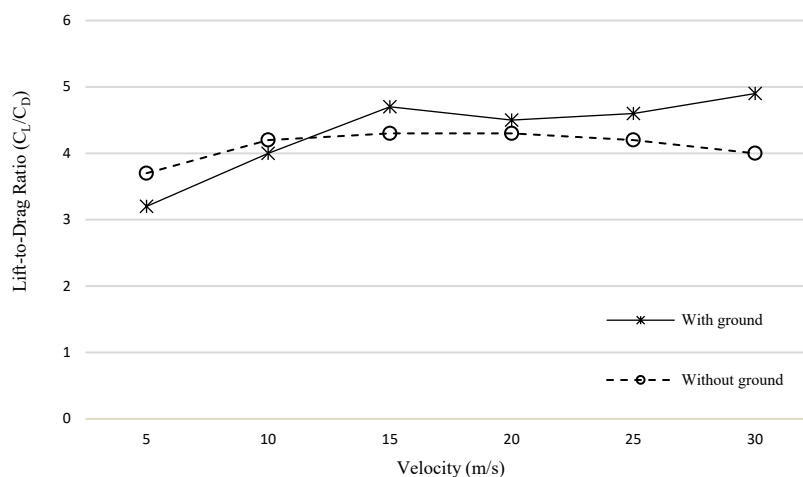


Figure 7: Comparisons on C_L/C_D with and without ground plate

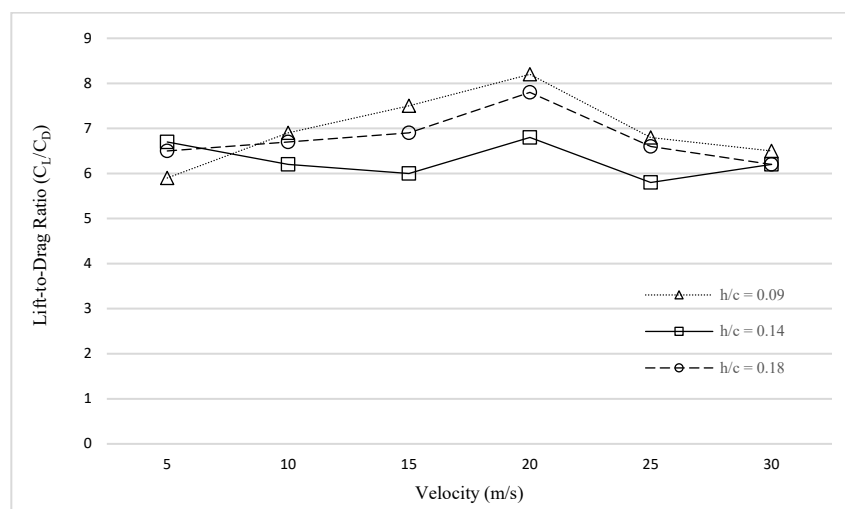


Figure 8: Comparisons on C_L/C_D with different ground heights

The dihedral angle of 85° is the current angle used by Airfish 8 on its wings. From this configuration, the angle of dihedral 85° was selected to be the parameter for comparing C_L/C_D for various ground heights of $h/c = 0.09, 0.14$ and 0.18 . Figure 8 shows the C_L/C_D result to determine the trends among the three different ground heights. The increment in the C_L and the reduction in the C_D resulted in a high ratio indicating the high performance of the WIG craft. The C_L/C_D was dominated by $h/c = 0.09$ compared to other ground heights. However, at 5 m/s speed, the C_L/C_D for $h/c = 0.09$, was found to be the lowest compared to other ground heights. After that, the trend for $h/c = 0.09$, which went up to the maximum C_L/C_D at the speed of 20 m/s. The trend started to decline for all parameters beyond the speed of 20 m/s. When the aircraft flew extremely near to the ground at about $1/4$ of the wingspan, it caused the formation of air cushion due to the compression between the wing and the ground. The lower surface of the wing created a high-pressure region that resulted in the increase in lift. This situation caused an increase in the performance of the WIG craft in terms of C_L/C_D . Average improvement for $h/c = 0.09, 0.14$ and 0.18 showed 63.59%, 51.06% and 61.34% enhancement, respectively. The best ground height for this testing was $h/c = 0.09$ as it showed the highest improvement.

