Journal of Aeronautics, Astronautics and Aviation, Vol. 57, No. 3S, pp. 815 – 826 (2025)
https://doi.org/10.6125/JoAAA.202503_57(3S).50

Conceptual Design of a New Two-Seater Hoverwing Craft

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ABSTRACT

This paper presents the conceptual design of a new two-seater Hoverwing, a Wing-in-Ground (WIG) craft, developed to advance the capabilities of ground-effect vehicles. The design process adheres to a structured systems engineering approach, utilizing tools such as Affinity Diagrams, Tree Diagrams, FAST Diagrams, and Quality Function Deployment (QFD) to guide development. A Morphological Matrix generated six potential design solutions, refined through Pugh Matrix analysis, with the final design chosen for its optimal aerodynamic performance, especially minimal center of pressure (COP) migration, determined through XFLR5 software simulations. The Hoverwing's mission profile includes personal recreation, coastal transport, and pilot training, offering a versatile platform for various applications. Key specifications include a weight range of 500-600kg, operating speeds between 120-150km/h, a range of 250-300km, and an endurance of 3-4 hours. This design ensures stable and efficient flight in ground effect zones while providing necessary control and stability for pilot training. The final design meets criteria for safety, performance, and fuel efficiency, marking a significant advancement in small-scale WIG craft.

Keywords: WIG craft, center of pressure, design process, systems engineering and pilot training vessel

I. INTRODUCTION

Wing-in-ground-effect (WIG) crafts utilize ground effect—aerodynamic phenomena that allow efficient low-altitude flight, especially over water. By improving the lift-to-drag ratio, WIG crafts achieve increased fuel efficiency and smoother dynamics during takeoff and landing. However, WIG crafts face unique challenges related to stability and control near surfaces, requiring comprehensive design integrating aerodynamic analysis and systems engineering.

This paper outlines the conceptual design of a two-seater Hoverwing WIG craft, fulfilling mission profiles such as personal recreation, coastal transport, and serving as a training platform for WIG pilots. Rooted in **systems engineering**, the design process addresses customer needs, defines functional and performance requirements, and systematically validates each decision against mission objectives.

Key performance parameters for the Hoverwing include an estimated weight of **500-600kg**, an operating speed of **120-150km/h**, a range of **250-300km**, and an endurance of **3-4 hours**. These specifications make the craft suitable for medium-range coastal transport, with sufficient flexibility for pilot training.

Manuscript received, July 31, 2024, final revision, November 26, 2024
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The design process follows the **systems engineering V-model**, progressing from identifying stakeholder needs and requirements through design synthesis, analysis, and verification. Utilizing tools like Affinity Diagrams, Tree Diagrams, and Quality Function Deployment (QFD), the functional and performance requirements were defined. After initial requirements were established, a Morphological Matrix generated six potential solutions, further evaluated through Pugh Matrix analysis. The final design, chosen for its minimal center of pressure migration, was verified through XFLR5 aerodynamic simulations.

These systems engineering approach ensures the Hoverwing meets mission requirements and optimizes efficiency and stability in ground-effect conditions, serving as an ideal platform for **training new pilots** and advancing WIG technology.

WIG crafts are a unique type of aircraft that capitalize on a phenomenon called ground effect to achieve efficient flight close to surfaces like water. This translates to benefits like improved lift-to-drag ratio during takeoff and landing, something familiar to airplane pilots. WIG craft, with their distinct features like large, low-aspect-ratio wings and tail fins [1], have been around since the 1960s [2], with companies like Boeing even exploring their potential for large-scale transport.

However, the development of WIG craft faces significant challenges. Their complex nature requires a systematic approach that combines aerodynamic investigation [3] and system engineering to assess risks and determine viability. Research has focused on enhancing altitude control [4], predicting effect forces, and refining aerodynamics. Initially, commercialization appears more feasible for smaller WIGE craft, whose success could pave the way for larger-scale models in the future [5]. This revised version emphasizes the potential of WIG craft as a niche transportation solution while acknowledging the development and commercialization challenges. It highlights the focus on smaller WIG craft as a potential steppingstone toward broader adoption [6].

This paper presents the advancement of WIG craft by outlining a design process for a two-seater Hoverwing WIG craft. The preliminary design process employs the Four Ws, Affinity Diagram, Tree Diagram, FAST Diagram, and QFD Diagram. A Morphological Matrix was then used to assess potential design solutions, resulting in six design options developed using matrix criteria. The solutions were visualized in sketches, and a final design decision was made using a Pugh Matrix. Based on COP migration analysis conducted with XFLR5 software, Design Solution Three exhibited the lowest COP migration, solidifying it as the optimal choice.

II. DESIGN PROCESS

Table1 shows the Four Ws (Who, What, Where, and Why), which establish the fundamental considerations for WIG craft. Graham Taylor's 2003 [7] study highlighted the significant hydrodynamic challenges WIG crafts face during takeoff, leading to reduced efficiency and increased power consumption, thereby impacting investment and maintenance costs. In 2020, Rattapol Sakornsin et al [8] emphasized the importance of addressing longitudinal stability issues in WIG crafts to enhance safety and facilitate the growth of a new aerospace-marine industry focused on aircraft designed to operate both within and outside ground effect zones.

2.1 AFFINITY DIAGRAM

Figure 1 (the Affinity Diagram) illustrates the relationship between customer requirements and functional requirements. Customer requirements are the features and capabilities that customers expect the Hoverwing craft to possess.

Table 1 Four W (Who, What, Where and Why) to established the fundamental issue of WIG craft

WHO is affected by the problem?	**WHAT** is the problem and how did It arise?	**WHERE** is it worth saving the problem?	**WHY** is it worth solving the problem?
Pilots and passengers	No Commercial Transport like conventional Aircraft	High lift by maximizing the WIG craft payload to accommodate larger amount of seater [7]	New aerospace industry segment for special aircraft which is uniquely designed to operate in the ground effect environment
Company owners and Investors	High Power to take off due to Hydrodynamic drag which affects investment and maintenance cost [7]	Reduced drag by minimizing the operational power requirement of current WIG Craft configuration [9]	Reduce investment and operational Cost
Engineering Development Team	Instability of the WIG craft due to high pressure in ground effect (IGE), when transiting from IGE to out of ground effect (OGE) which cause the WIG craft to back flip and crash	Solve the longitudinal stability issue of WIG Craft [8]	Increase safety

