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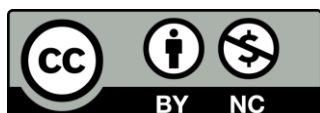
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AERODYNAMIC ANALYSIS OF UiTM'S ENERGY GLIDER WITH FITTED WINGLETS USING CFD SIMULATION

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Abstract: Gliders are aircraft with fixed wings that do not depend on an engine to fly. Depending on the design and size of the lifting surface, gliders can fly for long distances. Like other types of aircraft, wings of the glider must be designed in such a way as to provide lift to maintain flight level. The long, slender wings and lightweight design provide gliders with maximum lift-to-drag ratio. The purpose of this study is to determine the aerodynamic characteristics (i.e. lift, drag and moment) of UiTM's energy glider that has been incorporated with winglets, which are vertical wingtip extensions that can increase the aircraft's fuel efficiency and cruising range. In this study, the KFm-5a is used as the airfoil profile for the glider's wing. The glider is modelled using CATIA and the resultant model is then exported to Fluent Ansys, which is a computational fluid dynamic (CFD) analysis software. For the CFD analysis, the flow around the glider's model is simulated at Reynolds number of 4.7×10^5 and Mach number 0.1 (~35 m/s). The turbulence model used in this study is Spalart-Allmaras due to its efficiency in reducing the complexity of the problem and also the overall simulation time. The aircraft is pitched at a range of angles of attack from -2° until it reaches the stall angle with an interval of 2° . On the whole, the results show that the glider with the winglet has higher maximum lift-to-drag ratio of 13.7 at angle of attack of 4° as compared to the original glider without the winglet that has a maximum lift-to-drag ratio of only 12.4 at the same angle of attack. Nevertheless, the differences of lift and drag forces between these two glider configurations can be taken to be relatively small.

Keywords: glider; CFD; aircraft; aerodynamics; Fluent Ansys

1. Introduction

Gliders have a long range of flight that depends on the design and size of the lifting surface. Most modern gliders have a glide ratio that is greater than 60:1. In comparison to Boeing 747 aircraft, which is a conventional aircraft with glide ratio of 15:1, the gliders can glide for 96.6 km at a height of 1.6 km above sea level [1]. Some gliders have an altitude gliding engine that can be turned off once the necessary lift has been produced. Since the gliders can glide without relying on the engine, this enables it to have minimal environmental impact as the air pollution from engine combustion is reduced when flying the gliders. There are numerous different varieties of gliders, each with a unique wing design, aerodynamic efficiency, pilot position, controls, and intended usage. Typically, basic lightweight materials like wood, plastic and foam are used to make gliders. From the aerodynamics point of view, a glider can be referred to as 'heavier-than-air' aircraft that glides through air due to the dynamic reaction of air against its lifting surface [2]-[3]. Principle aerodynamic forces like weight (W), lift (L), thrust (T) and drag (D) are what enable gliders to fly. These principles will determine the glider's speed and direction of motion – upward

and downward. Generally, the main objectives of the energy glider design are to create an aircraft that can fly for as long as possible, for recreational uses (air sports and toys) and for further research.

The Kline-Fogleman airfoil is also known as the KFm airfoil, which is a simple airfoil in which the steps run in the direction of the chord length. The steps can be single or multiple. This KFm airfoil was designed by Richard Kline and Floyd Fogleman when he was experimenting with a high-strength paper airplane that would glide well, and after much experimentation, he was able to achieve this goal. Richard and Floyd found that this stepped airfoil concept was capable of resisting stall, whereupon they decided to apply for patent on this stepped airfoil [4]. In addition, such airfoil with the stepped upper surface could offer higher lift coefficient, higher lift-to-drag ratio and high stall angle [5]. This particular airfoil has a step in 50% chord with 50% depth [6]. Moreover, flight performance is greatly affected by drag created by vortices at the wing tips. Winglets are extensions of the wingtips and are used to minimize vortex formation, thereby improving fuel efficiency [7]. They are typically used on heavier cargo aircraft due to higher operating costs and higher fuel consumption on long-haul missions. The improvement in aircraft performance provided by winglets results largely from their ability to reduce induced drag, which is offset by their additional wetted area that increases profile drag. Profile drag is the drag created by the shape of the airfoil or wing section. Induced drag is the drag resulting from the generation of lift by a bounded wing [8]-[9]. In this study, the simplest and most commonly used winglet is used, which is the blended winglet. The blended winglet consists of an upwardly offset blade extension. Compared to many other types, the mixed wing is characterized by a smooth chord transition instead of an angular transition from wing to winglet. Even with simple, non-optimized design implementations, significant lift and drag improvements of almost 9% can be observed. The design has been initially researched by Boeing in the mid-1980s and developed by Aviation Partners Inc. in the early 1990s [10].

UiTM's energy glider has been the subject of a prior research. Its design, construction and flight testing all took place at UiTM Shah Alam. Since the original aircraft was developed for a Radio Control Aircraft, there has been no study to compare the obtained data (i.e. flight testing data) with analytical, numerical and experimental methods. Based on this notion, these are carried out in this study to obtain proper aerodynamic data for this energy glider and add aerodynamic analysis to the current design. The result is then used to improve the design of the energy glider in terms of aerodynamic characteristics. Figure 1 presents the original and downscale of UiTM's energy glider and its specifications. The glider is scaled down to $\frac{1}{4}$ from its original size.

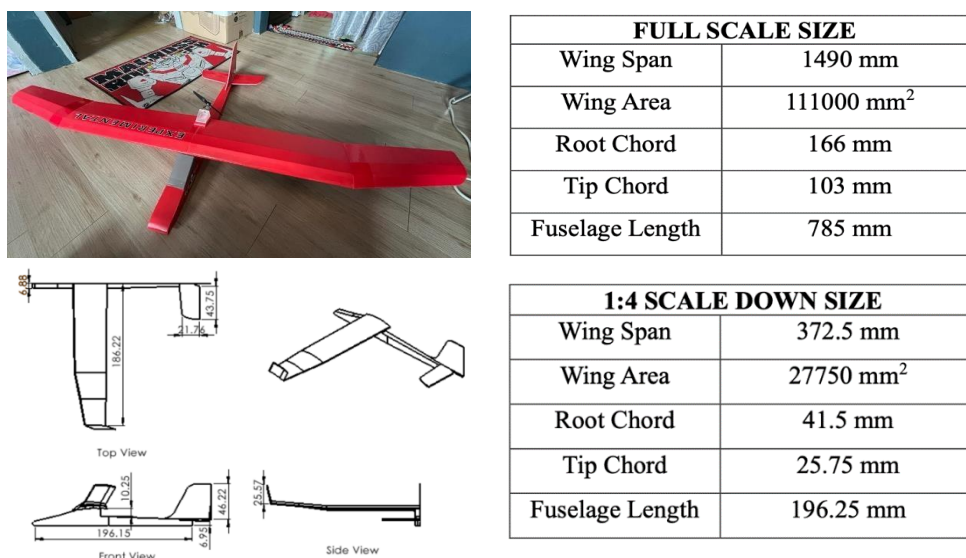


Figure 1: UiTM's Energy Glider and its specifications

The goals of this research are to determine aerodynamic forces such as lift coefficient (C_L), drag coefficient (C_D) and lift-to-drag ratio (L/D) through CFD simulation. The C_L and C_D can be calculated by Equation 1 and Equation 2. In these equations, L is the lift force, D is the drag force, ρ is the density of air, V is the subjected velocity and S is the wing area.

$$C_L = \frac{L}{0.5\rho V^2 S} \quad (1)$$

$$C_D = \frac{D}{0.5\rho V^2 S} \quad (2)$$

In this study, the freestream velocity is fixed at 35 m/s where the corresponding Reynolds number is 4.7×10^5 as calculated using Equation 3, where L represents the length of the aircraft and μ is a fluid dynamics viscosity. Moreover, the corresponding Mach number is 0.1 as calculated by using Equation 4, where γ is a specific heat ratio, R is a gas constant and T is a temperature. This indicates that the flow is subsonic.

$$Re = \frac{\rho v L}{\mu} \quad (3)$$

$$M = \frac{V}{\sqrt{\gamma R T}} \quad (4)$$

The flow around the glider is simulated, observed and analysed. The CFD analysis of energy glider performance on ANSYS Fluent is done until the stall angle α_{stall} is achieved. The scaled-down model is used to ease the simulation process. The UITM's energy glider design is for experimental purposes only.

It is shown that the market size of gliders is increasing in demand, both for commercial and military applications. The understanding of gliders' performance has been used to study the aerodynamics and flight control fundamentals. The ever-expanding range of gliders' applications such as in the military for training purposes indicates that the study of design and aerodynamics of energy gliders is vital to produce a better performance and reliable glider. Information gathered from this study can be used to further expand gliders in space exploration as gliders emit little to no pollution that can be harmful to the space environment.

2. Methodology

Figure 2 shows the flowchart of the methodology in this study. In short, this study starts with the measuring of the dimensions of the glider. The measurement data is recorded before the glider is drawn in computer-aided design (CAD) software, CATIA. The scaled-down half model of the glider is created, which allows for detailed visualization of the glider's design including its shape, dimensions and overall geometry. The CATIA file is then converted into .stp file format, which is a neutral file format for CAD data. This file is imported into Ansys Fluent Geometry. By importing the geometry into Ansys Fluent, it becomes possible to perform fluid flow analysis on the glider. A mesh is generated around the glider and its enclosure before going to the set-up section. The mesh size and density are determined based on desired level of accuracy and computational resources available. Additionally, boundary conditions are defined, specifying fluid flow properties and environmental conditions that the glider will experience during the operation. After the meshing process is done, the initial condition of this simulation needed to be set up including solver type, turbulence model, references value and also number of iteration. The

simulation results provide some insights into the glider's aerodynamic performance including lift, drag and other relevant flow characteristics.

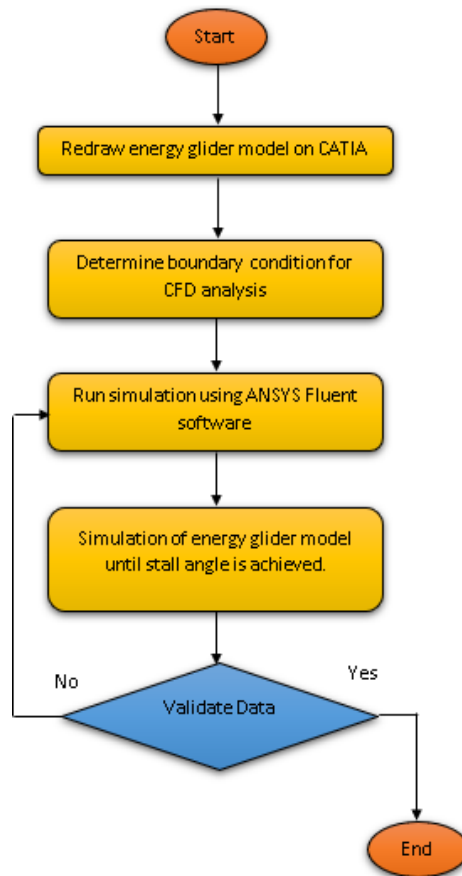


Figure 2: Flowchart of methodology for this study

2.1. Pre-processing

There is no detailed drawing for this aircraft. Therefore, the physical model is measured and drawn manually on CATIA by considering every detail and angle of the existing energy glider. Detailed drawing is required to obtain the most accurate model representation of the energy glider as shown in Figure 3. Compared to the original model, a winglet is added to improve the drag of the glider. The chosen type of winglet in this study is a blended winglet with an angle concerning the main wing of 56° . This blended type is chosen due to its simplest design.

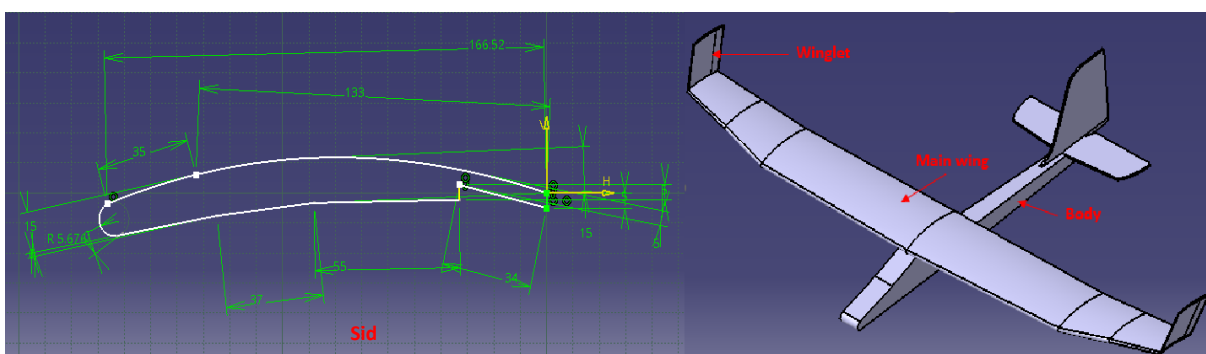


Figure 3: Energy glider fitted with winglets in CAD (in mm)

The glider drawing is then converted into STP file (.stp) to enable the drawing to be imported into Ansys Fluent software for simulation purposes. The drawing has been scaled down by 1-to-4 ratio from the original size to ease the meshing process and to save time for the simulation analysis. Figure 4 shows the drafting of the half-model scaled-down glider from the front view, top view and side view.

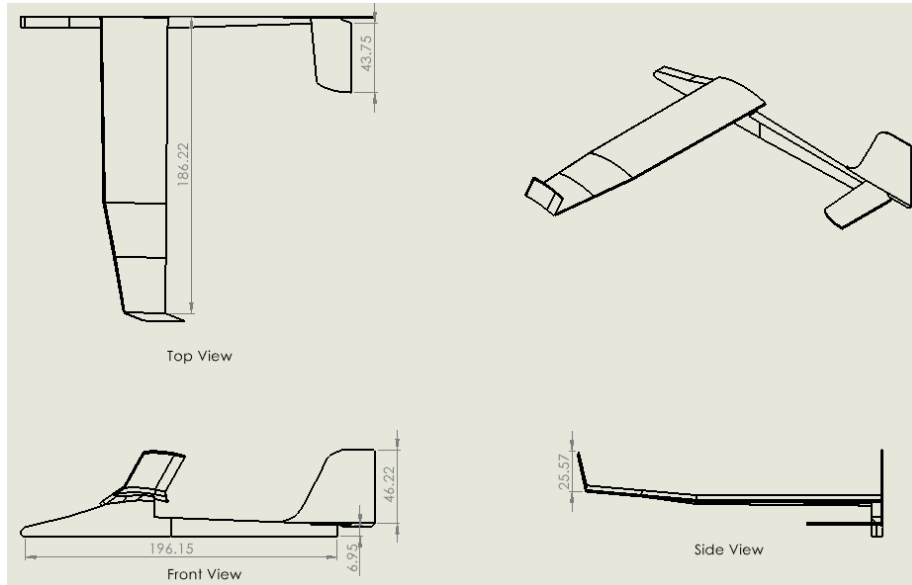


Figure 4: Isometric view of the glider

The early step in Ansys Fluent software is to import the drawing file to the geometry setup. In this section, the body and wing of the energy glider need to combine into one subjected body by Boolean Operation. Figure 5 shows the glider is pitched at angles of attack, α of 0° and 13° . It should be noted that the pitching point is based on the mean aerodynamics center (MAC) of the fuselage.

