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RESEARCH ARTICLE

Revolutionizing Wing-in-Ground Effect: Investigating Structural Rigidity

Rasidi Ibrahim[1]*, Iffat Syahmi Saroni[1], Aishah Ahmad[1], Zazuli Mohid[1], Chong Bin Hong[2], Razali Abidin[3]

[1]Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Batu Pahat, Johor, Malaysia
[2]HPMT Industries Sdn. Bhd, Taman Perindustrian, Shah Alam, Selangor, Malaysia
[3]Universiti Pertahanan Malaysia, Sungai Besi, Selangor, Malaysia

ABSTRACT - The Wing-in-ground (WIG) effect aircraft utilize the ground effect to maintain flight above water or another surface while minimizing continuous contact with the ground. The propulsion of this aircraft primarily relies on the aerodynamic lift generated by specially designed wings, hulls, or other components that harness the ground effect phenomenon. The problem statement that occurs once conventional boats fail to successfully carry out the mission of intercepting intruders trespassing on national waterways. Due to inherent constraints in watercraft technical standards, existing watercraft technology lacks the power to pursue intruders to their full extent. To further improve the WIG craft operation, we propose enhancing its performance by using materials with better mechanical qualities and optimizing the construction to lower its overall size. These enhancements aim to bolster the WIG craft's capabilities and enable more efficient and effective interception of intruders in water environments. This research aims to investigate structural material qualities suited for WIG effect application and structural rigidity characteristics, with a particular focus on the joining model. In order to accomplish these objectives, the study utilizes Solidworks simulation to replicate the WIG craft model. The static simulation involves testing four different parameters: Models A, B, C, and D. The key focus during the model simulation is varying the types of connections used. The simulation data is then examined to estimate the strength of the material structure. The material applied to the WIG craft structure is S-glass fiber and 6061 aluminum alloy. Model D produced acceptable values for the least maximum stress, strain, and resultant displacement, among other models. The maximum stress value of Model D is 1,601 MPa, which does not exceed the tensile strength of the material. For the rigidity analysis in operating conditions, the Solidworks flow simulation is conducted. The manipulated variable for flow simulation is the velocity of airflow. The velocities conducted are 60 km/h, 90 km/h, 120 km/h, 15 km/h and 180 km/h. The flow simulation shows the maximum total pressure exerted on the structure, where the highest velocity produced is 103433 Pa. From both static and airflow simulation, it was concluded that the WIG craft model has good rigidity in terms of withstanding the external load and airflow pressure during the cruising conditions proposed.

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1. INTRODUCTION

A heavier-than-air vehicle with an engine that is intended to operate close to a supporting surface to maximize the wing-in-ground (WIG) effect's potential is known as a wing-in-ground (WIG) effect vehicle. Wing in-ground effect is a relatively new concept in fast ship design, with broad applications in areas such as cargo transportation, tourism, rescue operations, and military functions. WIG craft provides an alternative method for increasing speed [1]. Malaysian territorial waters were patrolled using Wing-In-Ground (WIG) effect technology. In any winged vehicle that runs close to the water's surface, WIG, also known as the ground effect, reduces drag and boosts lift. It emphasizes the benefits of adopting WIG craft, such as increased endurance, maneuverability, and cost-effectiveness. WIG vessels can efficiently patrol broad regions for extended periods of time, negotiate complicated coasts and shallow waters, and save fuel, making them an appealing alternative for improving Malaysia's maritime security and protecting its territorial waters [2]. There is a phenomenon related to its operating mechanism. The ground effect (GE) is a phenomenon in which a body's lift-to-drag ratio increases while cruising very close to the surface of water or ground [2]. In modern industry, there will be more advanced technology that will help in completing human activities, especially for any complex task that will take a long time to complete. In this era, drone technology is widely used in the most common fields, such as the military, agriculture, delivery services and weather monitoring [3]. A drone is a type of unmanned aircraft. Drones are also referred to as unmanned aerial vehicles (UAVs) or unmanned aircraft systems (UAS).

The research in this paper focuses on the development of a Wing-In-Ground (WIG) craft that differs from commercially available drones in its unique means of operation. Unlike standard drones, the developed WIG craft operates without a pilot during the take-off and gliding phases. Pilots oversee specific tasks related to the craft's mission instead of operating the vehicles themselves. The purpose of this study is to examine the novel features and functionalities of the WIG craft and to highlight its potential applications and advantages in a variety of operational situations. Fabrication

***CORRESPONDING AUTHOR | Rasidi Ibrahim** | ✉ rasidi@uthm.edu.my
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manufacturing will involve a certain machining process that affects the quality of the fabrication component of the WIG structure [3]. The main element of the WIG craft development is the material used to manufacture and fabricate the craft using the most relevant material that is appropriate to be applied for the structure of the craft, including all parts such as wing, tail, cockpit, and the joined part for fully assembled WIG craft structure. In the manufacturing industry, material selection is important to make sure that the designated product development meets the international standard requirement and will produce the desired functions. In a recent study, researchers explored the application of natural fibers like kenaf and banana fiber to enhance progress toward sustainability goals [4].