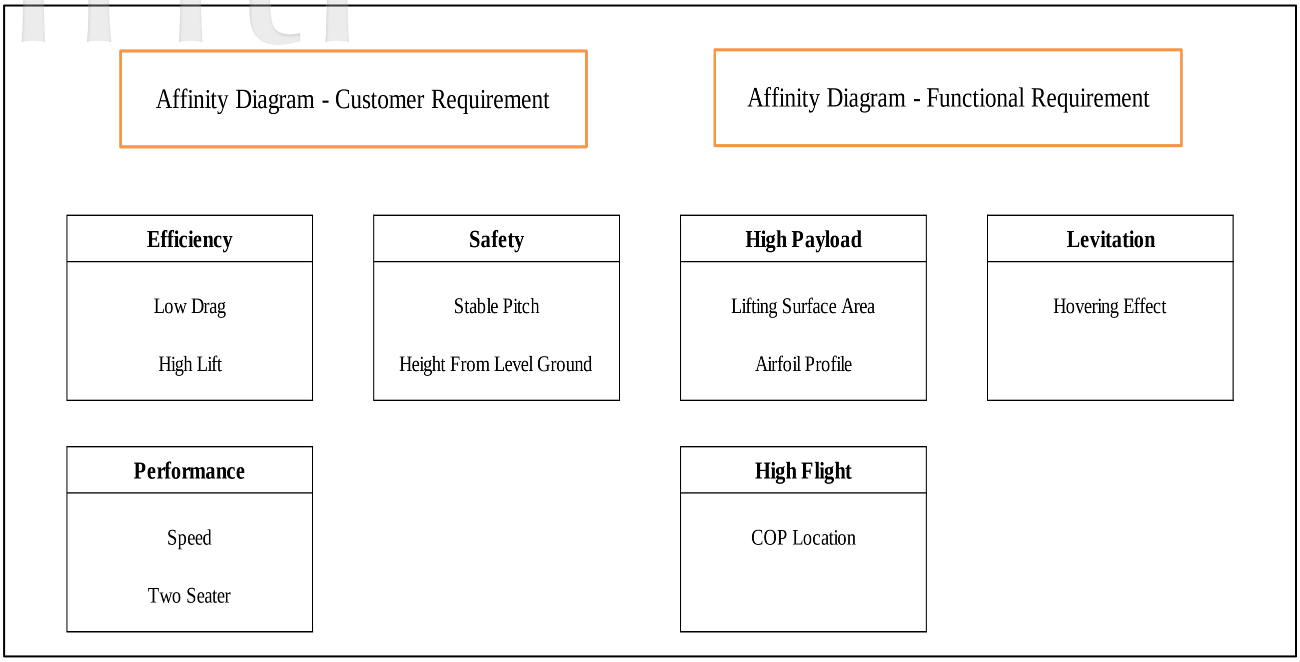


Figure 1 The Affinity Diagram method of two seats Hoverwing Craft

The functional requirements are the technical specifications that the Hoverwing craft must meet to satisfy customer needs. Customer requirements are divided into three categories: efficiency, safety, and performance. Functional requirements, in turn, are organized into three categories: high payload, high buoyancy, and high flight capabilities.

Customers expect the Hoverwing craft to perform well in terms of fuel consumption, space utilization, and safety. To meet these needs, the functional requirements include low drag, high lift, moderate speed, customizable design, stable pitch, and adequate ground clearance. Additionally, customers prioritize operational safety, which is addressed by ensuring stable pitch in the functional specifications.

The Hoverwing craft is also expected to support a high payload capacity. Functional requirements to achieve this include an optimized airfoil profile and sufficient lifting surface area.

2.2 TREE DIAGRAM

The Tree Diagram (Figure 2) illustrates the relationship between customer requirements and functional requirements for the new Hoverwing craft.

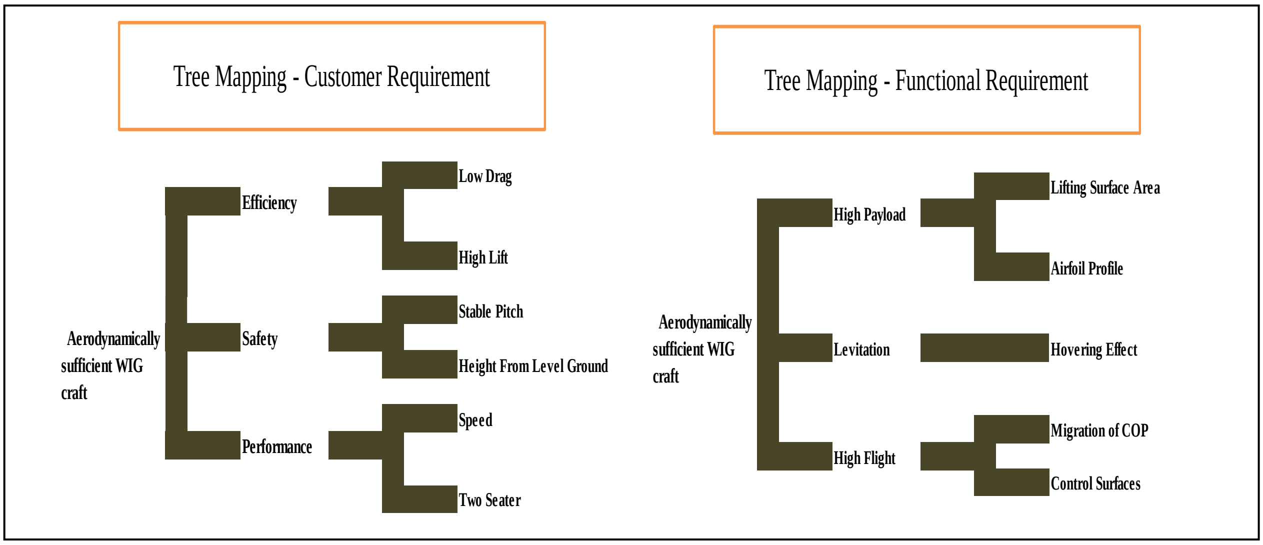


Figure 2 The tree diagram method of Hoverwing Craft

The functional requirements specify the capabilities that the Hoverwing craft must possess. First, the Hoverwing craft must have sufficient lifting surface area to generate the lift required for takeoff and flight.

Additionally, it must be capable of carrying a high payload or weight [10] Fuel efficiency is another critical requirement, which can be achieved with an airfoil profile designed to generate high lift. The craft must also have high buoyancy to float on water and the capability to hover in the air.

In terms of safety, the Hoverwing craft must be stable and safe to operate, achievable through a stable pitch or a low angle of attack [11]. It should also be capable of reaching high speeds. Finally, the Hoverwing craft requires control surfaces to enable maneuverability. Customer requirements include low drag, high lift, high flight capability, and overall performance. The craft should minimize drag to conserve fuel, generate enough lift for takeoff, and be able to reach sufficient altitude to avoid obstacles. Additionally, it should achieve a reasonable operating speed and meet the two-seater requirement for personal use [12].

2.3 FAST DIAGRAM

Figure 3 shows the FAST diagram of the new two-seater Hoverwing craft, illustrating how the different components work together to achieve its desired functions.