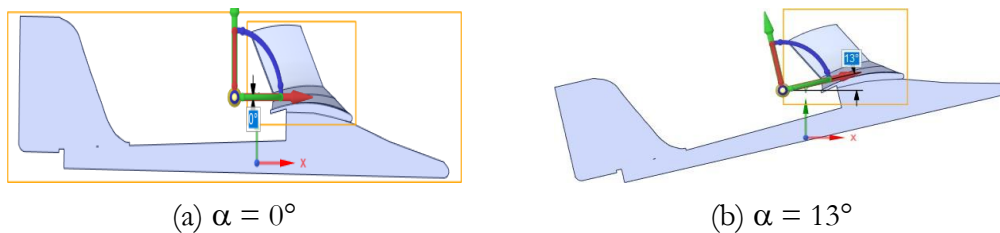


Figure 5: Pitching angles

2.2. Meshing

Meshing is the process of dividing the computational domain such as the enclosure created in the geometry, into very small sub-volumes. The process of meshing is extremely critical and great care must be taken to create a mesh to capture the correct flow behavior. The size of the computational domain used in this study is $L \times W \times H = 2.20 \text{ m} \times 1.19 \text{ m} \times 2.05 \text{ m}$, which is shown in Figure 6. This size will affect the total element of mesh and the result of simulation such as the airflow. Boundary condition, addresses how fluid enters and exits the simulation model. This process also includes the changes that have taken place between the model and its environment. In other words, one can also view that the boundary condition connects the model with its environment. The element size chosen for the glider has to be as small as possible to increase the accuracy of the result but this will also subsequently increase the time taken to complete the simulation. A grid independence study has been carried out to minimize the effect of grid size on the computing outcomes. It will generate a series of coarse, medium and fine

meshes to show how the solution varies between different mesh sizes. A grid independence analysis is undertaken and it is observed that the result is converged at the number of elements of about 1,950,000 as shown in Figure 7. This is taken as the reference for the meshing process.

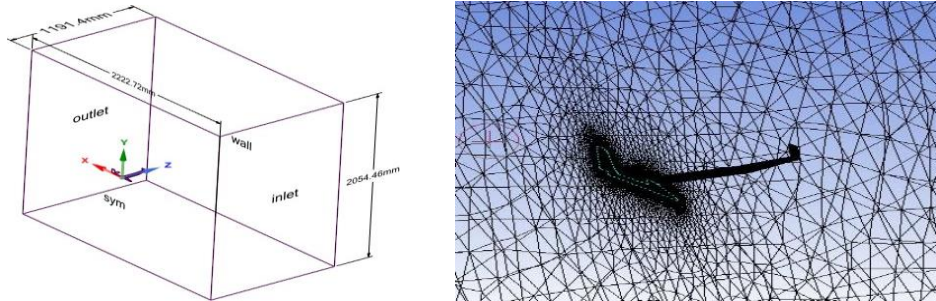


Figure 6: Flow domain and mesh on the glider's body

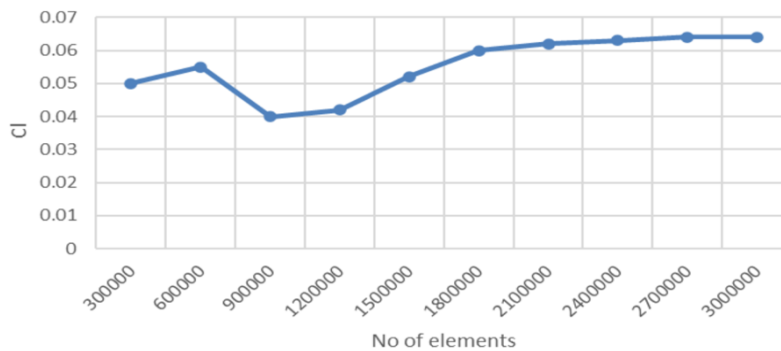


Figure 7: Results of the grid independence study

2.3. Processing

Important parameters such as solver, turbulence model, boundary conditions, reference values and number of iterations have been properly decided to simulate the realistic conditions. The setup is shown in Table 1. The Spalart-Allmaras modeling is used as the turbulence model because it is a simple model for solving a transport equation for turbulent viscosity (kinematic vortices). This model can calculate a local shear layer thickness for the length scale with one equation. The Spalart-Allmaras model has been developed specifically for wall-bounded flows and boundary layers with unfavorable pressure gradients in aerospace applications [11]. Figure 8 shows the residual graph where it shows all the lines which are continuity, x-velocity, y-velocity, z-velocity and nut converge at 198 iterations and undergo 25 minutes of completion time.

Table 1: Setup and solution

Parameter	Value
Solver	Type: Pressure-based; Time: Steady; Velocity formulation: Absolute
Turbulence model	Spalart-Allmaras
Boundary condition	Inlet velocity: 35 m/s; Inlet pressure: 101,325 Pa
Reference Value	Area: 0.008421 m ² ; Density: 1.225 kg/m ³ ; Pressure: 101,325 Pa; Temperature: 297 K; Velocity: 35 m/s
Number of Iteration	200 - 400

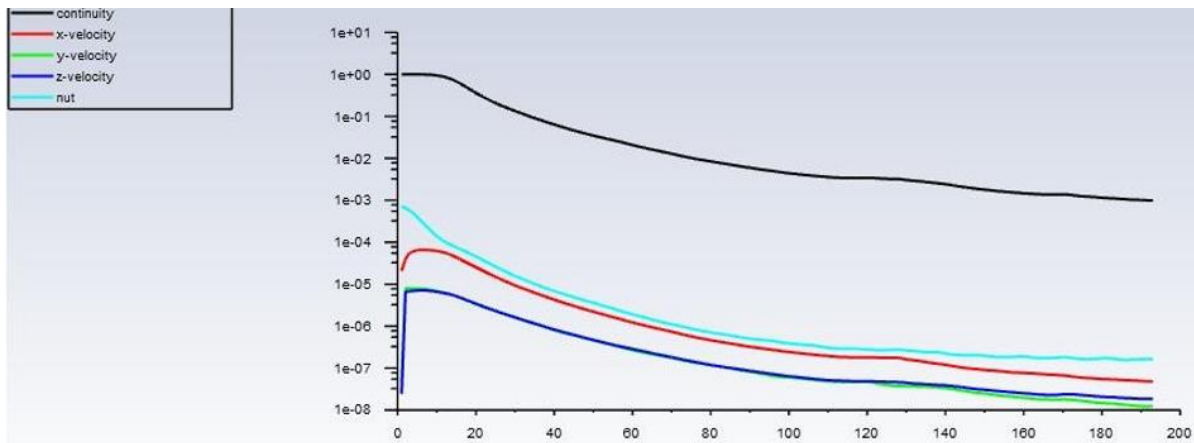


Figure 8: Example residual graph for 200 iterations

2.4. Post-processing

Visualization of the static pressure and the air velocity can be obtained from the simulation results as shown in Figure 9. Pressure contour is used to determine the magnitude of pressure at certain areas of the glider such as its nose as well as the leading and trailing edge of its wing. In addition, a velocity vector is used to represent speed and direction of the airflow in a domain or on a surface. Furthermore, the streamline in Figure 9 also shows the trend of the airflow in a domain or on a surface.

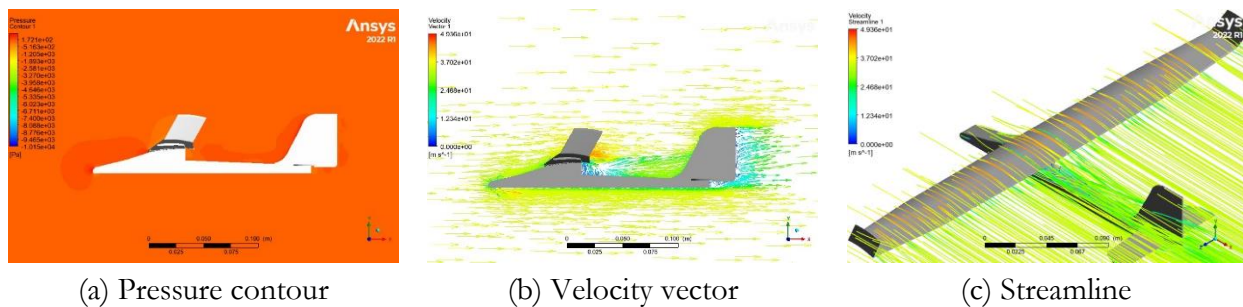


Figure 9: Example simulation output results at $\alpha = 0^\circ$

3. Results and Discussion

It is important to compare the aerodynamic performance of the original design with the modified design of the energy glider that is fitted with winglets in terms of C_L , C_D and L/D . It should be noted that the CFD simulation results for the original design of the UiTM's energy glider have been compared to the published data in Ref. [12] for validation process. Data validation can aid in detecting mistakes, as well as improving the accuracy of findings. Overall, the comparison shows that the CFD simulation results in this study match well and consistent with the findings in Ref. [12]. Therefore, the simulation settings used in this study can be taken as adequate to obtain results with a good accuracy.

3.1. Aerodynamics data

Figure 10, Figure 11 and Figure 12 show the relationship of C_L , C_D and L/D against angle of attack, α for the existing energy glider and also the modified energy glider fitted with winglets. In Figure 10, the plot shows the increment of C_L for both gliders (i.e. with and without winglet) when α is increased from 0° until 12° . However, it is observed that the lift force starts to decrease when α is about 14° and

this is called a stall angle, α_{stall} . For the existing glider, its α_{stall} is found to be 14° with a maximum C_L of 1.164 whereas for the modified glider with the winglet, its stall angle is the same but it has slightly higher maximum C_L of 1.173. The lift differences are small, which is just about 0.8%, and rather negligible. In Figure 11, it can be considered that the C_D of both gliders (i.e. with and without winglet) increases in a parabolic manner as α increases. At the stall angle for the existing glider, its C_D is found to be 0.178. On the other hand, for the modified glider with winglets, its C_D is 0.177 at the stall angle. The percentage difference is 7.15% and considerably small. A lower drag coefficient means that the shape of the airfoil with a winglet allows it to move easily through the air with minimum resistance. A lower drag coefficient can improve speed, range and fuel consumption. Since the drag force increases as α increases, it is vital to select the appropriate α at different phases of flight to ensure optimization of the glider's design. In Figure 12, it can be seen that L/D of the modified glider with winglet is higher when compared to that for the original glider design without the winglet. The maximum L/D for the glider without winglet is about 13.4 while that for the modified glider with winglet is 13.7, which both occurs at α of 4° . This means that the energy glider with a winglet generates a higher maximum L/D . In general, a higher L/D allows the modified energy glider with winglets to fly farther with the same amount of fuel as the original UiTM's energy glider design.