In this research, a significant challenge arose when the current watercraft proved insufficient in handling the task of countering invasions in the national waters. The existing watercraft technology lacked the capability to effectively pursue invaders, mainly due to engineering limitations. By incorporating wing-in-ground effect technology, weapon drones emerge as a viable alternative for Malaysian authorities to monitor and safeguard the nation's coastal areas. The structural stiffness of an armed drone is important to its effective functioning during tactical operations. The purpose of this research is to explore the interaction between armed drone design, material selection, and structural stiffness, with the ultimate goal of constructing a dependable and durable model. To obtain a completely constructed model, the study examines the properties of the drone's structure, such as design, geometry, form, and component arrangement. The study emphasizes structural stiffness as a critical component that requires careful examination and evaluation utilizing fundamental engineering concepts. Furthermore, the proper materials for the armed drone prototype are carefully chosen to ensure flawless performance and operational success. The research makes use of simulations in engineering software.

The purpose of this paper is to accomplish two primary objectives. In order to implement the wing-in-ground effect in aircraft design, the first step is to determine the relevant material properties. The second step will be to simulate a WIG craft model using Finite Element Analysis on SolidWorks software in order to determine its structural rigidity.

2. WING-IN-GROUND CRAFT MODEL ANALYSIS

Wing-in-Ground (WIG) craft, also known as ground-effect vehicles, utilize the ground effect phenomena to produce lift and decreased drag at low altitudes near the water's or earth's surface. Analyzing WIG craft models is critical for understanding their aerodynamic behavior, performance, and structural integrity. Researchers concentrate on optimizing the craft's design, selecting appropriate materials, and assuring flight stability and control. The normal pressure drag depends upon the viscosity of the air and is related to flow separation that involves dynamic and airflow stability during operation [5].

WIG craft is a multimodal vehicle that, in its primary operational mode, flies or glides above water or another surface without maintaining constant contact with it [6]. It is propelled through the air primarily by the aerodynamic lift produced on a wing (wings), hull, or component parts that are designed to use the ground effect action. This simulation study shows that airfoils are affected by being floated on a cushion of high-pressure air region above the ground surface. Furthermore, the stagnation point is located on the lower side of the symmetrical airfoils due to the ground effect. The presence of ground effects is determined by changes in the value of lift coefficients [7]. The craft is essentially gliding close to the ground while executing a flight because it wants to avoid being seen by any intruders, and its height is lower than the aircraft.

In this paper, the discussion of structure joining rigidity involved the condition of the WIG craft model, either static on land or ground or during cruising conditions.

2.1 Material in Aeronautic Engineering Type of Model Joining

Aeronautics industry competition encourages the development of aircraft with cheaper operational costs, such as longer service lives, improved fuel efficiency, larger payloads, and greater ranges [8]. The development of new materials and/or materials with improved qualities is one of the most important variables in this respect; the key goals are weight reduction and the extension of the service life of aircraft components and structures [9].

2.2 Type of Model Joining

Static simulation and flow simulation are the two simulation settings for the WIG craft model's parameter settings. Figure 1 shows the connector defined for the WIG model, in which different connections are applied to the same model. To prevent any disruption or error during the simulation execution, it is crucial to set up all the involved parameters appropriately. For Model A, the connection between parts applies the global interaction of the WIG craft model, the same as the initial joining configuration in Figure 1(a). For Model B, the joining definition is enhanced at the cockpit and hovercraft area where spot weld is defined, as shown in Figure 1(b). For Model C, the modification of the connection feature is applied at the horizontal stabilizer area where a rigid connector is implemented, as shown in Figure 1(c). From the connection enhancement between Model B and C, Model D is produced with the connection defined as the combination between spot weld and rigid connector, which demonstrates better joining features, as shown in Figure 1(d).