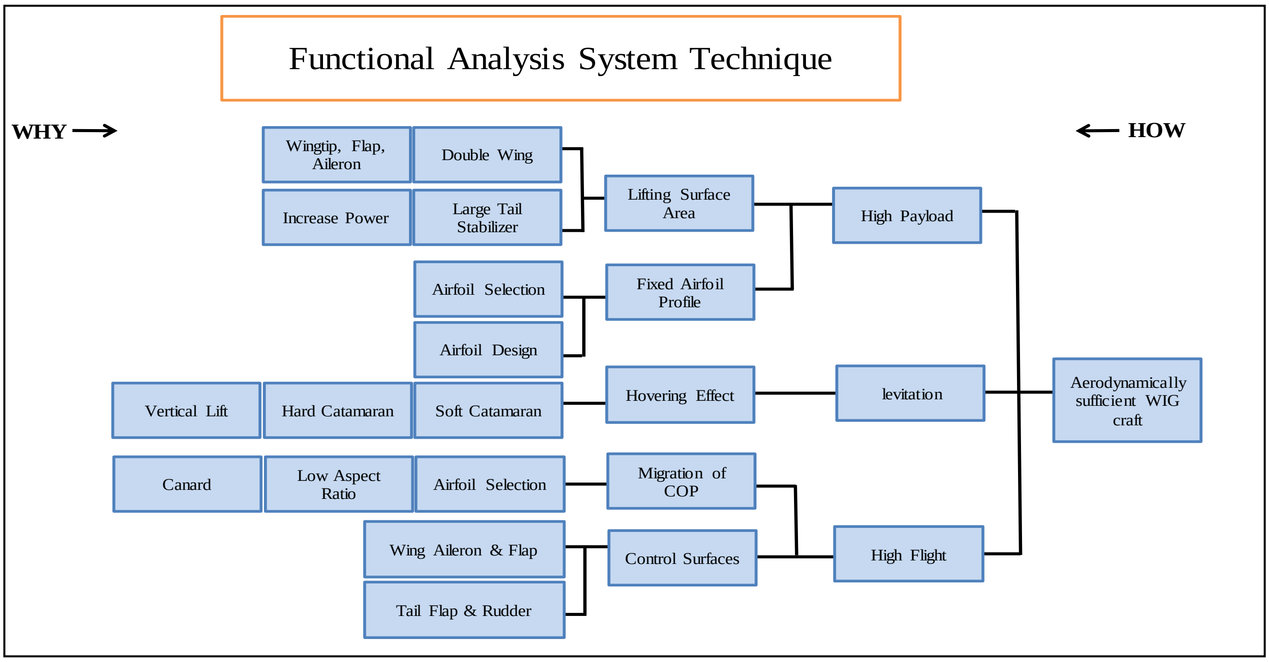


Figure 3 The Functional Analysis System Technique of Hoverwing Craft

The diagram is divided into two main sections: "HOW" and "WHY". In the "WHY" section, elements like wingtip design, double wings, power increase, and a large stabilizer are included to meet the requirement for sufficient lifting surface area. This area, along with a fixed airfoil, supports the need for a high payload capacity, which is a driving factor in the development of a new Hoverwing craft.

In the "HOW" section, achieving a high flight capability in the Hoverwing requires investigating COP migration and optimizing control surfaces. This leads to considerations such as incorporating a canard, selecting a low aspect ratio (AR) [13], and choosing the appropriate airfoil—all necessary for investigating and managing COP migration.

2.4 QUALITY FUNCTION DEPLOYMENT MATRIX

The Quality Function Deployment (QFD) matrix [14] in Figure 4 shows the priority ranking of various customer requirements for a new type of WIG craft, referred to as a Hoverwing craft. These priority ranks are based on the weighted importance score of each requirement, calculated by multiplying the customer importance rating by the technical importance rating. The weights are categorized as 9, 3, and 1, indicating strong, moderate, and weak relationships, respectively.

For example, the relationship between low drag and lifting surface area has a strong rating of 9. While a large wing area is essential for generating lift, it also inherently increases drag. Reducing the wing size can decrease drag but at the expense of lift. Similarly, the relationship between high lift and lifting surface area is rated strong at 9 due to the direct correlation between a larger lifting surface and greater lift generation, as it provides more "real estate" for airflow, leading to a significant lift increase.

The placement of that wing area relative to the center of gravity is more critical. Even a smaller wing can be designed for good stability if the center of lift is positioned correctly. The relationship between height from level ground and lifting surface area in aerodynamics is strong 9 because of ground effect, the presence of the ground alters airflow patterns and can increase lift for aircraft. The effect of lift increment also increased as the lifting surface area increase in ground effect condition. The relationship between aircraft speed and lifting surface area in aerodynamics is weak 1 due to although wing area does influence airspeed for generating lift, but it's not a perfectly proportional relationship While a larger wing area inherently generates more lift, it also creates more drag. To achieve a specific amount of lift at a desired cruise speed, an aircraft with a larger wing area might not need to fly as fast as an aircraft with a smaller wing area.

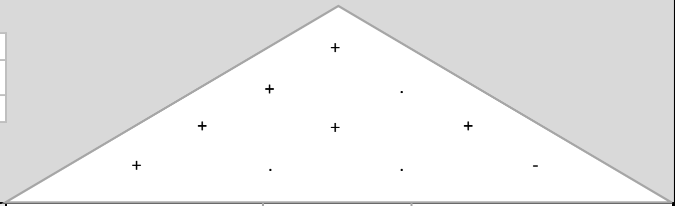
The relationship between stable pitch and lifting surface area is also rated strong at 9 because the wing area plays a key role in pitch stability. However, having a large wing area alone doesn't ensure good pitch stability; the placement of the wing area relative to the center of gravity (CG) is even more critical. Even a smaller wing can achieve good stability if its center of lift is properly positioned.

The relationship between height above ground level and lifting surface area is also rated strong at 9. In ground-effect conditions, proximity to the ground alters airflow patterns, which can increase lift. The lift effect is further enhanced as the lifting surface area increases in ground effect conditions

In contrast, the relationship between aircraft speed and lifting surface area is rated weak at 1. While the wing area does influence airspeed in terms of lift generation, the relationship is not perfectly proportional. Although a larger wing area inherently generates more lift, it also creates additional drag. Consequently, an aircraft with a larger wing area may not need to fly as fast as one with a smaller wing area to achieve the same lift at a desired cruise speed.