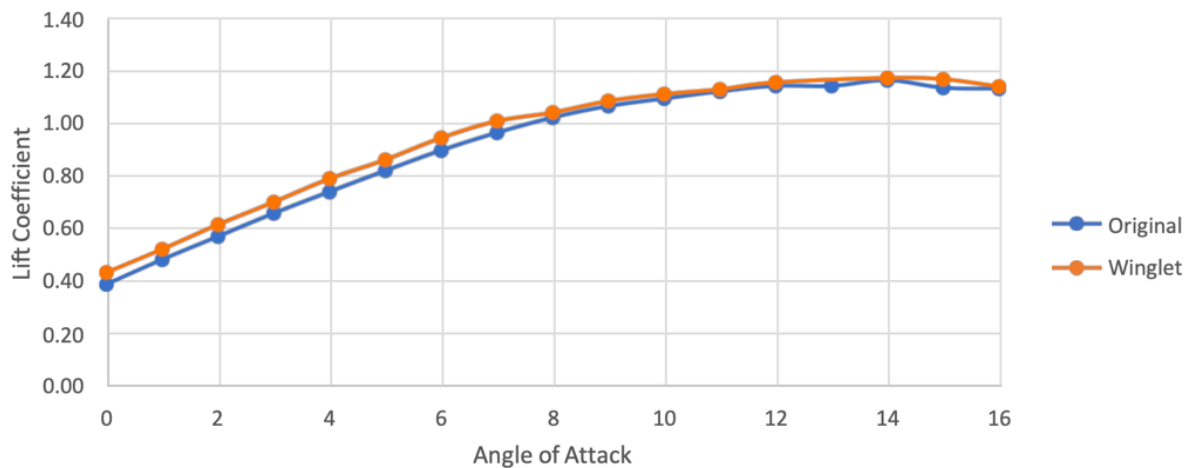


Figure 10: Lift coefficient versus angle of attack

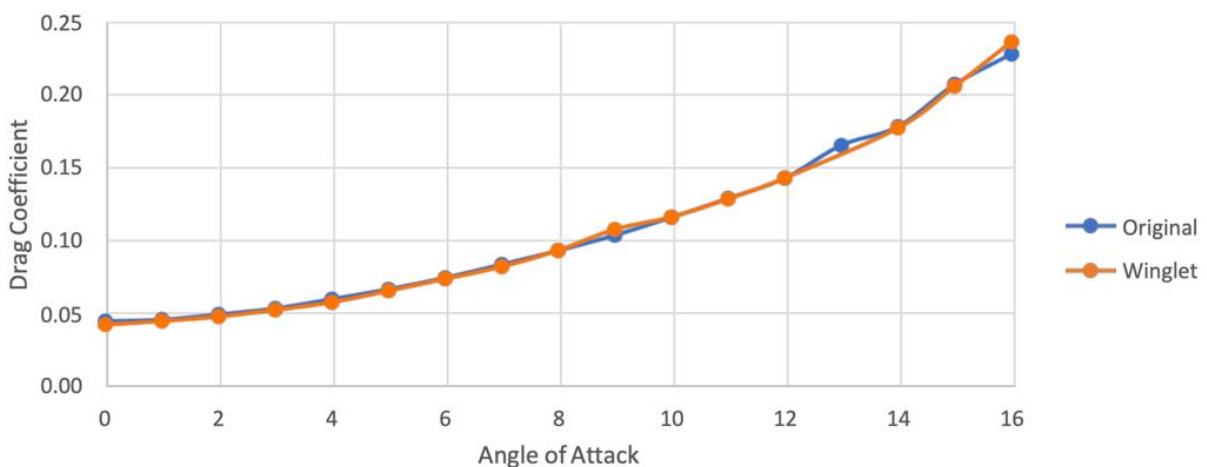


Figure 11: Drag coefficient versus angle of attack

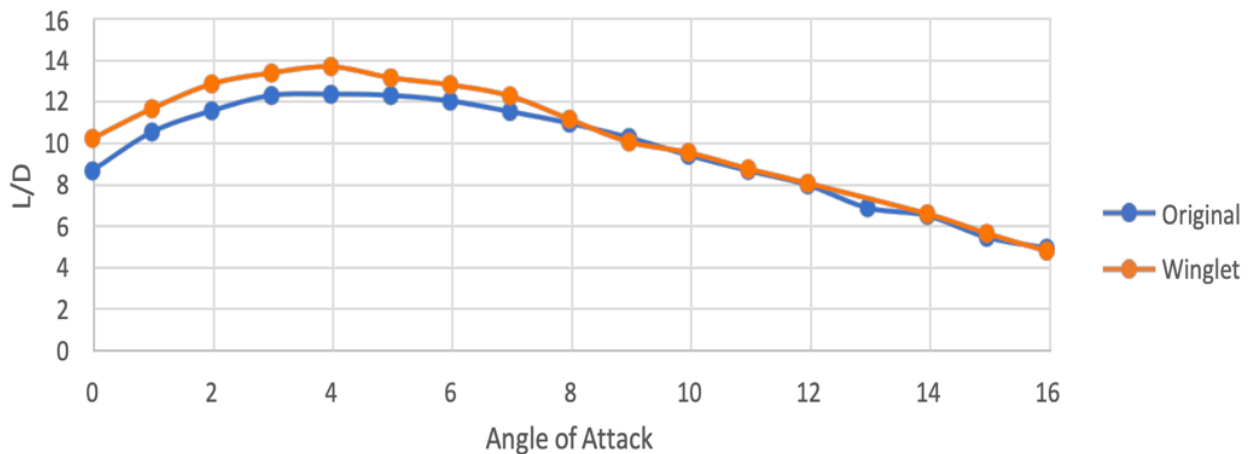
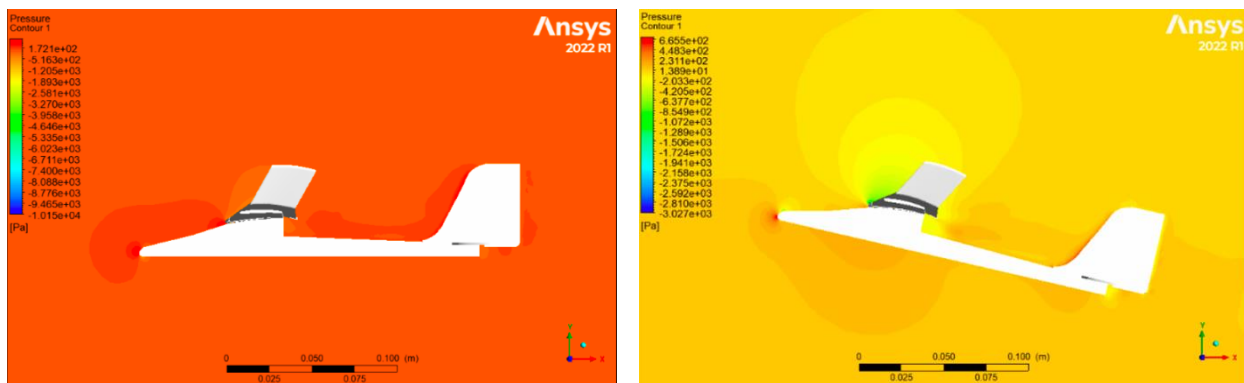


Figure 12: L/D versus angle of attack

3.2. Flow visualization

Figure 13 to Figure 15 are visualizing the flow around the modified glider’s body at angles of attack of 0° and 14° . Figure 13 shows that the glider experiences an equal distribution of pressure both at the body and wing at angle of attack of 0° , which is approximately 623.6 Pa. In the same Figure 13 for angle of attack of 14° , the glider encounters a high pressure at the leading edge of the wing and the nose of the glider, which is about 700.9 Pa. Around the glider’s body, it experiences pressure of about 79.65 Pa that is quite a small amount as compared to the nose and leading edge. Moreover, Figure 14 shows that the magnitude of the velocity on the glider at angle of attack of 0° is about 49.36 m/s. On the rear of the glider, the velocity is a bit slower, which is about 24.68 m/s. This may be due to the drag force on the body and tail of the glider. At the stall angle of 14° , the velocity magnitude is higher, which is about 64.39 m/s, as compared to when the glider is at angle of attack of 0° . At the trailing edge of the glider for this angle of attack of 14° , the velocity is about 32.19 m/s, which is about 50% of the velocity at the leading edge of the wing. The airflow on the glider at angle of attack of 0° is essentially smooth, or can be described as a laminar flow where there is no reversible flow occurring along the wing of the glider, as shown in Figure 15. In contrast, at stall angle of 14° , there is a separation of the airflow at the trailing edge of the wing. The turbulence flow can be seen in the blended area between the winglet and the main wing. As shown in Figure 15 for angle of attack of 14° , the flow at the winglet is smooth. This shows that the winglet successfully prevents the turbulence flow from occurring at the wingtip and this automatically reduces drag force at the wingtip of the glider.



(a) $\alpha = 0^\circ$

(b) $\alpha = 14^\circ$

Figure 13: Pressure contour results from CFD simulation analysis

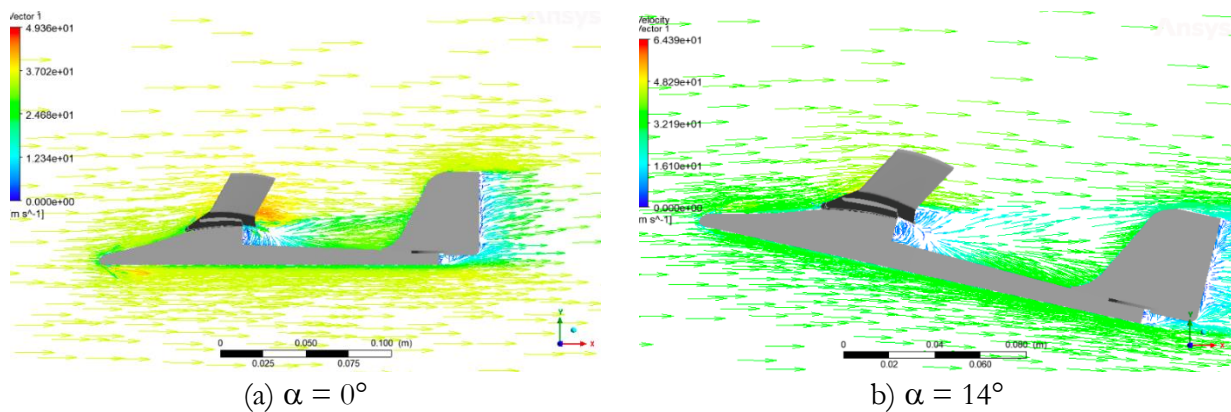


Figure 14: Velocity vector results from CFD simulation analysis

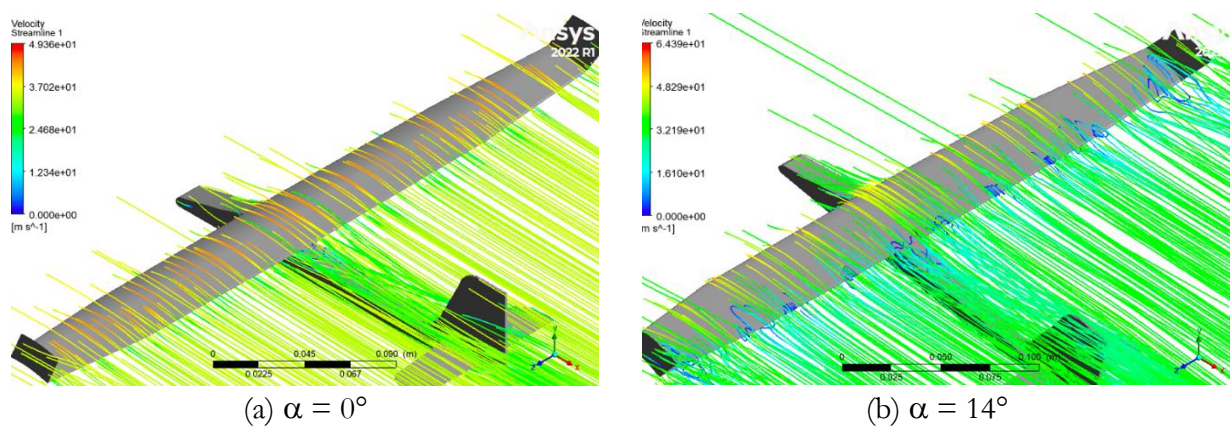


Figure 15: Velocity streamline results from CFD simulation analysis

4. Conclusion

In this study, the aerodynamic performance characteristics such as C_L , C_D and L/D of the existing energy glider and the modified energy glider with winglets have been successfully determined through CFD simulation in ANSYS Fluent. The obtained CFD results enable the study of the flow around the glider, as well as creating an improved design. There may be limitations faced due to the performance of the model. Overall, the results obtained from this research are proven to be successful and beneficial. Based on the results obtained, the modified UiTM's energy glider design with winglets has been shown to have better aerodynamic performance than existing design, especially in having a higher L/D . Further study can be further conducted in future to improve the glider design.

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References

- [1] S. Martin. (2015). How Gliders Fly and How They're Different Than Powered Aircraft. Retrieved from www.boldmethod.com/blog/article/2015/02/your-guide-to-glider
- [2] M. K. A. Muhamad and B. Basuno, 'A Long Endurance of Single Seater Glider Aircraft Design', *Journal of Aviation and Aerospace Technology*, vol. 1, no. 1, 2019.

-
- [3] Federal Aviation Administration, *Glider Flying Handbook*, Skyhorse Publishing Inc., 2007.
- [4] S. Shriwas, P. Singh, S. Shah and K. P. Kaurase, 'Introduction to Step Wing & Kline Fogleman Airfoil', *International Journal for Scientific Research & Development*, vol. 3, no. 2, pp. 503-506, 2015.
- [5] A. Kabir, Y. M. Akib, A. Hafiz and M. Islam, 'Comparison between Two Kline–Fogleman Modified (KFm) based Stepped Airfoils for Better Aerodynamic Performance', *International Conference on Innovation in Engineering and Technology (ICIET)*, Dhaka, Bangladesh, 23-24 December 2019.
- [6] A. Kabir, M. Islam, N. Jahan, Y. M. Akib and M. I. J. Mili, 'Numerical Simulation and Comparative Study of Aerodynamic Performance of Kline Fogleman Modified Backward Stepped Airfoils and the NACA 4415 Airfoil', *Bangladesh Maritime Journal*, vol. 5, no. 1, pp. 97-110, 2021.
- [7] G. Panagi, 'Investigation of Winglet Shapes on Aerodynamic Efficiency View Project', Bachelor Thesis, University of the West of England, 2019.
- [8] J. A. D. Ackroyd, 'Cayley's 1804 Glider', *Journal of Aeronautical History*, vol. 2019, pp. 98-107, 2019.
- [9] M. D. Maughmer, 'The Design of Winglets for Low-Speed Aircraft', *Technical Soaring*, vol. 30, no. 3, pp. 61-73, 2006.
- [10] H. Gongzhang and E. Axtelius, 'Aircraft Winglet Design', Project Report, KTH Royal Institute of Technology, 2020.
- [11] ANSYS FLUENT 12.0 Theory Guide. Retrieved from www.afs.enea.it/project/neptunius/docs/fluent/html/th/main_pre.htm
- [12] S. Hasman, 'Aerodynamics Performance of UiTM's Energy Glider with Winglet using CFD Simulations', Bachelor Thesis, Universiti Teknologi MARA, 2023.

GEOMETRICAL EFFECTS ON FUEL REGRESSION RATE IN MULTI-PORTS DESIGN HYBRID ROCKET MOTOR

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Abstract: The characteristics of a liquid and solid rocket motor are combined in a hybrid rocket motor. It is low-cost, safe, environmentally friendly and throttling-capable. However, the primary reason why hybrid rocket performance is not preferred over other rocket propulsion is its low regression rate. This study is concentrated on lab experiments and analytical calculations related to hybrid rocket motors. A single-port, three-port and four-port shape has been created and built using Solidworks software. The goal of this study is to determine how the number of ports and the oxidizer pressure affect the hybrid rocket motor's regression rate. The performance of the hybrid rocket motor will be represented by this regression rate, which can either increase or decrease. In the lab-scale experiment, the gaseous oxygen is used as the oxidant and paraffin wax as the fuel. The results show that a 200 kPa pressure oxidizer performs better than a 100 kPa, with a difference of 0.0012 m/s at 1 port, 0.0004 m/s at 3 port and 0.0024 m/s at 4 port. The final result demonstrates that four ports at 200 kPa achieved the highest regression rate, which was 0.0073 m/s. On the whole, the results indicate that increasing the number of ports and also oxidizer pressure will improve the regression rate and therefore subsequently increase the performance of the hybrid rocket motor.