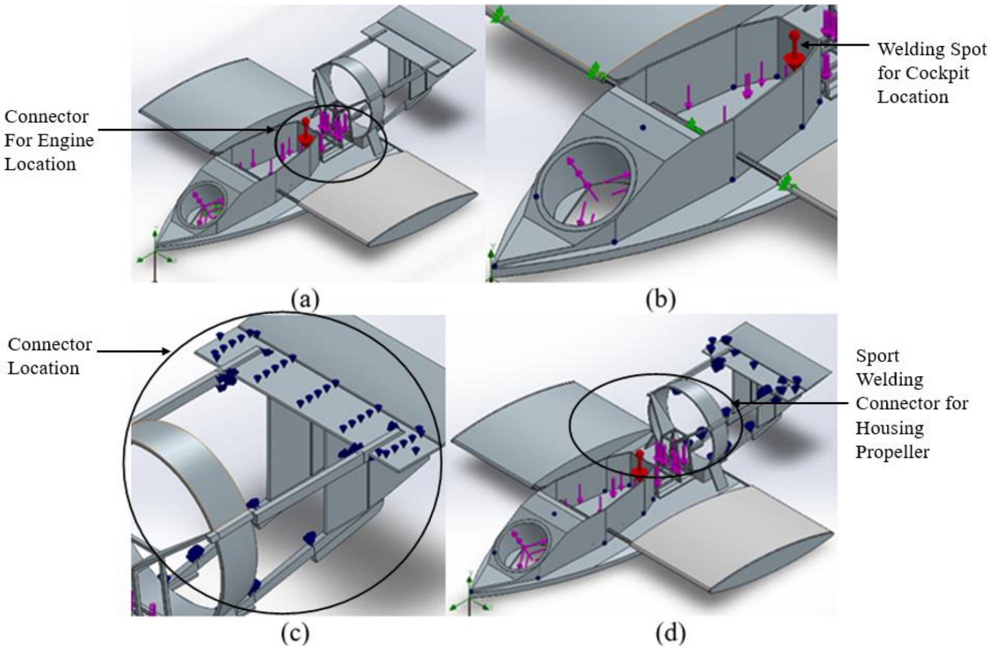


Figure 1. Joining definition: (a) global interaction; (b) spot welded cockpit; (c) rigid connector; (d) spot welded and rigid connector

2.3 Fluid Turbulence Model

Turbulence Model tailored specifically for analyzing fluid behavior in Wings operating within Ground Effect, an area of crucial importance in aeronautical engineering, for or optimizing aircraft design. The vector velocity field in this cartesian space is given by,

$$V = ui+vj+wk \tag{1}$$

where the x, y, and z components of velocity are given respectively by,

$$u = u\ (x, y, z, t) \tag{2}$$

$$v = v\ (x, y, z, t) \tag{3}$$

$$w = w\ (x, y, z, t) \tag{4}$$

The paper is focused on two pivotal aspects: achieving grid independence and validating the proposed model. Grid independence is critical in computational fluid dynamics (CFD) to ensure that simulation results remain unaffected by the mesh resolution used. This is key for ensuring the accuracy and reliability of the simulations.

Furthermore, the validation process aims to confirm the model's effectiveness in replicating real-world flow phenomena, particularly in the scenario of wings near the ground. By comparing the model's predictions with experimental data or established benchmarks, we can ascertain its capability to accurately capture real-world behavior. In the study conducted by Jithin et al. [10], an assessment was made regarding the efficacy of various turbulence models in numerically modeling the behavior of a 2D NACA4412 airfoil in ground effect. Additionally, Firooz and Gadami [11] investigated the impact of ground boundary conditions and turbulence models on the precision of numerical simulations concerning the ground effect of a 2D airfoil.

2.4 Methodology

In this study, simulation of engineering software is used to analyze the structure rigidity. The WIG craft model's connections with its component elements and its cruising speed are the manipulated variables. Table 1 shows the parameters used to be implemented in static simulation. From the simulation, the expected output or data are von Mises stress, total strain, resultant displacement and the factor of safety for all models.

Table 1. The static simulation parameter

Model	Connection definition
A	Global interaction
B	Spot weld
C	Rigid connector
D	Spot weld and rigid connector

For the flow simulation, the WIG craft model is required to be operated in the cruising state with different velocities set. Table 2 shows the flow simulation parameter.

Table 2. The flow simulation parameter

Velocity (km/h)	Altitude (m)	Gravity (m/s^2)	Temperature (ºC)
60			
90			
120	3	9.81	30
150			
180			

2.5 Material Application

Based on the WIG craft model operation and material properties, the materials utilized to create WIG crafts were selected for this study. Since the operational field is above the water's surface, the material must be light, robust, and thin. However, its outstanding corrosion resistance is of utmost importance. S-glass fiber composite and 6061 alloys were chosen as the materials to be used for the WIG craft structure and the engine mount. The WIG craft model's mass is 2293 kg. Table 3 and Table 4 describe the material properties of each material.

Table 3. S-glass fiber properties [2]

Property	S-glass fiber
Elastic Modulus	$7.2 \times 10^{10} N/m^2$
Poisson's ratio	0.22
Shear Modulus	$3.5 \times 10^{10} N/m^2$
Mass density	$2480\ kg/m^3$
Tensile strength	$4.585 \times 10^9 N/m^2$
Yield strength	$4.5 \times 10^9 N/m^2$

Table 4. 6061 Aluminum Alloy Properties

Property	6061 Alloy
Mass density	$2700\ kg/m^3$
Poisson's ratio	0.33
Elastic Modulus	$69.00 \times 10^9 N/m^2$
Thermal expansion	$2.40 \times 10^{-5} K$
Tensile strength	$0.124 \times 10^9 N/m^2$
Yield strength	$55.14 \times 10^6 N/m^2$
Thermal conductivity	$170\ K/m.K$
Specific heat	$1300\ J/kg.K$

2.6 Meshes and Boundary Condition

A mesh is a discretized representation of the studied geometry. It decomposes the complex geometry into smaller, more digestible parts in order to solve the analysis's governing equations numerically. Depending on the surface area and state of individual parts, the WIG craft model meshes are applied to the structure's surface. To prevent errors caused by surface conditions resulting from complicated geometry, a fine mesh density mesh technique is used for the cockpit surface and horizontal stabilizer at the tail part, as in Figure 2. By dividing the geometry into finite elements, meshing enables the application of finite element analysis (FEA) techniques. Through this procedure, the program is able to approximate how the structure will behave under different circumstances, including strain, stress, and deformation.