Quality Function Deployment

Project title: New Hoverwing Craft
Project leader: Ir.Ahmad Afifi
Date:



Customer importance rating (1: low, 5: high)	Customer Requirements - (What's) ↓	Desired direction of improvement (↑,0,↓) / Functional Requirements (How's) →	Payload ↑: Lifting Surface Area	Payload: Fixed Airfoil Profile	Levitation ↑: Hovering Effect	Flight ↑: Migration of COP	Flight: Control Surfaces
4	Efficiency	Low Drag	9	9	9	9	3
4		High Lift	9	9	3	9	9
5	Safety	Stable Pitch	9	3	1	9	9
5		Height from Level Ground	9	1	1	9	1
2	Performance	Speed	1	3	1	3	3
3		Two Seater	1	1	3	1	1
		Technical importance score	164	98	60	168	104
		Importance %	28%	16%	10%	28%	18%
		Priorities rank	**2**	**4**	**5**	**1**	**3**
		Current performance	High AR	Membrane	Soft Catamaran	?	At Tail
		Target	Low AR	Naca4412	Hard Catamarar	Fixed	At Wing
		Benchmark	Double Wing	Naca4412	Soft Catamaran	.ess Migratior	At Tail

Figure 4 The Quality Function Deployment method of new two seats Hoverwing Craft

The relationship between a two-seater aircraft and lifting surface area in aerodynamics is weak, rated at 1, as passenger capacity is a secondary factor. The number of seats only indirectly influences the weight. A two-seater aircraft can be light enough to fly efficiently with a proportionally smaller wing area than a larger passenger aircraft. There are also many two-seater aircraft designed for heavier occupants or additional cargo, which would require a larger wing area [15].

The relationship between a fixed airfoil profile and low drag is strong, rated at 9. This is because the fixed airfoil profile plays a critical role in determining how much drag an aircraft wing produces. By carefully designing the airfoil shape, engineers can significantly reduce drag and improve the aircraft's overall efficiency. Similarly, the relationship between a fixed airfoil profile and high lift is also strong, rated at 9, as the specific shape of an airfoil directly influences how much lift it can generate. Airfoils are designed to create a pressure difference between the upper and lower surfaces, with the curved upper surface and angled underside working together to create lift.

The relationship between a fixed airfoil profile and how high a WIG craft can fly (altitude) in aerodynamics is weak 1. This is because one of the factors affecting WIG craft altitude from ground level is engine power. A WIG craft needs sufficient engine thrust to overcome drag and climb to altitude. A powerful engine can overcome the limitations of a less-than-optimal airfoil for high altitude flight. The second factor is wing design. While the airfoil profile is a part of wing design, other factors like wing area and aspect ratio also play a role. A large, high aspect ratio wing can help an aircraft achieve higher altitudes by generating more lift at thinner air densities. The third factor is overall weight [16]. A lighter craft requires less lift to overcome gravity and can reach higher altitudes with a given engine and wing configuration. The relationship between a fixed airfoil profile and speed in aerodynamics is moderate, rated at 3, because the fixed airfoil profile plays a partial role in influencing an aircraft's speed capability. The optimal cruising speed for a particular aircraft is determined by the interplay between lift, drag, engine power, and overall aircraft design. The relationship between a fixed airfoil profile and a two-seater requirement in aerodynamics is weak, rated at 1. This is because the fixed airfoil profile is determined by the aircraft's weight and desired performance, rather than by the number of seats. The number of seats is a general classification and does not directly dictate a specific airfoil requirement.

The relationship between hovering effect towards the low drag, high lift, stable pitch, height from ground level, speed and two-seater requirements varies depending on the specific factor. The first comparison (hovering effect and low drag) is strong 9. Hovering inherently requires constant power to maintain lift, which creates drag. Low drag isn't a primary concern for hovering. The second comparison (hovering effect and high lift) is moderate 3. Hovering requires significant lift to counteract gravity and stay airborne. The airfoil profile and flight controls are specifically designed to generate high lift at low airspeeds. The third comparison (hovering effect and stable pitch) is weak 1. While some level of pitch stability is desirable, it's not the most critical factor for hovering. Precise control inputs from the pilot are more important for maintaining a stable hover. The fourth comparison (hovering effect and high from level ground) is weak 1. Hovering can be achieved at various altitudes, but “ground effect" (increased lift due to ground proximity) can be helpful during low-altitude hovering [17], especially for Vertical Takeoff and Landing (VTOL) aircraft. However, hovering doesn't necessitate high altitude. The fifth comparison (hovering effect and speed) is weak 1. Hovering by definition requires minimal forward airspeed. Speed control is crucial for maintaining a stable hover. The final comparison (hovering effect and two-seater requirement) is moderate 3. The ability to hover is independent of the number of seats. Both single-seat and multi-seat VTOL aircraft can achieve hovering flight.

The relationship between migration of COP towards the low drag, high lift, stable pitch, height from ground level, speed and two-seater requirements varies depending on specific context. The first comparison (COP and low drag) is strong 9. Drag is primarily influenced by the overall aircraft design [18] and airspeed. While COP shift can affect control forces, it also has a direct impact on drag such as induced drag. This drag is inherent to generating lift. As an airfoil creates lift, it also creates swirling airflow at the wingtips, which contributes to drag. Minimizing induced drag is a key goal in airfoil design and induced drag is reduced as aircraft transient into in ground effect zone. The second comparison (COP and high lift) is also strong 9. COP migration can directly affect lift. For example, high lift is generated by the design [19] of lifting surface to create more lift than their typical counterparts at a specific angle of attack and this has a significant impact on the migration of COP. This is crucial during takeoff, landing, and maneuvers. The third comparison (COP and stable pitch) is strong 9. This is a key relationship. An aircraft's stability relies on a predictable relationship between the COP location and the center of gravity (CG). If the COP migrates [20] significantly relative to the CG, it can lead to pitching moments that require pilot input or control system adjustments to maintain stable flight. The fourth comparison (COP and height from ground level) is strong 9. COP migration is dependent of altitude. Ground effect can influence airflow patterns near the ground, and it also can directly cause significant COP shift when out of ground effect along with a drastic change in lifting surface angle of attack. The fifth comparison (COP and speed) is moderate 3. Airflow characteristics can influence COP location. At higher speeds, the COP tends to move slightly forward compared to slower speeds. However, wing design and angle of attack play a more significant role in COP location than airspeed itself. The final comparison (COP and two-seater requirement) is weak 1. The number of seats doesn't directly affect COP migration. The aircraft’s overall weight distribution is the primary factor. A two-seater aircraft can be well-balanced with a minimal COP shift, and a larger multi-seater aircraft might experience more prominent COP migration depending on loading configuration.

The relationship between migration of control surfaces [21] towards the low drag, high lift, stable pitch, height from ground level, speed and two-seater requirements varies depending on specific factors. The first relationship (control surfaces and low drag) is moderate 3. Control surfaces like ailerons can be used for drag control to an extent. By adjusting the angle of ailerons slightly, pilots can induce a small amount of asymmetry in lift, which can be used to counter inherent drag caused by other factors like the fuselage or tail design. However, minimizing drag is more about the overall aircraft shape and wing profile. The second relationship (control surfaces and high lift) is strong 9. Control surfaces like flaps and slats are specifically designed to increase lift. By deploying these high-lift devices, the curvature of the wing is effectively increased, allowing for more lift generation at lower airspeeds, particularly during takeoff and landing. The third relationship (control surfaces and stable pitch) is strong 9. Control surfaces like elevators are crucial for maintaining pitch stability. By adjusting the elevator pitch [22], pilots can modify the angle of attack of the horizontal stabilizer, which generates a balancing moment to counteract pitching tendencies caused by wind gusts or maneuvers. The fourth relationship (control surfaces and height from ground level) is weak 1. Control surfaces themselves don't directly affect how high an aircraft flies. Altitude is achieved through a combination of factors like engine thrust, wing design for lift at cruising altitude, and pilot control of airspeed and climb rate. The fifth relationship (control surfaces and speed) moderate 3. While not the primary function, control surfaces can influence airspeed indirectly. Ailerons [23] can be used for slight speed adjustments by inducing drag.