Keywords: hybrid rocket motor; multiport geometry; regression rate; hybrid rocket fuel

NOMENCLATURE

A	: Area (m ²)	P_{atm}	: Ambient pressure (Pa)
a	: Regression rate coefficient	P_c	: Chamber pressure (Pa)
F	: Thrust force (N)	P_e	: Exit pressure (Pa)
G	: Mass flux (kg/m ² .s)	P_o	: Stagnation pressure (Pa)
g	: Gravitational constant (Nm ² /kg ²)	R	: Gas constant (J/kg.K)
I_{sp}	: Specific impulse (s)	\dot{r}	: Fuel regression rate (m/s)
L_p	: Port length (m)	r_{after}	: Radius after (m)
m	: Fuel length exponent	r_{before}	: Radius before (m)
m_{final}	: Final mass (kg)	T_c	: Chamber temperature (K)
$m_{initial}$: Initial mass (kg)	t_b	: Burning time (s)
\dot{m}	: Mass flow rate	V	: Velocity (m/s)
N	: Number of ports	γ	: Specific heat ratio
n	: Mass flux exponent	ρ	: Density

1. Introduction

Typically, liquid propellant is used as the oxidant while solid propellant is used as the fuel in hybrid rocket motors (HRMs). Hybrid rocket motors have several benefits, one of which is their safety [1]-[4]. In comparison to the rockets powered by liquid or solid fuel, hybrids are less likely to explode or fail catastrophically. This is because, unlike liquid or solid rocket motors, they use solid fuel grains, which cannot burst. Compared to solid rocket motors, hybrid rocket motors provide more controllability [2]-[9]. Precise thrust control is possible by adjusting the oxidizer flow rate to the fuel flow rate. In general, the cost of manufacturing and operating hybrid rocket motors is also lower than that of liquid or solid rocket motors [10]-[14]. This is because they may be produced using less expensive materials and require a smaller number of intricate components. Because of this, HRMs are drawn to the propulsion systems that can be used for a variety of purposes such as spacecraft propulsion systems, launch vehicles and sounding rockets. Nonetheless, HRMs have two clear disadvantages as a result of the characteristics of non-premixed diffusion combustion: the intrinsically low combustion efficiency and regression rate [2, 10, 15]. In HRMs, the fuel regression rate is the speed at which the fuel surface retreats during a burn. Due to the similar specific impulses of the different hydrocarbon fuels burned with a given oxidizer, this quantity has the first-order effects on the configuration (i.e. length and diameter of the combustion chamber) and consequently the performance of the motor [5, 9, 15]. For a single port motor, a high regression fuel will result in a combustion chamber design that is larger in diameter and shorter than a motor that uses a low regression rate fuel [4, 9]. Regression rate data accuracy is essential for comparing propellants, sizing fuel grains, forecasting hybrid motor performance and preventing burn-throughs.

Numerous studies have been carried out in an attempt to address these two issues. According to the results of 15 static firing tests, the fuel regression rate increases as the chamber pressure rises and decreases as the oxidizer port velocity increases. Axial-injection end-burning type fuel grains by high-accuracy three-dimensional printing have been developed in Ref. [2]. Moreover, the results from studies on the effectiveness of HRMs using the paraffin-based solid fuels in Ref. [3] and Ref. [4] have indicated that the fuels can increase the regression rate. This is highlighted in Figure 1 and Figure 2. Furthermore, the experimental result demonstrated that the application of simple cylindrical multiport design reduces the length-to-diameter ratio of the hybrid thruster and also improves rocket combustion performance. In the meantime, a multiport grain used in a hydrogen peroxide hybrid rocket motor is designed in Ref. [16] as depicted in Figure 3. According to the experimental data, as the number of ports increased, the regression rate improved and the O/F ratio fell while the oxygen mass flow rate remained constant.

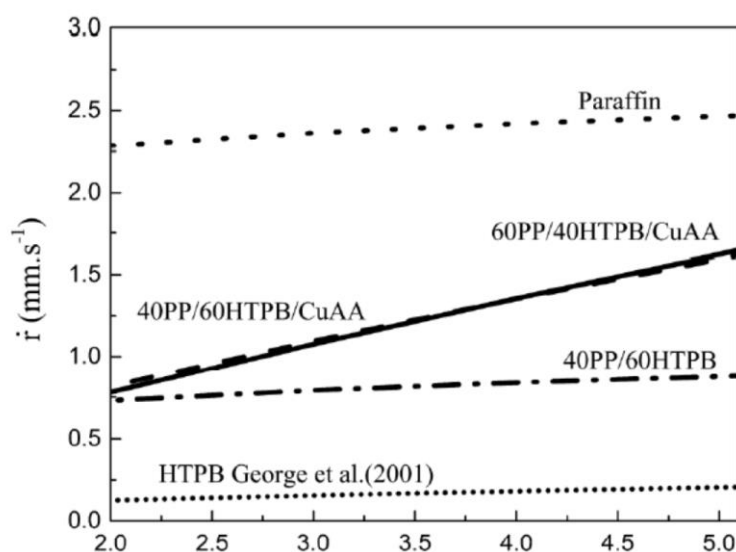


Figure 1: Comparison of regression rates of the four grains [3]

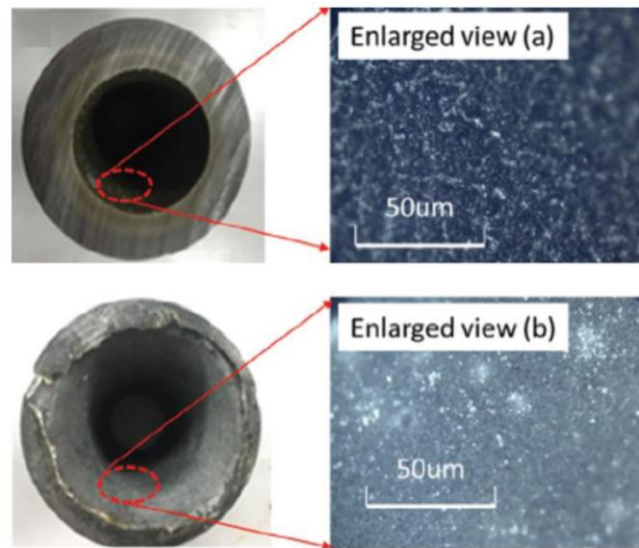


Figure 2: Solid fuel before and after firing test [3]



Figure 3: Final ports of the head and back end of the cross-sectional configuration of the HDPE solid fuel grain both before and after the test of hot firing for 1 port, 2 ports, 3 ports and 14 ports [16]

The oxidizer-to-fuel ratio has been shown to be positively shifted to almost its optimal value as the number of ports increases and the increase in the regression rate is reduced beyond four ports [17]. The hybrid rocket motor with multi-port fuel grain has been numerically and experimentally studied in Ref. [8] and Ref. [9]. The findings have demonstrated a relationship between the fuel port profile and flame location and the fuel regression rate distribution. Numerous studies demonstrate that segmented grain design may enhance combustion performance.

Based on findings from previous studies, the purpose of this work is to examine the combustion performance and local regression rate distribution of multi-segmented grains. Furthermore, a thorough analysis is conducted using the numerical simulation results to determine the impact of the segmented grain number and rotation between them, the segmented grain port numbers and the mid-chamber length on the performances. To determine how the grain design affects regression rate and combustion efficiency, aspects of steady flow fields and temperature distributions are examined.

2. Methodology

As indicated, the purpose of this study is to examine how various geometric configurations of the multiport designs affect various mass fluxes on regression rates. To analyze the impact on the regression rate of the hybrid rocket motors, several multiport design geometries were used in conjunction with the fuel and additive preparation. The design specifications have been completely specified, including the parameters to be measured, the cost and the availability of materials. Table 1 tabulates the measurements that were selected to fit the testbed at the IIUM Propulsion Lab. The experiment was conducted using paraffin wax as fuel and oxygen gas as an oxidizer. Furthermore, it has been shown that paraffin wax burns three times faster than regular fuel, achieves substantial thrust and performance, and is much less expensive, non-toxic and also safer than liquid oxygen (GOX). Throughout the experiment, numerous circular ports were used. The fuel requirements listed in Table 1 serve as the indicator. On the other hand, Figure 4 shows how the ports were arranged within the grain, as well as the diameter after firing. The images represent the outcomes of the three cases in this research.

Table 1: Experimental fuel specification

Specification	Fuel Casing (Aluminium)	Fuel		
		1-Port	3-Port	4-Port
Length (mm)	300	280	280	280
Outer diameter (mm)	101.6	95.6	95.6	95.6
Average mass (kg)	0.827	2.440	2.307	2.233

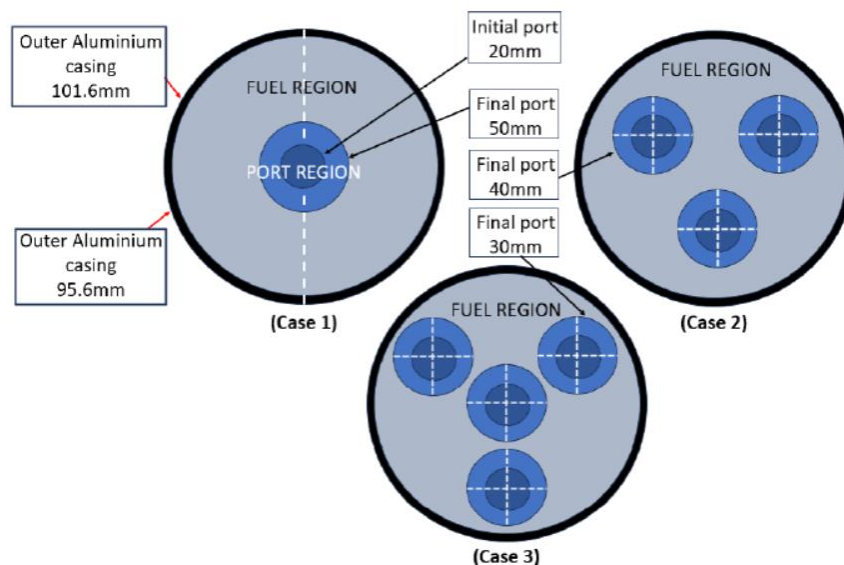


Figure 4: Port configuration and the diameter of the port grain after

Figure 5 illustrates the set-up of the hybrid rocket together with the placements each sensor. In the meantime, a schematic diagram illustrating the connections of every component in the hybrid rocket motor testbed is shown in Figure 6.

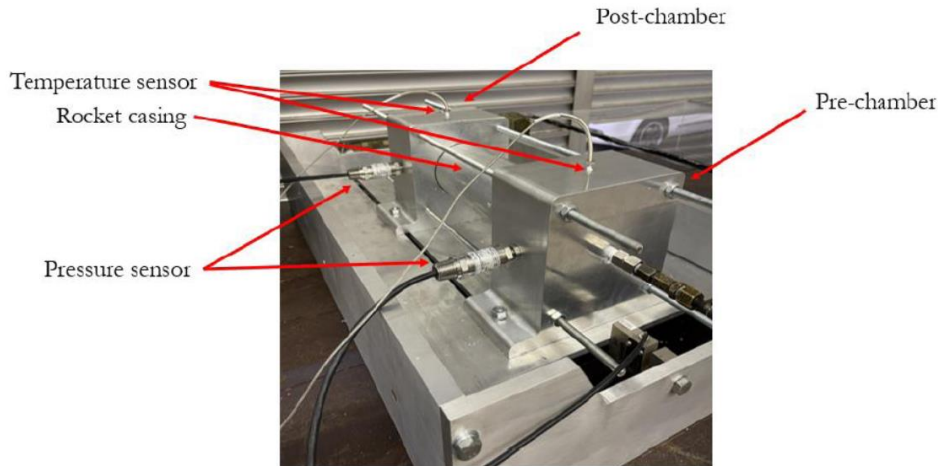


Figure 5: Experiment set up for this study

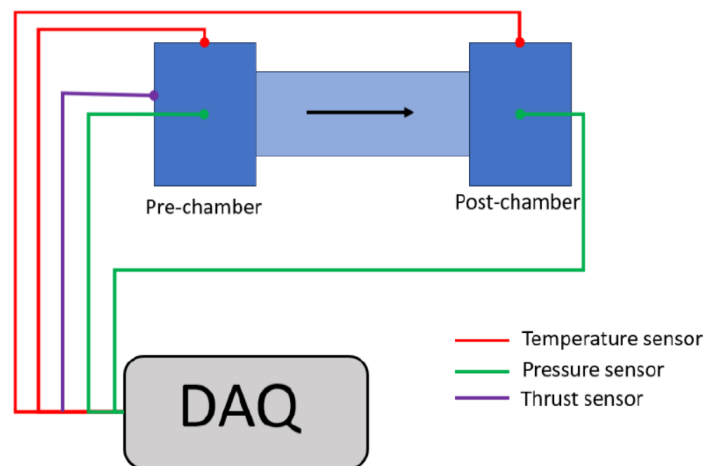


Figure 6: Schematic diagram of the HRM

On the other hand, Figure 7 depicts the feeding mechanism. The oxidizer is gaseous oxygen under self-pressurization without compressor. The following components were included: (1) gaseous oxygen (GOX) tank; (2) main tank cutoff valve; (3) GOX tank pressure gauge; (4) GOX supply pressure regulator; (5) GOX supply pressure gauge; (6) ball valve and (7) motor rocket with a feeding line, port, and convergent-divergent nozzle. Regarding the multiport, the feeding mechanism that was used only modified the fuel in the grain using either 3 or 4 ports.

A tube, hose, steel reducer, steel join, solenoid valve, ball valve and self-pressurized oxygen gas tank served as the feed system. A 10L GOX tank was used as the oxidizer since it was easy to operate and did not require injectors. Another reason is that it is easier to replenish and widely accessible on the market than other oxidizers. Just a basic match makes up the igniting mechanism. The matches were wrapped in a steel wool thread and fastened to a nichrome wire. The wires link the steel wool to a battery supply. Applying a current causes the steel wool to burn, which is followed by lighting the match at the end of the fuel. In Figure 8, the circuit is shown.

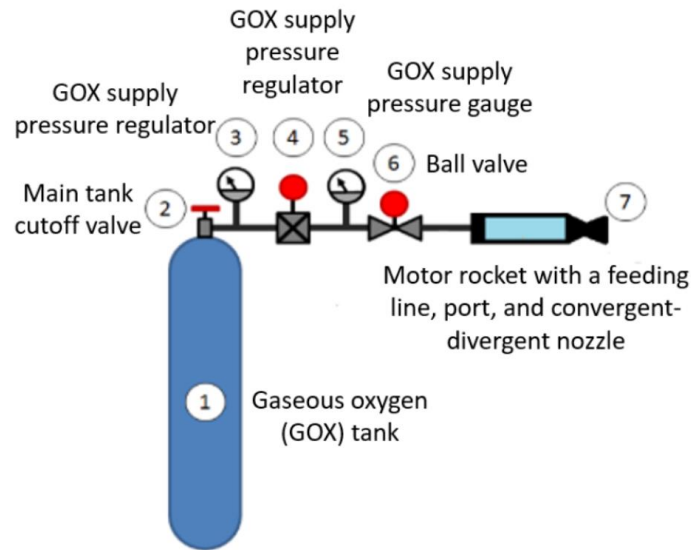


Figure 7: Feeding system

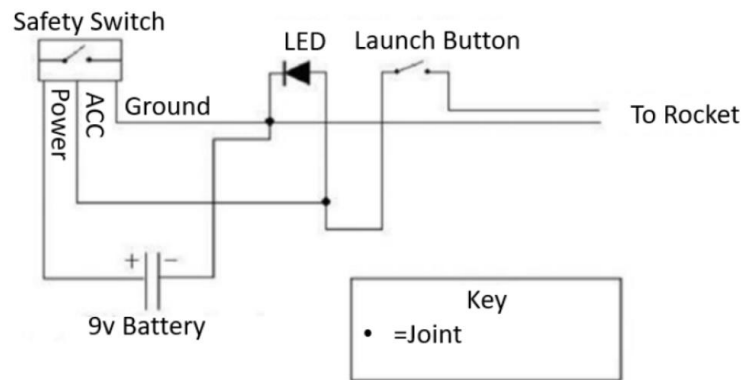


Figure 8: Ignition controller circuit

Regression rate, thrust and exit velocity are examples of performance metrics that were calculated using the relationships given in the following equations. Several crucial parameters such as temperature (in K) and pressure (in kPa) were entered into the formula after the experiment to determine the velocity exit, thrust and regression rate.

$$V_{\text{exit}} = \sqrt{\frac{2\gamma RT_c}{(\gamma - 1)} \left(1 - \left(\frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \right)} \quad (1)$$

$$\dot{m}_{\text{prop}} = \frac{m_{\text{after}} - m_{\text{before}}}{t_b} \quad (2)$$

$$F = \dot{m}_{\text{prop}} V_{\text{exit}} + (\rho_{\text{exit}} - \rho_{\text{atm}}) A \quad (3)$$

$$I_{\text{sp}} = \frac{F}{\dot{m}_{\text{ox}} g_o} \quad (4)$$

$$G_0 = \frac{\dot{m}_o}{NA_p} \quad (5)$$

$$\dot{r} = \frac{r_{\text{after}} - r_{\text{before}}}{t_b} \quad (6)$$

3. Results and Discussion

Three distinct cases were divided up in this study. Two different pressure oxidizers were used for each type of port. Theoretically, the oxidizer-to-fuel ratio would rise along with the input pressure such that it would result in the increase of the HRM regression rate. This investigation was carried out using 200 kPa and 100 kPa. Table 2 illustrates the radius change results for each pressure oxidizer of all three cases.