This simulation procedure continues by stating the boundary conditions, such as fixed features and load of the WIG craft model. For the fixed feature, this condition simulates supports or constraints by fixing specific model elements in place. The hovercraft part is defined as fixed geometry as it will not be moved and stay static. For the wing part, it is defined as a fixed hinge that is connected to the wing railing part. The fixed hinge is applied for both left and right wings, as shown in Figure 3. The payload of the WIG craft is calculated for static simulation, considering the mass of the engine, propellers, and passengers. Table 5 below shows the distributed payload location on the WIG craft model.

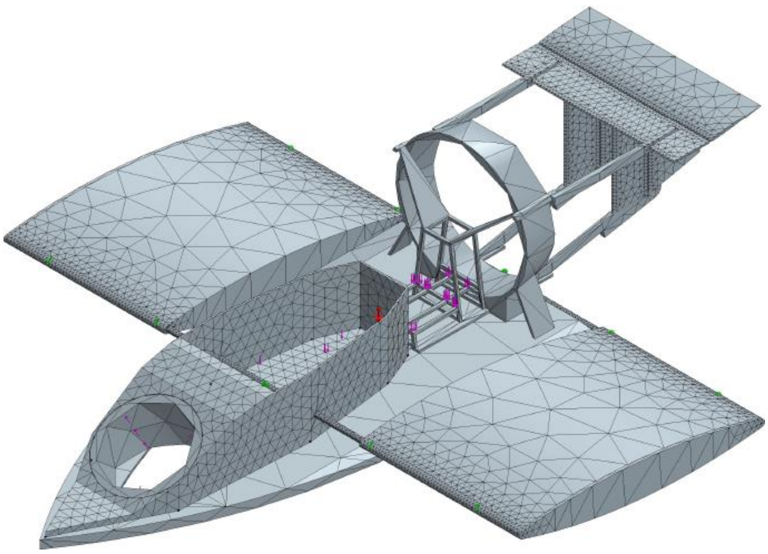
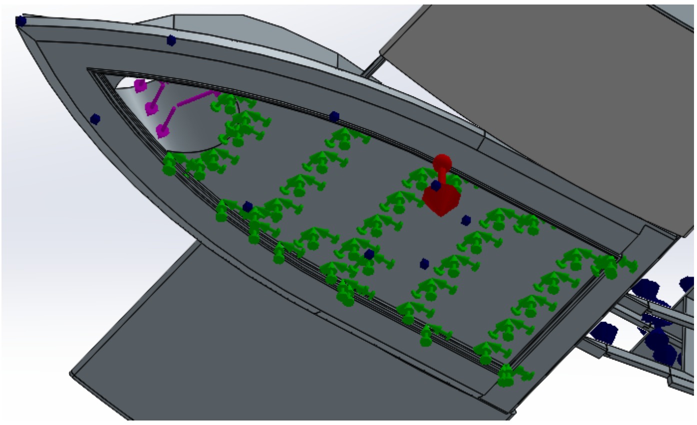
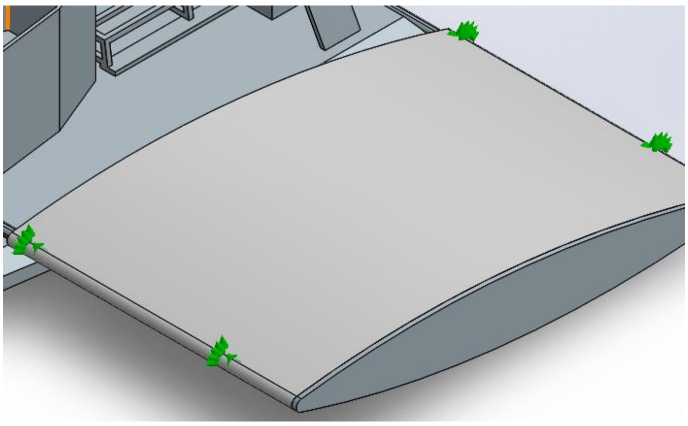


Figure 2. Meshing definition



(a)



(b)

Figure 3. Fixed feature definition: (a) fixed geometry; (b) fixed hinges

Table 5. The distributed payload location on the WIG craft model

Load	Value
Engine weight	1,962 N
Propeller	392 N
Passengers' weight	1,570 N

3. RESULTS AND DISCUSSION

For the research paper, SolidWorks simulation was employed to analyze von Mises stress, displacement, strain, and safety factors. Flow modeling was utilized for dynamic analysis to observe the distribution of theoretical pressure during the flight session.