Similarly, trimming the aircraft with elevators can affect overall drag, which can have a secondary effect on airspeed. The final relationship (control surfaces and Two-Seater Requirement) is weak 1. The number of seats on an aircraft doesn't influence the control surfaces themselves. The control surfaces are designed based on the overall aerodynamic properties of the aircraft, including its weight, wing design, and center of gravity location. A two-seater aircraft and a larger aircraft would likely have different sized control surfaces due to their varying weight and aerodynamic needs, but the basic principles of how the control surface function remain the same. Based on exploration of various aerodynamic concepts, it can be concluded that understanding the relationships between an aircraft's design and its flight characteristics is crucial. The top three priorities are low drag, high lift, and stable pitch. These priorities reflect the importance of these factors in ensuring the efficiency, performance, and safety of the crafts. Low drag is essential for the crafts to achieve high speeds and efficiency. Hoverwing crafts operate on the ground effect, which reduces drag, but they still face aerodynamic resistance. By designing the crafts with low drag features, such as a streamlined shape and efficient hovering system, fuel consumption can be reduced and aircraft performance can be improved.

Table 2 The Morphological chart method of two seats Hoverwing Craft

Solution Function	Solution 1	Solution 2	Solution 3	Solution 4	
Lifting Surface Area	Double Wing	Large Tail Stabilizer	Increase Power	Wingtip, Flap, Aileron	
Fixed Airfoil Profile	Airfoil Selection	Airfoil Design			
Hovering Effect	Soft Catamaran	Hard Catamaran	Vertical Lift		
Migration Of COP	Airfoil Selection	Low Aspect Ratio	Canard		
Control Surfaces	Wing Aileron & Flap	Tail Flap & Rudder			
Function	**Lifting Surface Area**	**Fixed Airfoil Profile**	**Hovering Effect**	**Migration Of COP**	**Control Surfaces**
Design Solution 1	Increase Power	Airfoil Design	Vertical Lift	Canard	Tail Flap & Rudder
Design Solution 2	Double Wing	Airfoil Selection	Soft Catamaran	Canard	Tail Flap & Rudder
Design Solution 3	Double Wing	Airfoil Selection	Hard Catamaran	Low Aspect Ratio	Wing Aileron & Flap
Design Solution 4	Wingtip, Flap, Aileron	Airfoil Design	Vertical Lift	Low Aspect Ratio	Wing Aileron & Flap
Design Solution 5	Double Wing	Airfoil Design	Soft Catamaran	Canard	Tail Flap & Rudder
Design Solution 6	Increase Power	Airfoil Selection	Hard Catamaran	Low Aspect Ratio	Wing Aileron & Flap

High lift is also essential for Hoverwing crafts to take off and maintain flight. The crafts operate on the ground effect, which provides additional lift, but they still need to generate enough lift to fly. By designing the crafts with high lift features, such as large wing area and efficient airfoils, required takeoff speed can be reduced and aircraft payload capacity can be increased. Stable pitch is essential for the Hoverwing crafts to maintain safe and controlled flight. The crafts can experience pitch instability due to the ground effect, which can lead to loss of control and crashes.

By designing the crafts with stable pitch characteristics, the risk of pitch instability can be minimized and overall safety can be improved. The other customer requirements, such as two-seater and speed, are also important, but they are not as critical as the top three priorities. This is because two-seater accommodation and speed can be improved to some extent through design optimization, but low drag, high lift, and stable pitch are fundamental requirements that must be met for WIG crafts to be successful.

2.5 MORPHOLOGICAL CHART

The Morphological chart shows in Table 2 indicates the various design solutions for a new type of Hoverwing craft. **Design Solution 1** focuses on maximizing hovering effect and reducing COP migration. The vertical lift design provides a strong ground effect, which allows the Hoverwing craft to fly at very low altitudes, without stalling. The large tail stabilizer helps to keep the Hoverwing craft stable in pitch. The canard [24] helps to reduce COP migration.

Design Solution 2 focuses on reducing wing area and improving efficiency. To improve lifting capacity while minimizing wingspan, this design solution adopts a double-wing configuration (hull and wing), similar to **Design Solutions 3** and **5**. Unlike other design solutions, this approach leverages the hull as an additional lifting surface [25]. Other than that, the soft catamaran hull provides lightweight and flexible concept, which reduces drag. The flap and aileron controls help to improve maneuverability.

Design Solution 3 is similar to **Design Solution 2**, but with a hard catamaran hull. The hard catamaran hull is more structurally rigid, which makes it better suited for rough seas.

Design Solution 4 focuses on improved maneuverability. The low aspect ratio wing reduces drag and increase speed at low speed. The increased power allows the Hoverwing craft to fly at higher speeds. The flap and aileron controls also assist to improve maneuverability.