Table 2: Experimental results data

Case	Pressure Oxidizer (kPa)	Burn Time (s)	Radius Port Before (m)	Radius Port After (m)
1	100	23	0.02	0.05
	200	12	0.02	0.05
2	100	26	0.02	0.04
	200	19	0.02	0.04
3	100	9	0.02	0.03
	200	3	0.02	0.03

The regression rate of the HRM can be obtained from Table 2 by applying the change in the radius divide with the burn time. Note that during each firing process, the fuel was never burned completely since the port changes before and after had to be analyzed. The outcome is tabulated in Table 3 after applying previous Equation 1 to Equation 6. These tables show the HRM's performance as well as the regression rate from various pressure oxidizers and ports.

Table 3: Calculated results from the experimental data

Case	Mass Flux (G_0)	Mass Flow Rate (kg/s)	Thrust, F (N)	Exit Velocity, V_e (m/s)	Regression Rate (m/s)
1	61.54	0.01	149.47	557.66	0.0011
	531.05	0.03	110.68	510.12	0.0023
2	20.51	0.04	93.90	604.31	0.0024
	177.02	0.04	198.32	693.16	0.0030
3	15.38	0.03	156.48	750.61	0.0049
	134.53	0.04	109.37	493.15	0.0073

According to the outcome, case 3 at 200 kPa achieved the maximum regression, which was 0.0073 m/s. The burning area in the grain will rise as the number of ports increases, which will also boost the HRM's combustion efficiency. Theoretically, as the pressure inlet increases, the HRM's velocity exit should go up as well. However, because the fuel wall between the cores collapsed and became one large core, case 3's velocity exit was only achieved at 493.15 m/s at 200 kPa. Figure 9 and Figure 10 illustrate the outcomes of the static firing. It is obvious that when the number of ports increases, a larger flame is produced as a result of the more fuel burn in port grain.



Figure 9: Single port with oxidizer pressure of 100 kPa



Figure 10: Four port with oxidizer pressure of 100 kPa

Furthermore, based on the regression rate result in Table 3, a bar graph is generated and displayed in Figure 11. Regression rate is chosen since it represents a critical issue that the HRM has encountered. According to the three cases, it can be seen that in both pressure oxidizers, four ports have significantly higher capacity than one port and 3 ports. Regression rate is increased from 0.0011 m/s to 0.0023 m/s for a single port as the pressure oxidizer changes. In the meantime, the pressure oxidizer changes only slightly for 3 ports. This indicates that increasing the pressure oxidizer does not greatly enhance the regression rate if there is no core at the center, such as port 3. The regression rate is largest at port 4, where it is 0.0049 m/s at 100 kPa and 0.0073 m/s at 200 kPa. Fuel results before and after the firing operation are displayed in Figure 12.

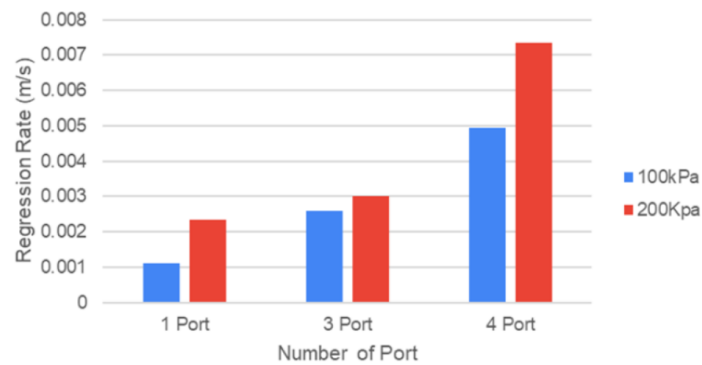
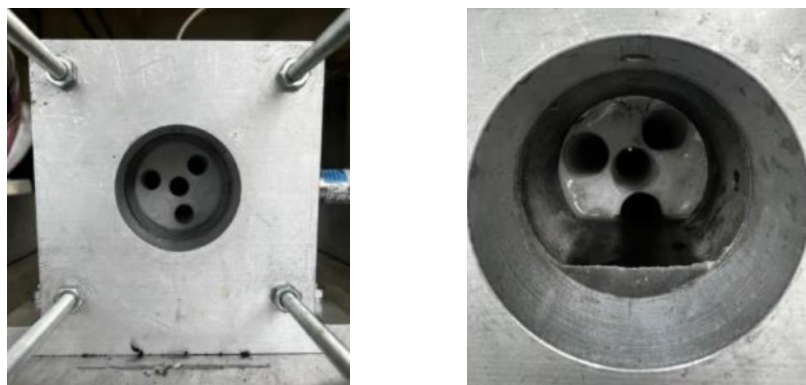


Figure 11: Regression of three types of port with various pressure oxidizer



(a) Before firing

(b) After firing

Figure 12: Four ports at 100 kPa

4. Conclusion

A few techniques for increasing the fuel's regression rate are the main subject of this study. While there exist other alternative methods, the primary focus of this paper is on the experimental multiport design with variable mass flux. A lab-scale hybrid rocket test facility has been successfully constructed using accessible components. Some conclusions can be drawn based on the obtained results:

- The fuel grain's geometry can enhance the regression rate by using numerous circular ports.
- The transient performance of the hybrid rocket can be greatly influenced by preliminary designs, starting mass flux, and number of ports used.
- The selection of oxidizers and fuels is a crucial factor in attaining enhanced performance, in addition to its thermochemical characteristics.

Acknowledgement

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References

- [1] B. Vignesh and R. Kumar, 'Effect of Multi-Location Swirl Injection on the Performance of Hybrid Rocket Motor', *Acta Astronautica*, vol. 176, pp. 111-123, 2020.

- [2] Y. Saito, T. Yokoi, H. Yasukochi, K. Soeda, T. Totani, M. Wakita and H. Nagata, 'Fuel Regression Characteristics of a Novel Axial-Injection End-Burning Hybrid Rocket', *Journal of Propulsion and Power*, vol. 34, no. 1, pp. 247-259, 2018.
- [3] K. P. Cardoso, L. F. A. Ferrão, E. Y. Kawachi, J. S. Gomes and M. Y. Nagamachi, 'Ballistic Performance of Paraffin-based Solid Fuels Enhanced by Catalytic Polymer Degradation', *Journal of Propulsion and Power*, vol. 35, no. 1, pp. 182-189, 2019.
- [4] G. Cai, Z. Zhao, B. Zhao, Y. Liu and N. Yu, 'Regression Rate and Combustion Performance Investigation on Hybrid Rocket Motor with Head-end Swirl Injection Under High Geometric Swirl Number', *Aerospace Science and Technology*, vol. 103, 2020.
- [5] B. Zhao, N. Yu, Y. Liu, P. Zeng and J. Wang, 'Unsteady Simulation and Experimental Study of Hydrogen Peroxide Throttleable Catalyst Hybrid Rocket Motor', *Aerospace Science and Technology*, vol. 76, pp. 27-36, 2018.
- [6] B. Kahraman, H. Karakas, B. N. Eren and A. Karabeyoglu, 'Erosion Rate Investigation of Various Nozzle Materials in Hybrid Rocket Motors', *Proceedings of the AIAA Propulsion and Energy Forum*, Online, August 2020.
- [7] L. Liu, X. He, Y. Wang, Z. Chen and Q. Guo, 'Regression Rate of Paraffin-based Fuels in Hybrid Rocket Motor', *Aerospace Science and Technology*, vol. 107, 2020.
- [8] H. Tian, Z. Guo, Z. Hao, L. Hedong and C. Li, 'Numerical and Experimental Investigation of Throttleable Hybrid Rocket Motor with Aerospoke Nozzle', *Aerospace Science and Technology*, vol. 106, 2020.
- [9] G. Cai, Z. Zhao, B. Zhao, Y. Liu and N. Yu, 'Regression Rate and Combustion Performance Investigation on Hybrid Rocket Motor with Head-end Swirl Injection under High Geometric Swirl Number', *Aerospace Science and Technology*, vol. 103, 2020.
- [10] Y. Wu, X. Yu, X. Lin, S. Li, X. Wei, C. Zhu and L. Wu, 'Experimental Investigation of Fuel Composition and Mix-enhancer Effects on the Performance of Paraffin-based Hybrid Rocket Motors', *Aerospace Science and Technology*, vol. 82, pp. 620-627, 2018.
- [11] M. N. F. M. Anuar, M. J. Sujana, I. Ismail and M. H. Azami, 'Experimental Evaluation on the Effects of Energetic Additives in the Hybrid Rocket Fuel', *Journal of Transport System Engineering*, vol. 11, no. 1, pp.13-21, 2024.
- [12] M. Franco, F. Barato, E. Paccagnella, M. Santi, A. Battiston, A. Comazzetto and D. Pavarin, 'Regression Rate Design Tailoring Through Vortex Injection in Hybrid Rocket Motors', *Journal of Spacecraft and Rockets*, vol. 57, no. 2, pp. 278-290, 2020.
- [13] T. Hui, D. Yu and Z. Hao, 'Three-dimensional Numerical Analysis on Combustion Performance and Flow of Hybrid Rocket Motor with Multi-Segmented Grain', *Chinese Journal of Aeronautics*, vol. 33, no. 4, pp. 1181-1191, 2020.
- [14] K. Veale, S. Adali, J. Pitot and M. Brooks, 'A Review of the Performance and Structural Considerations of Paraffin Wax Hybrid Rocket Fuels with Additives', *Acta Astronautica*, vol. 141, pp. 196-208, 2017.
- [15] K. Budzinski, S. S. Aphale, E. K. Ismael, G. Surina and P. E. DesJardin, 'Radiation Heat Transfer in Ablating Boundary Layer Combustion Theory Used for Hybrid Rocket Motor Analysis', *Combustion and Flame*, vol. 217, pp. 248-261, 2020.
- [16] B. Ahn, H. Kang, E. Lee, Y. Yun and S. Kwon, 'Design of Multiport Grain with Hydrogen Peroxide Hybrid Rocket', *Journal of Propulsion and Power*, vol. 34, no. 5, pp. 1189-1197, 2018.
- [17] H. Nagata, H. Shunsuke, Y. Kaneko, M. Wakita, T. Totani and T. Uematsu, 'Development of Regression Formulas for CAMUI-type Hybrid Rockets as Functions of Local O/F', *Proceeding of 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Nashville, USA, July 2010.
- [18] H. Tian, X. Li, P. Zeng, N. Yu and G. Cai, 'Numerical and Experimental Studies of the Hybrid Rocket Motor with Multi-Port Fuel Grain', *Acta Astronautica*, vol. 96, no. 1, pp. 261-268, 2014.

DEVELOPMENT AND IMPLEMENTATION OF VIRTUAL REALITY IN HIGHER EDUCATION FOR AVIATION: A CASE STUDY

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Abstract: This paper aims to introduce a practical approach for incorporating the virtual reality (VR) technology in aircraft operational maintenance training within aviation-oriented educational curriculum. Firstly, the development stages of the VR application are outlined. Subsequently, the paper elaborates further on the specific steps for integrating this VR application and its related instructional content into educational settings. Preliminary surveys and also feedback from the students have highlighted the VR's educational values for aviation-focused programs. All in all, this presented work is demonstrating how educators can practically and effectively integrate an advanced technology into the existing curricula to enhance student engagement and also interest within a university setting.

Keywords: virtual reality; aircraft maintenance; air transport management; experiential learning

1. Introduction

Virtual reality (VR) related technologies [1], which have been formulated in years 1960s [2], have recently been predicted as the potential booster for global economic growth. VR is expected to highly impact the development of digital economy in various fields including engineering, healthcare, training and education [2]. To date, this emerging technology has already demonstrated several major effects in improving productivity, efficiency and also operational costs. For instance, VR technology has shown its great benefits in product design and development areas [3-5]. Moreover, in training and education, many studies have highlighted the benefits in using VR, especially for procedural tasks, by enhancing learners' engagement and outcome [6-8]. In particular areas where content relevance and technological maturity are crucial, the adoption of specific VR-tech based applications remains constrained due to several inherent barriers [8]. These limitations become even more pronounced in the aviation sector, particularly in aircraft-related operations that are subject to very strict regulatory requirements by state and authoritative bodies concerned with safety within the industry. As a result, this situation leads to many challenges related to the costs and also the time required to develop the appropriate sophisticated applications for both industrial and educational use in aviation-related activities.

Any miscommunication and misunderstanding of the operating procedures of an aircraft can have serious impact on the safety of flight or maintenance operation [9]. The use of VR technology in aircraft training has several great advantages that include increased safety, cost savings, enhanced learning and improved skill transfer [10]. At the moment, in aviation industry, VR-related technologies have recently been deployed in training for some specific applications such as flight simulators for pilots, turnaround inspections and also marshalling for ground crew [11]. On the other hand, for aircraft engineering and

maintenance, very few VR-based applications are found in the published literature [12-13]. Additionally, it is also worth noting that not many works found in literature disclose or explain clearly with sufficient details about specific procedure (with clear references) to mimic and also produce the appropriate VR-applications, especially involving “real applications” with data directly sourced from the aircraft OEMs (such as Airbus or Boeing). Without these information, it is hard to claim that the applications are really applicable to real industry applications, which are strictly regulated by aviation authorities. Particularly, there is a lack of comprehensive strategies and practical approach for an effective integration of the VR applications into higher education programs in aviation. A conducted survey on 26 students of a first year university program has shown interesting results for the VR application [13], but it lacked a detailed explanation about the approaches or framework for integrating such systems into the higher education curricula.