3.1 Static von Mises Stress Analysis

Based on the analysis of the von Mises simulation, it could be concluded that the WIG craft model's improved part connections had a significant impact on lowering the maximum stress placed on the model, as shown in Figure 4 and Figure 5. As a result of the need to avoid exceeding the tensile strength limit, the pattern demonstrates that the maximum stress decreases. The pattern shows that the maximum stress drops with the concern to avoid reaching the tensile strength limit. According to Karmarkar's 2018 study, materials are said to begin yielding when the von Misses stress reaches a certain level, or what is known as yield strength [12]. The maximum von Mises stress value does not reach or meet the 4,600 MPa yield strength of S-glass fiber. Hence, it can be concluded from the von Mises stress data below that none of the four models' structures would yield or permanently deform.

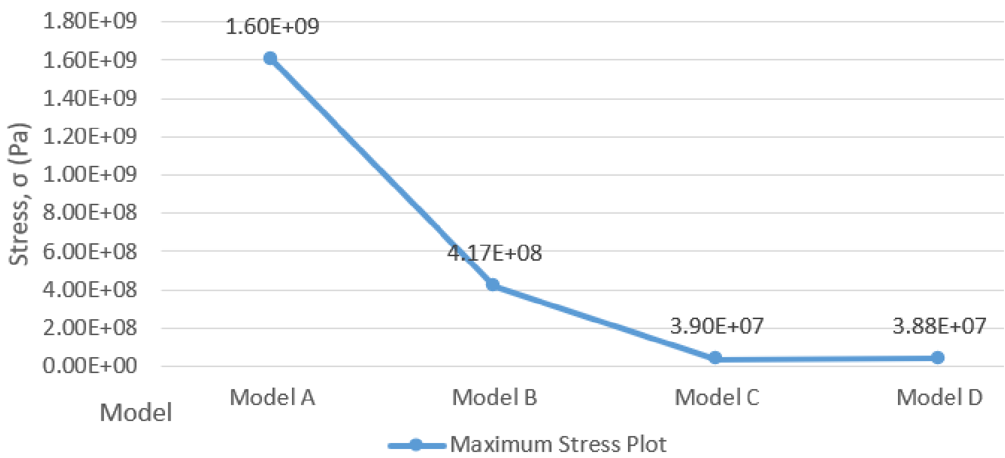


Figure 4. Maximum von Mises stress

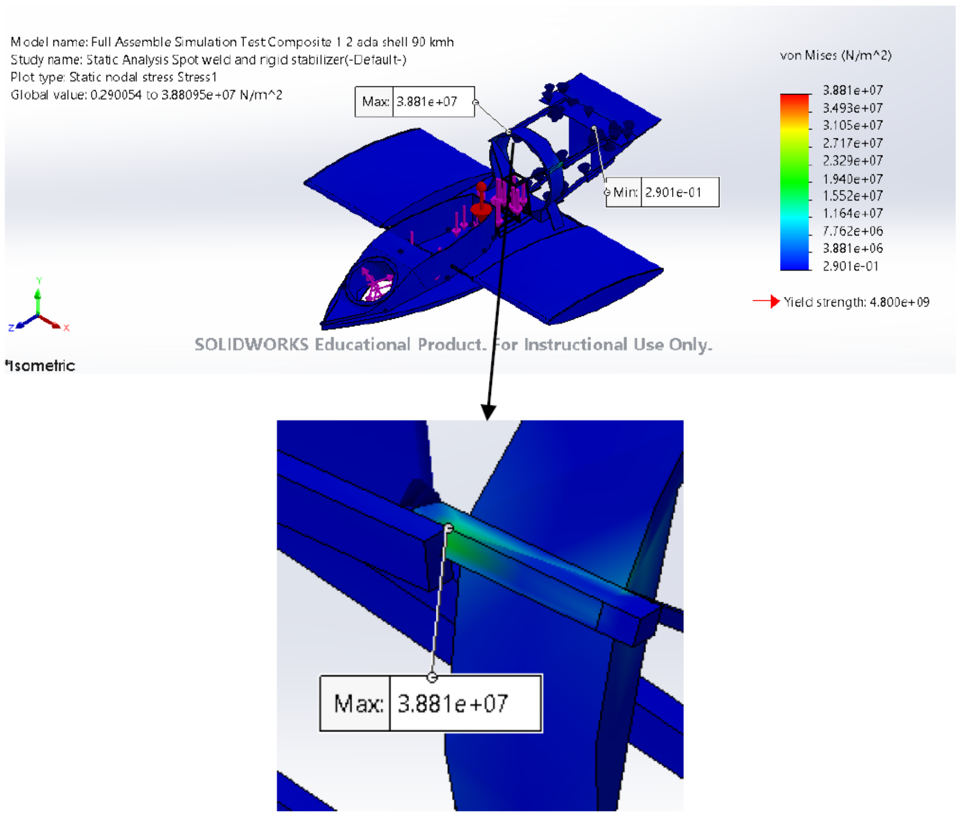


Figure 5. Maximum von Mises stress point on WIG craft model

3.2 Static Strain Analysis

According to the strain simulation findings, the better part connections of the WIG craft model resulted in a considerable reduction in the maximum strain acting on the models, as shown in Figure 6 and Figure 7. The trend shows that the maximum strain value lowers due to a desire to avoid exceeding the tensile strength limit, which is related to the maximum stress that occurred on the WIG craft model.