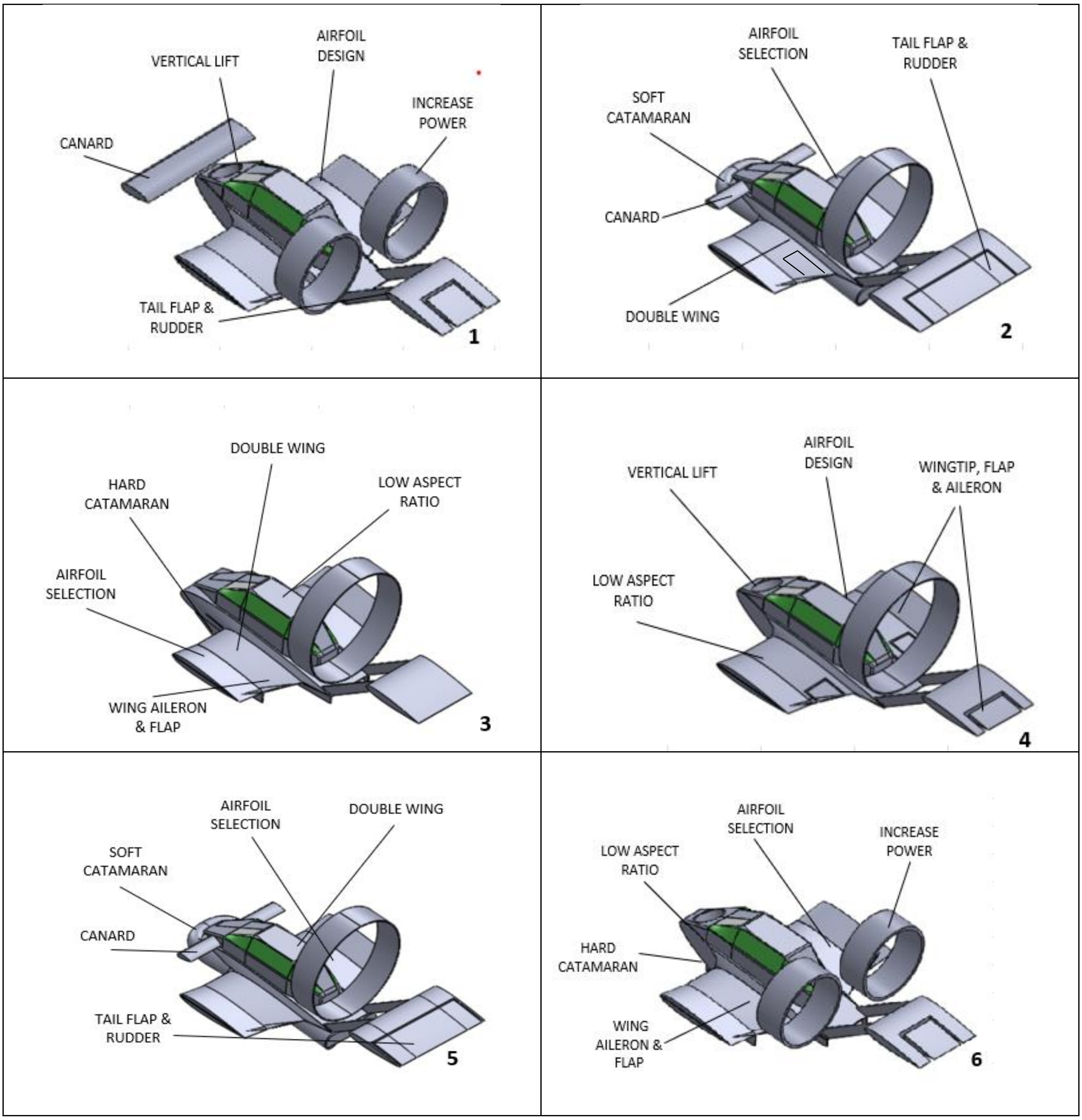


Figure 5 The six design solution concept of Hoverwing Craft derived from morph matrix

Design Solution 5 is similar to **Design Solution 2**, but with a lower wing aspect ratio. The lower wing aspect ratio reduces COP migration and improves longitudinal stability.

Design Solution 6 focuses on reducing structure weight. The hard catamaran hull is lighter than a soft catamaran hull. The reduced structure weight improves performance and efficiency. The best design solution for a new Hoverwing craft will depend on the specific requirements of the application. For example, if the Hoverwing craft is designed for passenger transport, then **Design Solution 1** or **Design Solution 2** may be the best choice. If the Hoverwing craft is designed for cargo transport, then **Design Solution 3** or **Design Solution 4** may be the best choice. If the Hoverwing craft is designed for maritime patrol, then **Design Solution 5** or **Design Solution 6** may be the best choice. Figure 5 shows the design solution conceptual design.

Based on the total scores in the Pugh analysis matrix shown in Figure 6, **Design Solution 3** is the best option, achieving the highest total score of 42, followed by **Design Solution 6** (38), **Design Solution 1** (32), **Design Solution 5** (32), **Design Solution 4** (30), and **Design Solution 2** (-14). **Design Solution 3** scores well across all evaluation criteria except for speed, with the highest ratings in low drag, high lift, stable pitch, and the two-seater requirement.

Design Solution 6 also performs well overall, though it scores slightly lower than **Design Solution 3**, particularly in two-seater requirements. **Design Solution 1** scores well in low drag, high lift, and speed, but has lower ratings in pitch stability and overall performance. **Design Solution 4** performs well in altitude from ground level, high lift, and stable pitch but scores lower in speed and the two-seater requirement. **Design Solution 5** also has strong scores in low drag, high lift, and altitude, but scores lower in speed and pitch stability. **Solution 2** has the lowest total score of -20, with low scores across most evaluation criteria except for low drag.

In summary, **Design Solution 3** emerges as the best option based on the Pugh analysis. It achieves strong scores across all evaluation criteria and stands out as the most balanced and high-performing choice.

Pugh Matrix Hoverwing

Critical Quality	*Weight* *(1 being least important, 10 being most important)*	Design Solution 1	Design Solution 2	Design Solution 3	Design Solution 4	Design Solution 5	Design Solution 6
Low Drag	8	1	1	1	-1	1	1
High Lift	8	1	-1	1	1	1	1
Stable Pitch	10	1	-1	1	1	0	1
Height From Level	10	0	-1	1	1	1	1
Two Seater	6	1	1	1	1	1	1
Speed	4	0	0	0	1	0	-1

Summary Table

Total "1s"	4	2	5	5	4	5
Total "0s"	2	1	1	0	2	0
Total "-1s"	0	3	0	1	0	1
Total	32	-14	42	30	32	38

Figure 6 The PUGH Matrix of Hoverwing Craft

III. ANALYSIS

Figure 7 represents a comparative analysis of COP migration for six different airfoil configurations on a WIG craft using XFLR5 software. As the angle of attack (AOA) increases, all configurations exhibit a general upward trend in COP migration, indicating a rearward shift of the COP. This can influence stability and control surface such as flap and aileron on wing [3]. Among the configurations, Final Iteration N0012 demonstrates the least COP migration, suggesting potential advantages in terms of stability and control. Conversely, Final Iteration AWIG exhibits the most significant COP migration, which could pose challenges in maintaining control at higher AOAs. The remaining configurations (Final Iteration Flat, DHMTU, N4412, and Clark Y) show intermediate levels of COP migration. The choice of airfoil configuration has implications for WIG craft design. Low COP migration configurations may offer enhanced stability and control but potentially compromise lift or increase drag. In contrast, high COP migration configurations could provide higher lift coefficients but require more complex control systems to manage stability.

Figure 8 illustrates the final design selected using the established design methodology. The Final Iteration NACA 0012 airfoil emerged as the preferred choice for the Hoverwing WIG craft design. The wing span is 1.02m, wing area is 0.603m², chord length is 1m, mean aerodynamic chord is 0.705m, the aspect ratio is 1.699, take off velocity is 25m/s, CL is 0.387 and CD is 0.029.

The aspect ratio is within the typical conventional range for WIG [1] is which is from 1.5 to 4. Its superior stability and control characteristics, demonstrated by minimal COP migration across the tested AOA range, significantly contribute to the overall safety and performance of the aircraft. This selection aligns with the design objectives of ensuring reliable and predictable flight behavior, especially in challenging operating conditions. While other configurations offered potential advantages in certain areas, the NACA 0012's balanced performance and robust stability made it the most suitable option for this application.