Based on the current state of VR application, it is the primary objective of this study to present a comprehensive practical approach to incorporate emerging technologies such as VR into educational programs in institutes of higher learning. This research work outlines the development of a VR-based application from the beginning, along with the strategy and essential steps for integrating this advanced technology-based application into an existing curriculum. Initial feedback from the preliminary groups of student participants is also shared, which provides some insights into the effectiveness of the research project and recommendations for future enhancements.

2. Methodology

In this study, the implementation of the self-developed VR-based application follows two primary stages:

- **Development:** New specific VR applications, which are relevant for the purpose of teaching and training, are developed from scratch
- **Implementation:** The developed VR applications are integrated into the formal teaching curricula in universities. In this case, an aviation-related educational programs in Singapore has been selected. Feedback from the users or learners are collected within each of the stages as the indicators or measures for effectiveness and improvements of the VR applications as well as the related teaching approach

For the first stage, the VR application is developed using four phases in loop as indicated in Figure 1, namely analysis, design, development, and test and feedback. Each of the phases consists of several interconnected tasks that need to be addressed [14]. In this study, the maintenance procedure relating to removal of the nose landing gear (NLG) wheel system of an Airbus A320 aircraft, the most popular narrow body aircraft type around the world, is selected. It should be noted that the maintenance work on landing gear wheel systems, such as removal or installation, is the daily tasks of aircraft engineers in real life.

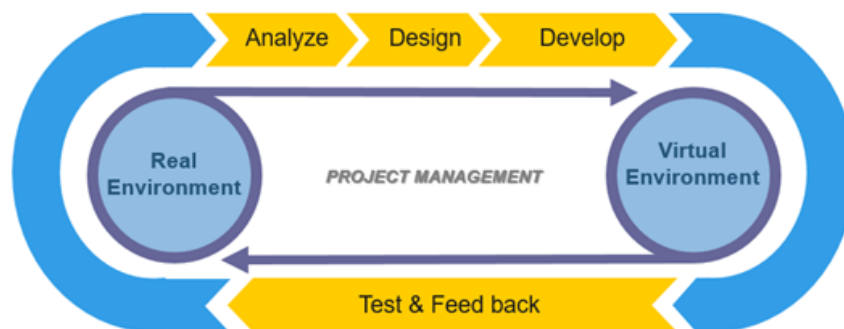


Figure 1: Development phases of VR application

In short, the analysis phase requires a careful analysis of procedural tasks involved in the selected maintenance work. The Airbus AMM procedures coded as “32-41-12-000-001-A” and “32-41-12-400-001-A” that are referenced for removal and installation of the NLG wheel system of an Airbus A320 are utilized [15]. The reference documents provide a detailed guideline to perform the maintenance job such as the safety warning, job set-up information, work zones, referenced, job set-up and also working procedure. Meanwhile, following design phase of the information system include determination of the simulation flow, designing the users’ interfaces and experience in the virtual environment. Two practical modes, including training mode and also assessment mode, have been designed. Following the selected maintenance procedure, several working scenes including in the aircraft cockpit and on parking ramp are simulated. In this study, the selected VR devices are Oculus Quest 3, a standalone headset equipped with two controllers that allow to integrate virtual hands to interact with virtual environment [16]. Next, development phase is to implement the design ideas and carry out the development of VR application. Studying and determining the appropriate program development workflow, from the modeling of 3D objects using CAD software to coding and integrating in VR devices, is crucial for the success of the project. In this study, the full-scale 3D models are created utilizing the computer-aided design (CAD) software (i.e. Solidworks), texturing is carried out by using free software “Blender” and finally the open source C# language-based VR platform, “Unity” is utilized. Last but not least, the next successive phase “testing” involves activities carried out by experienced experts to verify if the VR application has been well-developed and produced from the information technology perspectives and also from procedural compliance perspectives. Testing and verifying whether the developed VR application can properly and adequately reflect the reality in the aircraft maintenance practices are vital for the success of this kind of applied research following the strict requirements from authorities and industry. In this study, several experienced aircraft maintenance experts, who have more than 10 years of direct experiences with the certified qualifications from Vietnam Civil Aviation Authorities, are invited to test the VR application and give their critical feedback for gradual improvement. In addition, other target end users of the VR application such as students and trainers are involved in this phase to give their perception feedback.

On the other hand, for the implementation stage, it is realized that the developed VR application could be used in various training and educational programs at different levels (i.e. vocational or bachelor degrees) that are related to aviation for appropriate modules or courses. Moreover, when considering how to integrate new content, especially involving emerging technologies, into an existing content and program, there are two viable approaches: creating a separate module or incorporating into the existing module(s). For this pilot study, the latter option is done. Incorporating modern technologies directly into existing curriculum offers several benefits, including seamless integration with minimal disruption to the current educational structure. This approach not only help to enhance the comprehension of the traditional content by placing it in a modern technological context, but it is also less resource-intensive as well compared to creating a new module. For this study, the application is incorporated into the Maintenance Management module within the existing Air Transport Management (ATM) program for the Bachelor of Science degree in an autonomous university, Singapore Institute of Technology (SIT). The existing curriculum of the related course has been modified by introducing a new content called “Emerging Technology and Digitalization in Aircraft Maintenance”, which is taught in two in-class sessions accounting for 15% of the total in-class time of the related module (i.e. a module has 6 credits and the total degree program consists of 180 credits). The main goal is to provide an awareness level to the students of such a highly specialized VR-application. With regards to the scope and also the allotted time in current formal module, the content for teaching is limited to only introduction of VR technology and practicing awareness for learners. The content aims to provide students with an appreciation of such emerging technology with application in the field, in addition to learning of a particular standard aircraft operation related industrial procedure (i.e. aircraft maintenance on A320’s landing gear system) that is strictly regulated in all phases. Through this, learners could enjoy their first experience in reality-

like working environment on commercial airplane with trained safety awareness as strict requirements in any real industrial aircraft-related procedures.

Table 1 summarizes the sequence of the in-class teaching steps. What is novel about this practical approach is that, prior to instructing the learners on use of VR applications, a workshop is conducted (i.e. Step 3) on emerging technologies to provide detailed insights into development of sophisticated VR-based application from scratch, using the limited resources available in the university setting. This approach equips the students with a deep understanding of the related technologies such as VR, which in turn enhances their appreciation of how these emerging technologies can be applied to their specific learning content in the subsequent step (i.e. Step 4). Furthermore, surveys are also conducted before and after the session in order to get information and feedback from learners. In this case, the purpose of before-training survey is to know the background and knowledge level of the participants about VR and the subject while the after-training survey is intended to investigate the learners' first perception on the effectiveness of the VR-based teaching.

Table 1: Step-by-step teaching approach using VR

Steps	Activity	Description	Supporting tools, equipment
1	Pre-training survey	To investigate learners' profile and background.	Online survey form (Google sheet)
2	Lecture	To lecture learners the involved aircraft related procedure (Airbus AMM) using classical technique of teaching (without support of VR application and devices).	Documents (pdf format) Ex. Airbus AMM
3	Workshop	To present principles of Virtual reality technology and development phases of a new application (in aviation).	VR devices (Oculus Quest 2 or 3 for demonstration)
4	Virtual Reality practice	To teach learners to understand the involved procedure (Airbus AMM) by practicing in VR. Several steps are presented: (i) familiarize the VR devices; (ii) familiarize the VR working environment and practicing required tasks; (iii) assessment (group).	VR application and devices (Oculus Quest 2 or 3); 7 units of devices were employed in class for this pilot project
5	Post-training survey	To preliminarily investigate learners' interest and feedback.	Online survey form (Google sheet)

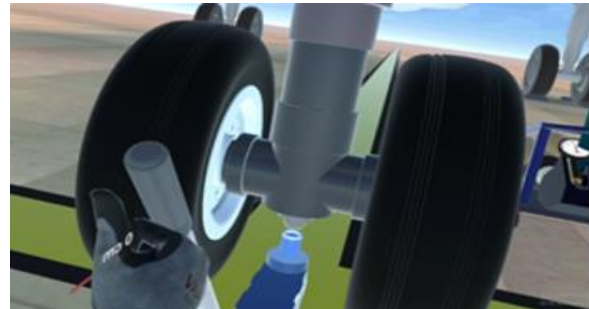
3. Results and Discussion

3D full-scale models of the Airbus A320 aircraft, related component assembly, tools, equipment and accessories (i.e. safety tag), which are associated with the involved Airbus AMM procedures, are modeled using CAD software tool. In addition, the corresponding work environment and scenes where

the selected maintenance actions will be carried out such as the parking ramp, aircraft’s cockpit and the others are also well modeled in the application. As typical examples demonstrating the success of the current project, Figure 2 and Figure 3 represent the comparison between a real-life maintenance action and developed VR-based simulations on the studied aircraft systems for jacking the nose landing gear and removing two locking nuts in the assembly of the Airbus A320 aircraft, respectively.



(a) Reality

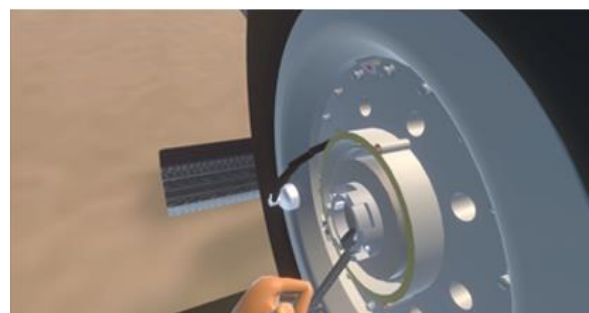


(b) Virtual simulation

Figure 2: Jacking of the nose landing gear for Airbus A320 aircraft



(a) Reality



(b) Virtual simulation

Figure 3: Removal of two locking nuts (Ref. AMM task 32-41-12-020-050-A)

For this pilot study in implementing the VR application, constructed surveys have been designed and tailored to obtain the essential initial feedback from students enrolled in the module of “aircraft maintenance management” in Air Transport Management degree program at SIT. One class is typically consisted of 60 students, in which relevant 36 students (i.e. more than 50% of the class size) have joined the full VR-related teaching sessions as depicted in Figure 4. They all have responded to the conducted surveys. It should be noted that the majority or approximately 97.2% of the student participants were in the second year of the training program.



(a) Familiarize with VR device



(b) Virtually conducting the system assembly task

Figure 4: Students’ gestures during VR-based training session in class

In this study, the age of the participants is predominantly between 18 to 25 years old, constituting 91.7% of the cohort, with a smaller segment of 8.3% between the ages of 26 to 35 years old. Regarding gender, 66.7% of the participants are male and the rest are female. Furthermore, a prior experience with VR as claimed by the learners varies: 45.1% of them had no previous VR experience, 47.1% of them had limited experience whereas the small remaining percentage had moderate VR experience. The post-training survey data reveals the amount of time participants spent practicing with the VR application. 38.9% of them have engaged with VR tool for 1 to 3 hours. The remaining 61.1% of them reported spending less than 1 hour on the VR application, indicating a brief introductory interaction with the technology due to the VR-devices and the time limitation of the training sessions designed to be concise in this pilot study. After the training, the learners in the VR training program provided their feedback across several aspects. The survey addresses overall perception of the learners regarding the relevancy and efficacy of VR-based teaching method in aiding the intended learning outcomes like understanding of the knowledge and acquiring the skills applicable to the subject. The descriptive results of the five questions in post-training survey, rated over a 5-point Likert scale, are shown in Table 2. The learners' perception is considered 'positive' if rated 4 or 5 on the 5-point Likert scale, 'neutral' if rated 3 and 'negative' for the rating of 1 or 2.

Table 2: Descriptive results of the post-training survey

Question	Content	% Answers			Score	
		Positive (%)	Neutral (%)	Negative (%)	Mean	Mode
Q1	VR technology helps in understanding complex aircraft maintenance procedures	69.4	19.4	11.2	3.94	5
Q2	Effectiveness of VR compared to traditional learning methods	83.3	16.7	0.0	4.22	4
Q3	Impact of VR on interest in aircraft maintenance	77.8	19.4	2.8	4.11	4
Q4	Contribution of VR experiences to practical skills in aircraft maintenance	75.0	22.2	2.8	4.08	4
Q5	Accessibility of VR technology for educational needs in aircraft maintenance	52.7	33.3	14.0	3.53	3

On the whole, data in Table 2 indicates a favorable perception towards the VR technologies in the studied context. Some key insights and discussions can be drawn from this descriptive data. Firstly, a majority of 69.4% think that VR aids them in grasping the complex maintenance procedure. An average rating of 3.94 and a mode of 5.0 (out of 5.0) denote a consensus among the respondents. Secondly, the VR-based approach appears as superior to the traditional approach. This is acknowledged by 83.3% of the students, which is also reflected by the average score of 4.22 and a mode of 4.0 (out of 5.0) for the VR-based tools' attributes. Thirdly, VR-based teaching approach has successfully heightened interest in aircraft maintenance for 77.8% of the students. The impact, scoring an average of 4.11 with a mode of 4.0 (out of 5.0), suggests that VR not only make the learning process more engaging but also more intriguing, possibly leading to greater motivation among students. Moreover, 75% believe that VR has a role in enhancing their practical skill sets. The average score, which is approximately 4.08, and a mode of 4.0 (out of 5.0) indicate a generally positive belief in the VR contribution towards skills improvement. This is aligned with the VR's hands-on, experiential learning capabilities, which are vital in procedure-related training. Nonetheless, it should also be noted that accessibility rating is mixed, where 52.7% of the participants reported a satisfactory accessibility while 14% encountered difficulties and a third of them were ambivalent. In this case, the lowest average score of 3.53 and a mode of 3.0 (out of 5.0) can be taken to imply that the respondents found the VR technology moderately accessible for educational needs in this case application. Additionally, the post-training survey also include four open questions to identify specific features of VR-technology that the students find as most beneficial in enhancing their learning experience and to uncover any challenges that the learners encountered when using such technology. The results reveal that students find realistic simulation, hands-on practice, and also visual and interactive learning as the most beneficial aspects of the VR technology for learning aircraft maintenance procedures. However, they have also faced some challenges including physical discomfort (i.e. headset fit for Quest 3 glasses) and initial learning curve in getting accustomed to the VR system.