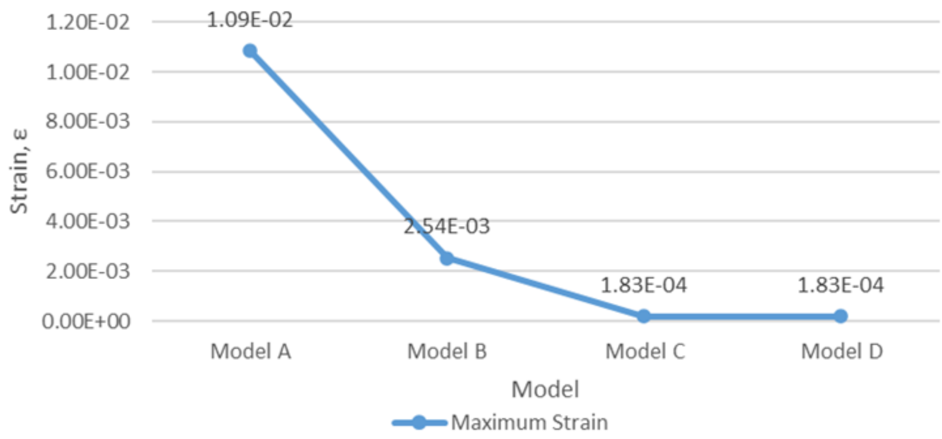


Figure 6. Maximum strain plot

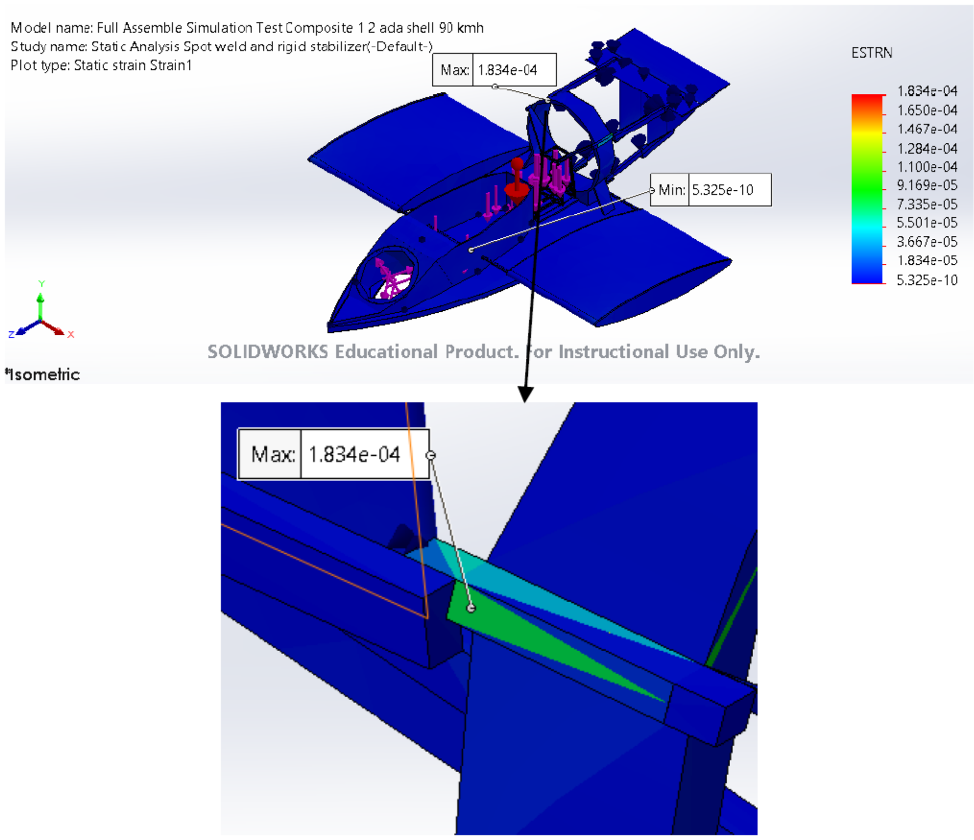


Figure 7. Maximum strain point on WIG craft model

3.3 Resultant Displacement Analysis

Based on the findings of the analysis, it was found that improving the connected connecting component will raise the displacement value, where it has been greatly reduced with a little adjustment without affecting the structural solidity of the model. Figure 8 depicts the displacements caused by the simulation. The connection of the assembly parts has been improved for Models B, C, and D by using more joining processes in simulation. As a result, the displacement of both models is less than that of Model A. It explained that Model D has a better joining configuration, which resulted in the least resultant displacement value. The resultant displacement result shows that the enhanced WIG craft model will affect the displacement value, with minor deformation occurring when the payload is applied on the WIG craft model. According to Jansson, although the elastic deformation of the aircraft structure is typically not considered when conducting a flight mechanics study, there are various instances of flight dynamics events where the rigid body approximation is insufficient [13]. Therefore, the deformation caused by the payload is insignificant when the joining modification is applied to the model.