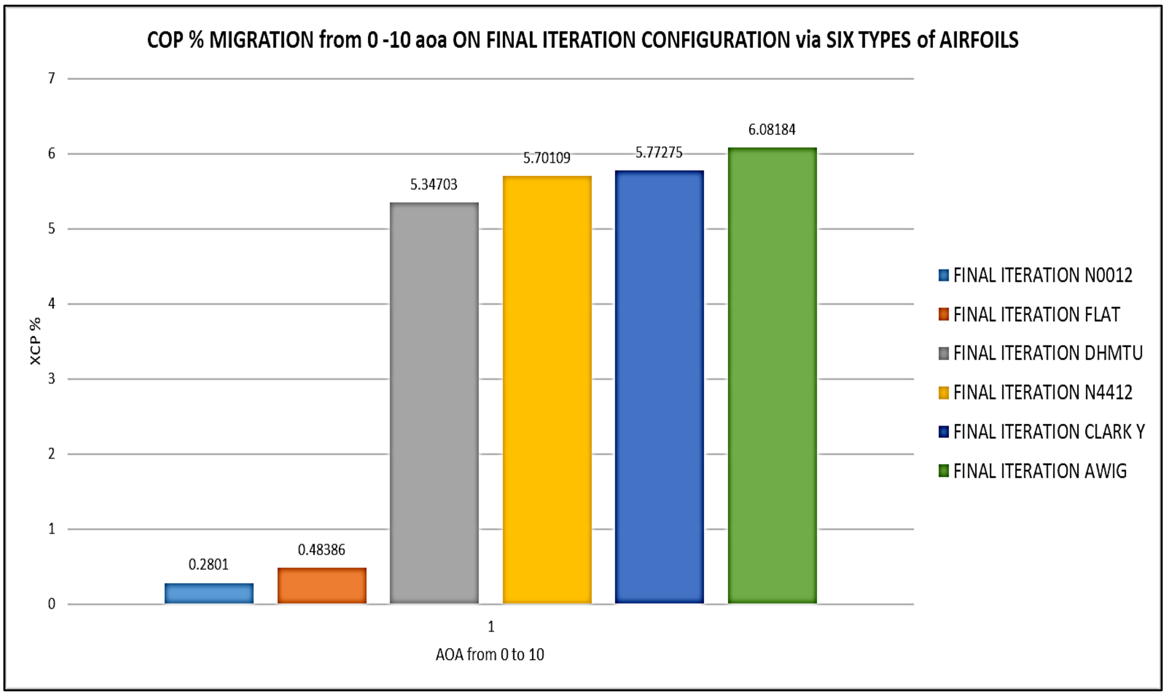


Figure 7 COP migration percentage of the final design selection configurations via six types of airfoils

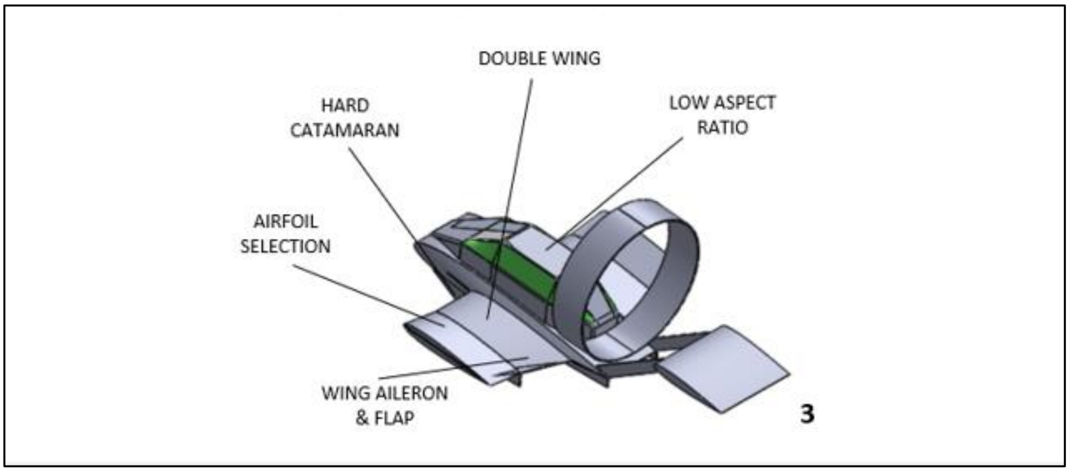


Figure 8 the final design selected using the established design methodology

IV. FINALIZING AND CONCLUSIONS

The methodology outlined previously is a step-by-step process for designing and developing a new two-seater Hoverwing craft. It begins with the design process to determine a suitable design solution for the new two-seater Hoverwing. The initial design stage leverages several tools like the four Ws, Affinity diagrams, Tree diagrams, FAST diagrams, and QFD diagrams to gather ideas and prioritize design goals. A Morphological Matrix helps evaluate different design solutions for the two-seater Hoverwing. This process generates six potential designs based on the established criteria. Sketches are created to visualize these options, and the final design selection is made using a Pugh Matrix for comparative evaluation. Finally, based on the minimum center of pressure migration analysis conducted in XFLR5 software, design solution 3 have the lowest COP migration and further establish the design selection criteria.

The technical specifications of the benchmark model for the current two-seater Hoverwing design are outlined as follows:

- **Weight**: Estimated between **500-600 kg**, ensuring the craft is light enough for efficient ground-effect operation.
- **Operating Speed**: Between **120-150 km/h**, optimized for both recreational use and pilot training.
- **Range**: Approximately **250-300 km**, making it suitable for medium-range coastal transport and extended training sessions.
- **Endurance**: **3-4 hours** at optimal cruising speed, providing sufficient flight time for various mission profiles.
- **Wing Span**: **5.10 meters** with a **15.58 m²** wing area, designed to maximize lift in ground effect.
- **Takeoff Velocity**: **25 m/s**, ensuring quick and efficient takeoffs from both land and water.
- **Airfoil**: NACA 0012, chosen for its minimal center of pressure migration, contributing to stable and predictable flight performance.

These specifications ensure the Hoverwing's functionality as a versatile WIG craft, suited for training pilots, recreational use, and coastal transport.

ACKNOWLEDGMENTS

We are grateful to the industry expert, Ir. Adruin Shazaen Bin Mohd Mustaffa. The WIG craft pilots Major Syed Abdullah and Lt. Kol. (B) Assoc. Prof. Mohamed Tarmizi. The whole design process of the new two-seater hoverwing (WIG) craft was thoroughly discussed with him. Ir. Adruin who is also professional and chartered engineer have many ships and vessel design experiences and tremendous achievement.

We would like to thank Universiti Putra Malaysia and Tan Sri Syed Azman Syed Ibrahim Endowment Fund for supporting and funding this research work under the Geran Penyelidikan Industri (Endowmen Tan Sri Syed Azman) No. 1/2022 [AERODYNAMIC PERFORMANCE ANALYSIS OF GYROCOPTER CHANNEL-WING (GCW) DESIGN].