The students have proposed several improvements such as the multi-player functionality with enhanced audio integration and more practicing time.

4. Conclusion

This work has presented the full cycle of development and implementation of a VR-technology-based application, which is developed in-house from scratch into existing module within Air Transport Management degree program at SIT. The VR application is successfully developed from scratch to fully digitalize the selected work following the strict procedures from the aircraft manufacturer. This implies possible realization of affordable and accessible training solutions, which are based on emerging state-of-the-art technology, enable users including students, lecturers and professional personnel to learn and also practice aircraft-related tasks right in a room-based environment, avoiding any hazard and risks in actual physical working conditions surrounding commercial aircraft. Regarding the teaching approach, the obtained initial feedback from surveys after experiencing VR-training by the students in a university-level aviation program generally reflects the relevancy and efficacy of such practical implementation in this context of higher education. The compacted complex content that includes both the VR-technology and commercial aircraft operational related aspects, designed and taught in a time-constrained teaching session, has amplified initial success of this pilot project in terms of teaching outcomes.

For future works, current VR application will be expanded to other associated aircraft maintenance tasks as related to Airbus A320 ATA 32 system while some of the technical and ergonomic aspects will be improved. Other aircraft systems such as power plant, as well as additional aircraft types like Airbus 350 and Boeing 737 aircraft, can potentially be added as extension of current application. Furthermore, different environmental working conditions such as day, night, visibility levels and weather conditions could also be incorporated to evaluate their effects towards the completion of the maintenance work. Additionally, the presented development methodology can be applicable to many other critical missions in aviation such as emergency and safety (including emergency landing and evacuation, firefighting), or to daily operational activities of airlines (i.e. pre-flight checks). Last but not least, an in-depth study on the learning effectiveness for the target end-users (i.e. learners in various aviation-related programs and levels) will also be elaborated.

References

- [1] P. Milgram and H. Colquhoun, 'A Taxonomy of Real and Virtual World Display Integration', *Mixed Reality: Merging Real and Virtual Worlds*, vol. 1, pp. 1-26, 1999.
- [2] P. Cipresso, I. A. C. Giglioli, M. A. Raya and G. Riva, 'The Past, Present and Future of Virtual and Augmented Reality Research: A Network and Cluster Analysis of the Literature', *Frontiers in Psychology*, vol. 9, 2018.
- [3] M. Lorusso, M. Rossoni and G. Colombo, 'Conceptual Modeling in Product Design Within Virtual Reality Environments', *Computer-Aided Design and Applications*, vol. 18, no. 2, pp. 383-398, 2020.
- [4] P. A. Arrighi and C. Mougnot, 'Towards User Empowerment in Product Design: A Mixed Reality Tool for Interactive Virtual Prototyping', *Journal of Intelligent Manufacturing*, vol. 30, no. 2, pp. 743-754, 2019.
- [5] A. Berni and Y. Borgianni, 'Applications of Virtual Reality in Engineering and Product Design: Why, What, How, When and Where', *Electronics*, vol. 9, no. 7, 2020.
- [6] C. P. Fabris, J. A. Rathner, A. Y. Fong and C. P. Sevigny, 'Virtual Reality in Higher Education', *International Journal of Innovation in Science and Mathematics Education*, vol. 27, no. 8, 2019.
- [7] W. Alhalabi, 'Virtual Reality Systems Enhance Students' Achievements in Engineering Education', *Behaviour & Information Technology*, vol. 35, no. 11, pp. 919-925, 2016.

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- [8] C. D. Craig and R. Kay, 'A Systematic Overview of Reviews of the Use of Immersive Virtual Reality in Higher Education', *Higher Learning Research Communications*, vol. 13, no. 2, 2023.
- [9] S. A. Shukri, F. I. Romli, W. T. F. W. Badaruddin and A. S. Mahmood, 'Importance of English Language in Aviation Maintenance: A Malaysia Case Study', *Journal of Aeronautics, Astronautics and Aviation*, vol. 53, no. 2, pp. 113-120, 2021.
- [10] Y. C. Wang, J. J. Chiou and M. H. Ho, 'The Application of Virtual Reality in Aircraft Training Assessing Critical Factors', *Journal of Aeronautics, Astronautics and Aviation*, vol. 55, no. 2S, pp. 267-275, 2023.
- [11] J. R. Marks, 'Leveraging Augmented Reality in Support of Aircraft Towing Evolution', Master's Thesis, Naval Postgraduate School, Monterey, USA, 2023.
- [12] Á. Gómez-Cambronero, I. Miralles, A. Tonda and I. Remolar, 'Immersive Virtual-Reality System for Aircraft Maintenance Education: A Case Study', *Applied Sciences*, vol. 13, no. 8, 2023.
- [13] W. C. Wu and V. H. Vu, 'Application of Virtual Reality Method in Aircraft Maintenance Service - Taking Dornier 228 as an Example', *Applied Sciences*, vol. 12, no. 14, 2022.
- [14] N. T. Hoang and L. V. Thuan, 'Digitalizing Aircraft Maintenance Tasks using Virtual Reality: Application in Nose Landing Gear Wheel Removal Procedure', *Proceedings of 6th Southeast Asia Workshop on Aerospace Engineering*, Ho Chi Minh City, Vietnam, 20-21 October 2022.
- [15] Aircraft Maintenance Manual. Retrieved from <https://w3.airbus.com/>
- [16] C. M. Craig, J. Stafford, A. Egorova, C. McCabe and M. Matthews, 'Can We use the Oculus Quest VR headset and Controllers to Reliably Assess Balance Stability?', *Diagnostics*, vol. 12, no. 6, 2022.

REVIEW OF FLIGHT DYNAMICS AND CONTROLLER DESIGN FOR UNSTABLE APPROACH DURING LANDING

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Abstract: This paper provides the essential literature review of aircraft controller design for the crucial landing phase. Fundamental ideas, modeling strategies, controller design approaches and most current developments in establishing safe and stable landings are covered in this overview. The purpose of the insights shared here is to support ongoing improvements in aircraft safety and operational effectiveness during landing.

Keywords: flight dynamics; stability; aircraft landing; unstable approach; controller design

1. Introduction

The number of air traffic worldwide has been on an increasing trend throughout the years. Though COVID-19 pandemic has seriously interrupted the progression, it has been projected that the recovery in the world's air passenger volume post-COVID 19 will rapidly resume to the traffic levels of 2019 in just one to two years [1]. In general, the high air traffic volume has brought about few important issues and challenges to the aviation industry, particularly in term of ensuring passenger safety and maintaining efficiency and sustainability of flight operations. Aircraft landing is one of the most crucial flight phases and it needs to be safely and precisely performed [2]. More often than never, aircraft face hard landing during an unstable approach, which is a concern for the aviation industry since this situation can cause notable damage to the aircraft's structure and affect the safety of the onboard passengers [3]. Unstable approaches have been accounted for 5% of all approaches worldwide and in nearly all cases, it becomes the leading risk factor for accidents during the landing flight phase [4].

The Accident Classification Task Force (ACTF) of International Air Transport Association (IATA) defines unstable approach as a factor to an aircraft accident when the crew proceeded to land the aircraft although they already had knowledge about any vertical, lateral or speed deviation in the portion of the flight close to landing [5]. In order to obtain the safe approach and landing, a carefully ordered sequence of changes to the configuration and also speed of the aircraft is necessary. These criteria must be met for an approach to be classified as stable. When these criteria are not satisfied, often due to unexpected changes, the approach is classified as unstable and the risk of landing accident or incident is increased [6]. Based on the reported statistics, majority of aircraft accidents occurred during the landing phase, which is about 65% of them, and these incidents were predominantly caused by unstable approach [7]. It should also be noted that pilot's workload is high during the landing phase as it is necessary to change both vertical and horizontal positions of the aircraft while at the same time reducing the aircraft speed and altering its configuration by deploying landing gear and flaps for the landing [8]. There are several different factors that could contribute towards unstable approaches in the landing phase. For instance, on top of the human factors, the complexity of the aircraft's flight dynamics during the landing phase

and the influence of the flying environment such as weather conditions and characteristics of the aircraft system can all affect the occurrence of unstable approaches [9]. A hard landing is a type of landing that often occurs because of unstable landing approach where the aircraft makes excessive impact with the runway due to a greater vertical speed than it supposed to [10]. Hard landing can have various negative effects on the aircraft, especially in damaging its systems and compromising its structural integrity. As reported, 41% of hard landing incidents have resulted from unstable approach [11].

There are limited literatures discussing about unstable approaches and most of them are focused on the perspective of air crew and also on statistical analysis of Question–Answer Relationship (QAR) or flight record [12]. The Gaussian Process (GP) offers fundamental, realistic and probabilistic method for creating kernel machines for data modelling [13]. A research on unstable approach detection method has been developed using previous real life flight data and several methods are introduced to determine unstable approach such as using the tracking data of surveillance with wind data, parameters of aircraft and knowledge of navigation [14]. This method improves the results of detecting of unstable approach, which has been proven by a case study. In the meantime, another study uses Gaussian process to detect unstable approach based on the historical flight data by analyzing the flight path anomaly. A model has been made for anomaly detection continuously throughout the aircraft’s flight path to detect instability. It detects anomaly continuously during flight and sends data to ACTO to take the necessary action [13]. On the other hand, Ref. [15] discussed the hard landing incidents from the perspective of crew members and maintenance personnel. In the maintenance guidelines, certain SOP is provided to detect the hard landing and unstable approach for different aircraft. Furthermore, another conducted study is focused on understanding hard landing and unstable approach with the data of airspeed, runway, altitude and other related factors. It should be noted that different air traffic law and regulation agencies impose different SOPs to determine unstable approach and guidance to be followed by pilots in order to avoid hard landing and ensure the safety of onboard passengers and the aircraft’s structure [16].

Different analyses are done to understand hard landing according to QAR data. By understanding the QAR data for different aircraft, specific hard landing criteria for different aircraft could be identified and the requirements for safe and stable landing can be established and implemented. Information from flight data monitoring (FDM) is typically used to find indicators of problematic approaches in aviation. Investigating the variables or parameters that might signal the presence of unstable approaches during aircraft’s landing is the ultimate goal. In this paper, several flying parameters and their links with unstable approaches, most likely using dataset of flight data gathered during landing operations, are examined. Patterns and correlations between the flight parameters and the occurrence of unstable approaches can be established using statistical analytic techniques and machine learning algorithms [17]. In conjunction to this, such prediction of unstable approach can then be applied to develop suitable controller in order to avoid hard landing. In order to effectively provide a solution to this problem, this study will explore the answers for the following critical questions:

- What are the primary causes of hard landing during unstable approach?
- How can flight dynamic models accurately represent the behavior of an aircraft during unstable approaches?
- What are the control techniques that can be used to design suitable controller for preventing hard landing during landing phase?
- What are the limitation for designing the controller?
- How might the information gained from this study be used to improve landing procedures and flight safety in various types of aircraft?

Finding the answers to these questions will provide better understanding and leads to the best approach to improve safety during landing.

2. Flight Dynamic Modelling for Aircraft Landing

To understand stability of any aircraft in order to design a control system for it, it is very important to develop its flight dynamic model. The development of flight dynamic model of an aircraft during the landing phase has been discussed [18]. Such model development process is challenging since the landing process consists of several different phases and the aircraft's movement is continuously changing during each of these landing phases. In addition to the aerodynamic moment and force, gravitational force also acts on the aircraft during landing and once it touches down on the ground, the friction force starts to act on its wheels and subsequently on its structures. The longer the aircraft moves through the runway, the effects of aerodynamic forces become smaller and those of friction force are increased, which affect the longitudinal motion of the aircraft. Figure 1 show the forces acting on the aircraft during flight and the aircraft's motion parameters in the vertical plane.

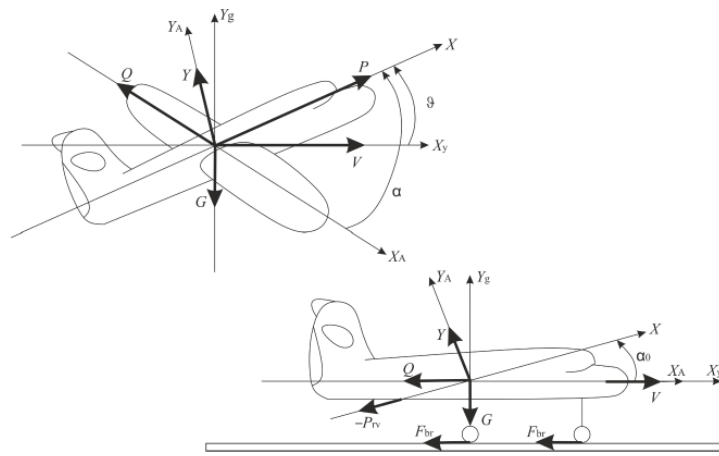


Figure 1: Forces acting on the aircraft during flight [19]

During landing, the forces acting on the aircraft are expressed by Equation 1 to Equation 3, where C_y and C_x are the aerodynamic force coefficients, S is the wing area, ρ is the air density and v is the air speed.

$$m \frac{dV_x}{dt} + m(\omega_y V_z - \omega_z V_y) = \sum F_x \quad (1)$$

$$I_z \frac{d\omega_z}{dt} = \sum_{i=1}^m M_{z_i} \quad (2)$$

$$m \frac{dy_y}{dt} + m(\omega_z V_x - \omega_x V_z) = \sum F_y \quad (3)$$

As the airplane flies during flight, aerodynamic forces that are acting on the aircraft includes lift, Y and drag, X . They can be calculated using the following Equation 4 and Equation 5, respectively.

$$Y = C_y S \frac{\rho v^2}{2} \quad (4)$$

$$X = C_x S \frac{\rho v^2}{2} \quad (5)$$

Furthermore, adding the consideration of effects from gravitational forces, G and aircraft's engine thrust, P , the resultant equations are derived.

$$m \left(\frac{dv_x}{dt} + \omega_y v_z - \omega_z v_y \right) = P_X - X - G \sin \theta \quad (6)$$

$$m \left(\frac{dv_y}{dt} + \omega_z v_x - \omega_x v_z \right) = Y - G \cos \theta \quad (7)$$

In the meantime, the kinematic properties of the aircraft will also undergo several modifications as it moves along the runway. The aircraft's angular velocity will not change and both angle of attack and pitch will be constant. The direction of the aircraft's engine thrust, P is changed after its wheels make contact with the runway. The rolling resistance force will take the form of Equation 8, where k_{fr1} is the rolling resistance coefficient and G is the aircraft's weight. Furthermore, the dynamic model of aircraft landing can be stated as Equation 9.

$$F_{f11} = k_{f11}(GY) \quad (8)$$

$$m \frac{dV}{dt} = -P_{rv}(\Delta t) - X - F_{fr1} - F_{fr2(pd)} - K_{1Ux}U_x - K_{2Uy}U_y \quad (9)$$

Since X and Y components of the aerodynamic forces are also developed in accordance with U_x , the relationships can be re-written as Equation 10 and Equation 11.

$$K_{1Ux}U_x = \Delta X = \left(C_x^V S \frac{\rho V^2}{2} \right) U_x + \left(C_x^M S \frac{\rho 2V}{2} \right) U_x = \frac{S \rho V^2}{2} \left(\frac{C_x^M}{a_H} + \frac{2C_x}{V} \right) U_x \quad (10)$$

$$K_{2cy}U_y = \Delta Y = \left(C_y^V S \frac{\rho V^2}{2} \right) U_y + \left(C_y^M S \frac{\rho 2V}{2} \right) U_y = \frac{S \rho V^2}{2} \left(\frac{C_y^M}{a_H} + \frac{2C_y}{V} \right) U_y \quad (11)$$

3. Automatic Control of Aircraft During Landing

Flight Dynamics Model (FDM) is representation of a set of mathematical equations that are used for calculation the forces that are physically acting on any flying vehicles. The motion of an aircraft is related to its six degrees of freedom (6DOF) from the second Newton's Law, which could be described as a system of first-order non-linear differential equations. The equations of motion can be taken as the fundamental for all models related to flight dynamics. In FDM, non-linear equations have been used to describe the flight stability of an aircraft. In this case, mathematical representation of the aerodynamic forces and moments that are acting on the aircraft and the equations of motion for the aircraft are used to develop the 6DOF non-linear flight model.