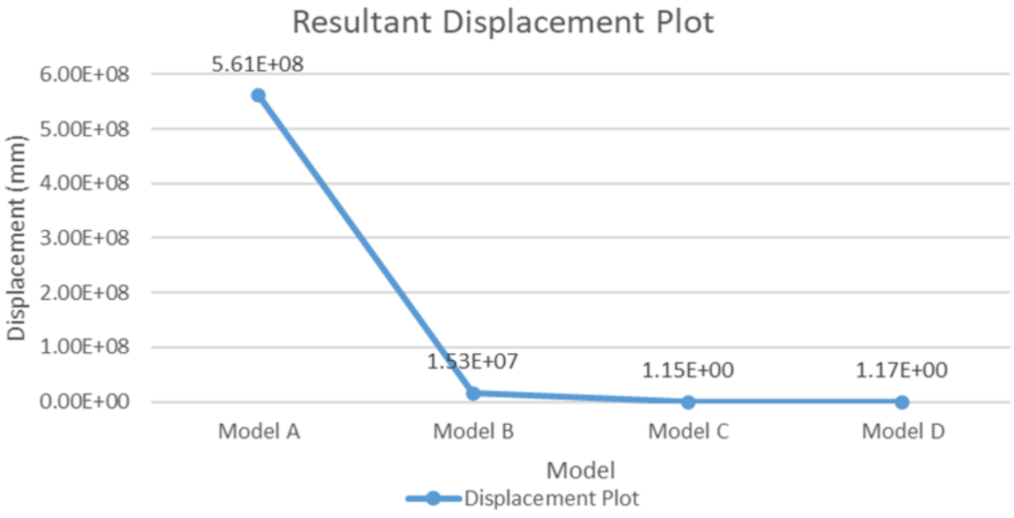


Figure 8. Maximum resultant displacements

3.4 Flow Pressure Analysis

In this simulation, the model should be able to attend a flight when the power is turned on. The WIG craft can go at speeds of 80 km/h, 90 km/h, 120 km/h, 150 km/h, and 180 km/h. During cruising, the WIG craft is simulated to go through specific conditions, most notably the pressure and temperature of the surrounding sea, as well as the airflow velocity. The simulation was performed using SolidWorks Flow Simulation to calculate the maximum pressure, minimum pressure, and total pressure acting on the WIG ship during the cruising conditions.

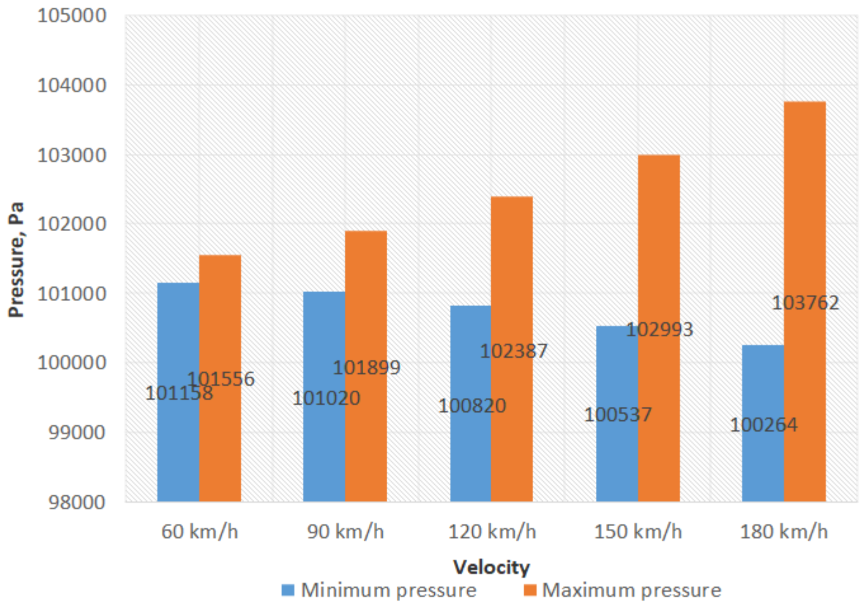
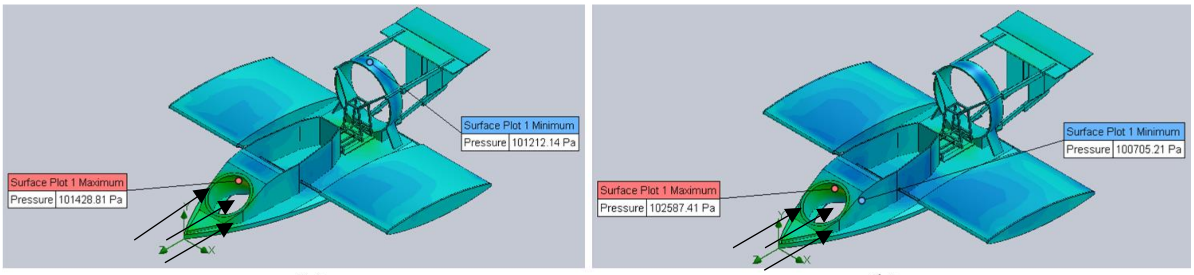