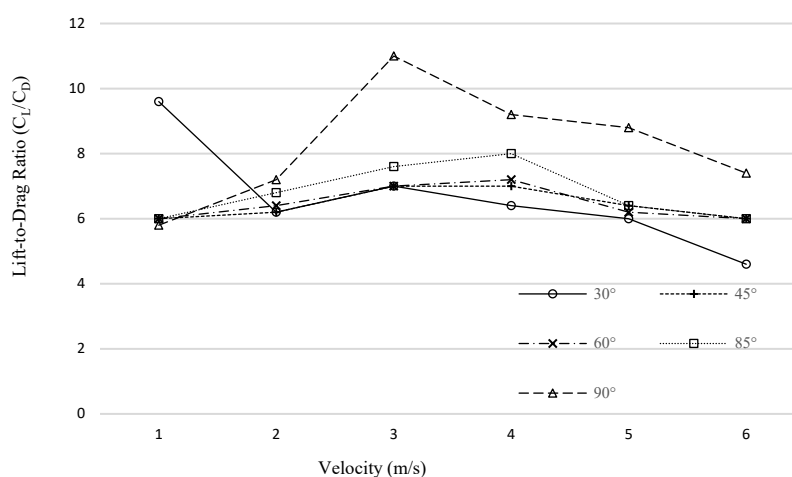


Figure 9: Comparisons on C_L/C_D with different dihedral angle

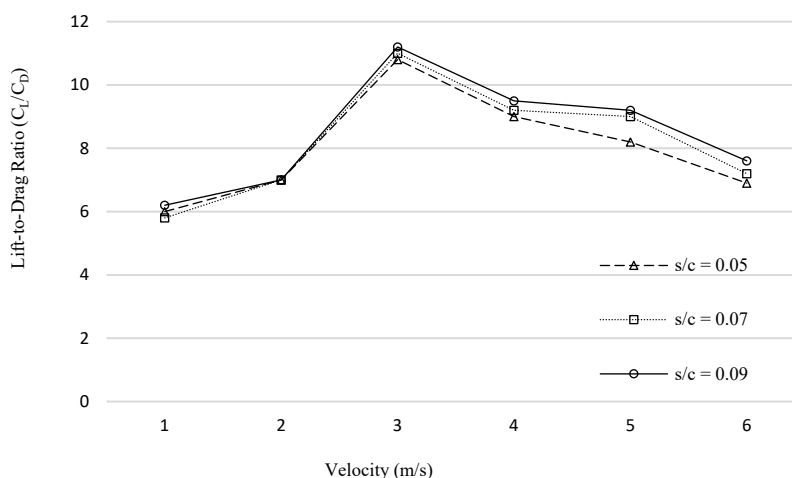


Figure 10: Comparisons on C_L/C_D with different winglet height

Next, various δ of 30° , 45° , 60° , 85° , and 90° , were investigated with a fixed ground height of $h/c = 0.09$. The comparison of the C_L/C_D with various δ is illustrated in Figure 9. Winglet at $\delta=90^\circ$ was found to produce the best C_L/C_D compared to other dihedral angles. The C_L/C_D reached the maximum when the speed achieved 15 m/s. Therefore, a speed of 15 m/s was the ideal and effective speed for the WIG craft with the greatest aerodynamics performance. These various dihedral angles, which were 30° , 45° , 60° , 85° , and 90° , showed a good improvement in lift to drag ratio by 66%, 57%, 55%, 66% and 92%, respectively. From the analysis, 90° of dihedral angle demonstrated the best result in improving aerodynamics performance.

Winglet heights of $s/c = 0.05$, 0.07 and 0.09 were subsequently selected for the comparison of the aerodynamics performance. The WIG craft currently uses winglet height of $s/c = 0.07$ for the wing configurations. The result shown in Figure 10 proved that the winglet height slightly increased the aerodynamics performance. It was found that winglet height of $s/c = 0.09$ increased the lift by around 65% on average compared with that using winglet height of $s/c = 0.05$. From the graph, it can be observed that C_L/C_D for winglet height of $s/c = 0.09$ reached the peak when the speed achieved 15 m/s. C_L/C_D started to decline from the speed of 20 m/s to the maximum speed of 30 m/s. The best aerodynamics improvement for winglet height was $s/c = 0.09$ as it showed an additional of 12% increase in aerodynamic performance against the baseline height.

4.0 CONCLUSIONS

The effect of ground clearance distance, dihedral angle and height of winglet were tested in this study. From the results obtained, the best aerodynamics performance of Wing-in-Ground (WIG) craft has been shown by the lowest ground height, $h/c = 0.09$, dihedral angle of $\delta = 90^\circ$ and winglet height of $s/c = 0.09$. The best effective operating speed was discovered at 15 m/s with 99% enhancement from the baseline result.

Acknowledgement

This research was supported by the Ministry of Higher Education (MOHE) through the funding from UPNM/STFC-NEWTON/2018/TK/01. The authors also want to thank Universiti Pertahanan Nasional Malaysia (UPNM) for sponsoring the project through Graduate Research Assistant Fellowship under PPPI Trust Fund UPNM.

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