REFERENCES

[1] Wiriadidjaja S, Mohamad ZH, Mohd Rafie AS, Elhadi M, Fariduzzaman & Hasim F, “Wing-in-ground-effect Craft as a Potential Domestic Transport Vehicle,” AIAA Applied Aerodynamics Conference, 2016. http://dx.doi.org/10.2514/6.2016-3879

[2] Wieselsberger C, “Wing resistance near the ground,” NASA-TM-77, 1922. https://digital.library.unt.edu/ark:/67531/metadc54179/

[3] Pua'at A, Zhahir A, Hamid MFA, Gires E, Ahmad MT, Hassan A, “Center of Pressure Migration Investigation of Different Wing Configuration,” *Journal of Aeronautics, Astronautic and Aviation*, Vol. 54, No. 3, 2022, pp. 261-272. https://doi.org/10.6125/JoAAA.202209_54(3).03

[4] Matdaud Z, Zhahir A, Pua'at A, Hassan A, Ahmad MT, “Stabilizing Attitude Control For Mobility Of Wing In Ground (WIG) Craft – A Review,” *IOP Conference Series: Materials Science and Engineering,* (Southeast Asia Workshop on Aerospace Engineering (SAWAE 2019)), Vol. 642, 012005, 2019, pp. 1-11. https://doi.org/10.1088/1757-899X/642/1/012005

[5] Wiriadidjaja S, Zhahir A, Mohamad ZH, Razali S, Pua'at A, Ahmad MT, “Wing-in-ground-effect craft: A Case Study in Aerodynamics,” *International Journal of Engineering & Technology*, 7, 4.13, 2018, pp. 5-9. https://doi.org/10.14419/ijet.v7i4.13.21319

[6] Pua’at A, Matdaud Z, Zhahir A, Ahmad MT, “Case Study on Aerodynamic Stability of Bixel Wing-In-Ground Effect Craft,” IOP Conference Series: Materials Science and Engineering, (Southeast Asia Workshop on Aerospace Engineering (SAWAE 2019)), Vol. 642, 012001, 2019, pp. 1-14. https://doi.org/10.1088/1757-899X/642/1/012001

[7] Taylor GK, “Are You Missing The Boat? The Ekranoplan In The 21st Century- Its Possibilities And Limitations,” 18th Fast Ferry Conference, Nice, France, 2002, pp. 1-12.

[8] Sakornsin R, Thipyopas C, Atipan S, “Experimental Investigation of the Ground Effect of WIG Craft—NEW1 Model,” Innovation Aviation & Aerospace Industry—International Conference 2020 (IAAI 2020), 2020, pp. 1-6. https://doi.org/10.3390/proceedings2019039017

[9] Yang W, Czysz PA, “WIG craft serves niche transportation needs,” *World Review of Intermodal Transportation Research*, Vol. 3, No. 4, Saint Louis University, 2011, pp. 1-13. https://dx.doi.org/10.1504/WRITR.2011.041720

[10] Placek R, Ruchała P, Stryczniewicz W, “Ground Effect Influence on the Aerodynamic Characteristics of Ultralight High-Wing Aircraft – Wind Tunnel Tests,” *Journal of KONES Powertrain and Transport*, Vol. 24, No. 2, 2017, pp. 183-190. http://dx.doi.org/10.5604/01.3001.0010.2931

[11] Maimun A, Tofa MMB, Ahmed YM, Jamei S, “Aerodynamic Characteristics of a WIG Craft by Numerical Simulation,” International Conference on Marine Technology, Kuala Terengganu, Malaysia, 2012. http://eprints.utm.my/34435/

[12] Lucero A, “Using Affinity Diagrams to Evaluate Interactive Prototypes,” International Federation for Information Processing, J. Abascal et al. (Eds.): INTERACT 2015, Part II, LNCS 9297, 2015, pp. 231-248. https://doi.org/10.1007/978-3-319-22668-2_19

[13] Cadete BJP, Aero-Structural Optimization of Sailplane Wings, [Master's Thesis, Universidade Técnica de Lisboa], 2011. https://fenix.tecnico.ulisboa.pt/downloadFile/3779577986967/BrunoCadete_Thesis.pdf

[14] Chan LK, Wu ML, "Quality Function Deployment: A Comprehensive Review of Its Concepts and Methods," *Quality Engineering*, Vol. 15, No. 1, 2002, pp. 23-35. http://dx.doi.org/10.1081/QEN-120006708

[15] Koh FHA, "Ground Effect on Lift Generating Body," [Master's Thesis, National University of Singapore], 2013. http://scholarbank.nus.edu.sg/handle/10635/47351

[16] Ng DEB, "Structure Design and Analysis for a Small-Scale Wing in Ground (WIG) vehicle," National University of Singapore, 2005.

[17] Hameed H, "The design of a four-seat reverse delta WIG craft," *The Maldives National Journal of Research*, Vol. 7, No. 1, 2019, pp. 7-28. https://doi.org/10.62338/8nsr3z50

[18] Leonhardt E, The Ekranoplan Vehicle Design Project. 2004. http://doi.org/10.18260/1-2--12824

[19] Hiemcke C, "Design of a Wing Section in Ground Effect: Application to High Speed Ground Transportation," [Doctor of Philosophy's Thesis, Iowa State University], 1994. https://doi.org/10.31274/rtd-180813-9737

[20] Wang H, Teo C, Khoo BC, Goh CJ, "Computational Aerodynamics and Flight Stability of Wing-In-Ground (WIG) Craft," *Procedia Engineering*, Vol. 67, 2013, pp. 15-24. https://doi.org/10.1016/j.proeng.2013.12.002

[21] Lee Q, "Stability Control and Performance for an Inverted Delta Wing-In-Ground Effect Aircraft", [Bachelor's Thesis, National University of Singapore], 2006. https://icarushoverwing.files.wordpress.com/2011/05/thesis-2.pdf

[22] Abudaram Y, Stanford B, Ifju Y, "Wind Tunnel Testing of Load-Alleviating Membrane Wings at Low Reynolds Numbers," 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, Orlando, Florida, 2009, pp. 1-16. https://doi.org/10.2514/6.2009-1468

[23] Ko LS, "An Experimental Investigation of the Aerodynamics and Vortex Flowfield of a Reverse Delta Wing," [Doctor of Philosophy's Thesis, McGill University], 2017. https://escholarship.mcgill.ca/downloads/70795b34z.pdf

[24] James D, Collu M, "Aerodynamically Alleviated Marine Vehicle (AAMV): Bridging the Maritime-to-Air Domain," SNAME 13th International Conference on Fast Sea Transportation, Washington, DC, 2015, pp. 1-12. https://doi.org/10.5957/FAST-2015-019

[25] Charles G. Bixel, Jr, "Hovercraft Ground-Effect Vehicle, Patent Number: 5,105,898" U.S. Patent Documents, 1992, pp. 1-11. https://patents.google.com/patent/US5105898A/en