Figure 9. Minimum and maximum pressure of WIG craft model

According to the graph in Figure 9, during the increment of WIG craft model velocity, the minimum pressure acting during the cruising condition decreases due to the least amount of pressure influence on the model structure. The air going over the bending upper surface of the wing will move faster and create less pressure than slower air traveling across the flatter underside of the wing [14]. The results for the maximum total pressure reveal the same pattern, which increases with regard to the speed of the WIG craft. Figure 10 shows the different points of pressure performed during cruising mode, especially for the minimum pressure point. The maximum pressure was impacted at the same point as the WIG craft model along the velocity increment, which acted in front of the WIG craft model due to the airflow barrier, especially in the cockpit area. For minimum pressure impact, the spot would be dissimilar where there are two points allocated the least minimum value, which is at the top of the turbine holder and at the sidewall of the cockpit area. This is due to the fact that less air resistance occurs while the WIG craft cruises at a certain velocity. Figure 10 shows the area of pressure distributed on the model. Figure 10(a) shows the pressure acted on the body of the model structure at 60 km/h flow speed, while Figure 10(b) shows the pressure acted on the model structure with the highest velocity, which is at 180 km/h.



(a) (b)

Figure 10. Pressure distribution of WIG craft model: (a) at 60 km/h; (b) at 180 km/h

The output of the flow simulation is the total maximum pressure, with the highest maximum total pressure at 180 km/h. The maximum total pressure is defined as the sum of the maximum pressure values applied to the model structure. The speed and maximum total pressure connection are exactly proportional. As a result, the airflow simulation was completed successfully and without error. Burke claims that where a fluid's speed increases, the internal pressure of the fluid (whether liquid or gas) drops [15]. As the velocity of a model increases during flight, the area of maximum pressure on its surface changes accordingly. Research on various subjects like football dynamics [16], aircraft wall temperature [17], turbopump performance [18], flow boiling in tubes under high flight acceleration [19], and hypersonic wing pressure loads [20] all indicate that alterations in velocity can impact pressure distribution. For instance, in aircraft studies, an increase in velocity led to higher wall pressure and temperature, while in flow boiling simulations, pressure drops were influenced by flight acceleration levels and directions. Therefore, as the model's velocity increases during flight, the pressure distribution on its surface may shift, affecting the maximum pressure area due to the complex interactions between velocity changes and pressure variations in different systems.

Since the airflow is affected most in front of the model, the pressure is primarily concentrated at the top of the cockpit between the vertical stabilizer and the passenger seat at the highest velocity. The model was able to withstand pressure during flight mode because of the enhanced link between the cockpit and the hovercraft, which was made possible by using Model D from static simulation. WIG craft model stress, strain, and displacement are not affected significantly by the airflow velocity since the changes in the result value are insignificant for each model.

4. CONCLUSION

Based on the result and discussion presented in this study, it concluded that the objectives stated could be achieved by the material utilization and the assembly technique, which are closely associated with a rigidity study of a certain structure dependent. By studying the static and dynamic conditions of the WIG craft, the material selection for the entire WIG craft construction, which largely uses composites of S-glass fiber, is able to endure external force and pressure without exceeding the material limit. This study is carried out in accordance with the specifications of the actual model, with most of the mate parts coupled by a joining technique. The connecting sections have been improved by modifications to the connection parts where the stress is concentrated, particularly in the cockpit and horizontal stabilizer portions. By comparing the four types of connection in the WIG craft model, Model D is the most compatible and suitable for application to the actual WIG craft prototype. Model D produced acceptable values for the least maximum stress, strain, and resultant displacement, among other models. The maximum stress value of Model D is 1,601 MPa, which does not exceed the tensile strength of the material. For the rigidity analysis in operating conditions, the SolidWorks flow simulation is conducted. The manipulated variable for flow simulation is the velocity of airflow. The velocities conducted are 60 km/h, 90 km/h, 120 km/h, 15 km/h and 180 km/h. From the flow simulation, the maximum total pressure exerted on the structure is observed, where the highest velocity produced is 103433 Pa. From both static and airflow simulation, it concluded that the WIG craft model has good rigidity in terms of withstanding the external load and airflow pressure during cruising conditions.

Furthermore, the rigidity of the WIG craft structure in dynamic conditions is properly observed, resulting in the pressure exerted on the WIG craft structure having no effect during the cruising condition in which the structure could withstand the amount of pressure acting on the WIG craft model. The results revealed that the WIG craft model is safe to run and function at an altitude of 3 meters above the ground, either on water or on land.

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