A unique sliding mode control strategy in lateral-directional plane has been proposed to be used to automatically manage an aircraft during the landing phase. A navigation system and a control system make up the two main components of this proposed control system. With this system, the aircraft will follow the intended lateral path and heading angle generated by the guidance system during the landing approach. The aircraft's roll and yaw rates are managed by the control system while the tracking of the intended lateral path and heading angle is done using a sliding mode controller. The effectiveness of this suggested control system in managing lateral motion of the aircraft during landing has already been

demonstrated in Ref. [20], even in the presence of external disturbances and uncertainties, using a high-fidelity aircraft simulator. The non-linearization of the aircraft's non-linear dynamics is achieved based on the small disturbance method of a trajectory of equilibrium. The general non-linear model can be expressed by Equation 12 to Equation 19.

$$\dot{\beta} = a_{11}\beta + a_{12}p + a_{13}r + a_{14}\phi + b_{11}\delta_a + b_{12}\delta_r + \frac{a_{11}}{V_0}V_{vy} \quad (12)$$

$$\dot{p} = a_{21}\beta + a_{22}p + a_{23}r + b_{21}\delta_a + b_{22}\delta_r + \frac{a_{21}}{V_0}V_{vy} \quad (13)$$

$$\dot{r} = a_{31}\beta + a_{32}p + a_{33}r + b_{31}\delta_a + b_{32}\delta_r + \frac{a_{31}}{V_0}V_{vy} \quad (14)$$

$$\dot{\phi} = p \quad (15)$$

$$\dot{\psi} = r \quad (16)$$

$$\dot{Y} = -V_0\beta + V_0\psi + V_{vy} \quad (17)$$

$$\dot{\delta}_a = -\frac{1}{T_a}\delta_a + \frac{1}{T_a}\delta_{a_c} \quad (18)$$

$$\dot{\delta}_r = -\frac{1}{T_r}\delta_r + \frac{1}{T_r}\delta_{r_c} \quad (19)$$

Virtual dynamic model design and analysis is very important for understanding and design of flight characteristic of any aircraft. It is recommended to explore all mechanisms and fundamental concepts of flight dynamics. This is an initial inquiry that commences by scrutinizing the modeling of all pertinent actions that affect the system being studied through utilization of the aircraft's dynamics. The primary objective is to devise a simplified approach for mathematical calculation of the dynamic equations of the aircraft and then forecast the initial phase of flight via dynamic simulation. This is accomplished by using both symbolic and numerical computations in a versatile program constructed on the MATLAB simulation environment. Initially, the system dynamic model is symbolically generated and proficient computational techniques are then employed to numerically solve it, resulting in a solution. A sample flow chart diagram of the control system for the aircraft's motion in lateral plane is shown in Figure 2.

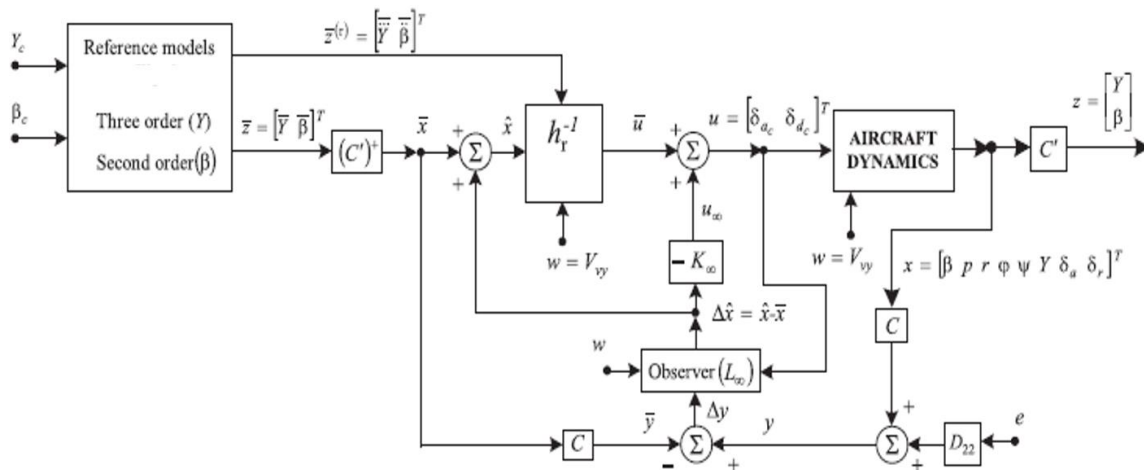


Figure 2: Block diagram of an aircraft's controller in lateral plane using H-infinity control [20]

A study shows the effectiveness of using PID controller design theory in designing an automatic landing system of an aircraft for the longitudinal plane using dynamic inversion concept to non-linearize the system. The design of aircraft's landing control for longitudinal phase using fuzzy logic technique has been discussed and from the result, the performance of the controller is significantly enhanced [21]. Moreover, controller design in the longitudinal plane using dynamic inversion and H-infinity control method can also improve the performance of the designed controller, which can be applied in the lateral directional plane of the aircraft. The idea of the "H-infinity norm", a mathematical way of defining how sensitive a system is to disturbances, serves as the foundation for H-infinity management. In H-infinity control, a controller is developed to minimize the system transfer function's H-infinity norm while still adhering to certain performance criteria such as stability and also tracking demands [22]. The dynamic inversion technique provides an excellent precision tracking whereas H-infinity control provides robust stability against uncertainties introduced by various disturbances and noise signals. This combination makes the outcome of the controller better and decreases the overshoot and settling time [23].

When designing the controller for the H-infinity control, optimization procedures and linear matrix inequalities (LMIs) from control theory are used. The process usually entails simulating the dynamics of the system, including uncertainties and disturbances, then formulating an optimization problem to identify the best controller for minimizing the H-infinity norm. The control system's implementation of the resulting controller allows for reliable performance. For designing the aircraft's landing control system, both longitudinal and lateral planes are treated simultaneously and the controller's performance is similar to the controller designed for different planes. The pilot must correct the lateral deviation of the aircraft from the runway before the two main phases of landing in longitudinal plane. The automatic landing system (ALS) consists of three different sub-systems that have been developed separately. The numerical simulations are used to implement, test and validate the entire ALS. For longitudinal stability, pitch controller is developed using linear quadratic gain (LQR) method, which is the controller design method that gives optimal controlled feedback gains for close loops and is used for high performance control system designing. LQR is widely used to design high performance control systems and to find optimal gains [24]. LQR is a controller that is similar to the method of selecting the location of poles. The difference is that, instead of select the poles location, feedback gain values of matrix K is obtained by minimizing the cost function to design the controller according to the design requirements.

A continuous-time linear system could be expressed as Equation 20 while the cost function could be defined as in Equation 21. In these equations, the state weighting factor is Q whereas the weighting factor is R of the variables of the control. Unlike the classical or digital logic, which processes discrete values of 1 or 0 (true or false, respectively), fuzzy logic analyzes the analog input values using the logical variables that take continuous values between the analog input values. It is a mathematical system that ranges between 0 and 1. The algorithm provides a scope to represent uncertainties based on a complex model. Fuzzy controller with use of a neural network can provide signal of aircrafts stability in different landing phase and the linearized model provides error signal and improve the performance of automatic flight control system of aircraft [25].

$$\dot{x} = Ax + Bu \quad (20)$$

$$J = \int_0^{\infty} (x^T Qx + u^T Ru) dt \quad (21)$$

4. Conclusion

From the literatures, it has been found that there are many literatures that have discussed the hard landing and also unstable approach criteria and determination. Aircraft often face hard landing during

an unstable approach, which is a matter of concern for the aviation industry as it causes damage to the aircraft's structure and affects the passenger's safety. Many published articles are discussing the unstable approach criteria for different types of aircraft, which are dictated by the different safety and regulation authorities. Nevertheless, there are limited literatures that talk about determining the unstable approach and most of them have been focused on the perspective of air crew and others such as statistical analysis of QAR or flight record. There are some conducted studies on developing new models for the aircraft's unstable approach. These models can detect unstable approach to prevent hard landing more efficiently and link with flight control system to make the aircraft stable. Another important aspect of the research is the flight dynamic modelling of the aircraft during flight and during landing. Regarding the automated flight control system for landing, there are different studies based on PID, LQR and H-infinity control strategy. For aircraft's control during landing, the important aspect is its stability for longitudinal plane and lateral plane. There are studies discussing control design in these planes. The current limitation of the literatures is that there are not many literatures that study about controller design for hard landing prevention during aircraft's unstable approach for landing. Therefore, use of existing methods and data to develop a controller for unstable approach that can prevent hard landing needs to be further explored in future.

References

- [1] M. C. Gelhausen, P. Berster and D. Wilken, 'Post-COVID-19 Scenarios of Global Airline Traffic until 2040 that Reflect Airport Capacity Constraints and Mitigation Strategies', *Aerospace*, vol. 8, no. 10, 2021.
- [2] C. Krammer, C. Mishra and F. Holzapfel, 'Testing and Evaluation of a Vision-Augmented Navigation System for Automatic Landings of General Aviation Aircraft', *Proceedings of AIAA Scitech Forum, Orlando, USA, 6-10 January, 2020*.
- [3] M. B. Messaoud, 'A Thorough Review of Aircraft Landing Operation from Practical and Theoretical Standpoints at an Airport Which May Include a Single or Multiple Runways', *Applied Soft Computing*, vol. 98, 106853, 2021.
- [4] R. J. de Boer, T. Coumou, A. Hunink and T. van Bennekom, 'The Automatic Identification of Unstable Approaches from Flight Data', *Proceedings of the 6th International Conference on Research in Air Transportation, Istanbul, Turkey, 26-30 May 2014*.
- [5] Y. Rui and L. Renli, 'Detection Strategy of Unstable Approach Based on Possibility Measure', *Proceedings of the Chinese Control and Decision Conference, Nanchang, China, 3-5 June 2019*.
- [6] D. Moriarty and S. Jarvis, 'A Systems Perspective on the Unstable Approach in Commercial Aviation', *Reliability Engineering & System Safety*, vol. 131, pp. 197-202, 2014.
- [7] J. H. Jeon, J. Song, C. J. Jung and B. H. Song, 'A Study on Countermeasures to Prevent Unstable Approach to Improve Aviation Safety', *Journal of the Korean Society for Aviation and Aeronautics*, vol. 26, no. 3, pp. 1-8, 2018.
- [8] Y. H. Lee and B. S. Liu, 'Inflight Workload Assessment: Comparison of Subjective and Physiological Measurements', *Aviation, Space and Environmental Medicine*, vol. 74, no. 10, pp. 1078-1084, 2003.
- [9] R. Mori, 'Anomaly Detection and Cause Analysis During Landing Approach using Recurrent Neural Network', *Journal of Aerospace Information Systems*, vol. 18, no. 10, pp. 679-685, 2021.
- [10] D. Gil, A. Hernandez-Sabate, J. Enconniere, S. Asmayawati, P. Folch, J. Borrego-Carazo and M. A. Piera, 'E-pilots: A System to Predict Hard Landing During the Approach Phase of Commercial Flights', *IEEE Access*, vol. 10, pp. 7489-7503, 2021.
- [11] International Air Transport Association, *Unstable Approaches: Risk Mitigation Policies. Procedures and Best Practices*, 2016.

- [12] L. Wang, C. Wu and R. Sun, 'An Analysis of Flight Quick Access Recorder (QAR) Data and Its Applications in Preventing Landing Incidents', *Reliability Engineering & System Safety*, vol. 127, pp. 86-96, 2014.
- [13] N. P. Singh, S. K. Goh and S. Alam, 'Real-time Unstable Approach Detection using Sparse Variational Gaussian Process', *Proceedings of the International Conference on Artificial Intelligence and Data Analytics for Air Transportation*, Singapore, 3-4 February 2020.
- [14] L. Sherry and J. Shortle, 'Improving the Nowcast of Unstable Approaches', *Proceedings of 8th International Conference on Research in Air Transportation*, 2016.
- [15] N. Bardou and D. Owens. (2014). Hard Landing, a Case Study for Crews and Maintenance Personnel. Retrieved from <https://safetyfirst.airbus.com>
- [16] Civil Air Navigation Services Organization. (2013). Unstable Approaches: Air Traffic Control Considerations. Retrieved from <https://www.icao.int>
- [17] D. A. Carroll, *Examining Unstable Approach Predictors Using Flight Data Monitoring Information*, Embry-Riddle Aeronautical University, 2020.
- [18] A. Suharevs, P. Trifonovs-Bogdanovs, V. Šestakovs and K. Mamay, 'Dynamic Model of Aircraft Landing', *Transport and Aerospace Engineering*, vol. 3, no. 1, pp. 38-43, 2016.
- [19] B. Etkin and L. D. Reid, *Dynamics of Flight: Stability and Control*, John Wiley & Sons, 1995.
- [20] R. Lungu and M. Lungu, 'Automatic Control of Aircraft in Lateral-Directional Plane During Landing', *Asian Journal of Control*, vol. 18, no. 2, pp. 433-446, 2016.
- [21] R. Lungu, M. Lungu and L. T. Grigorie, 'Automatic Control of Aircraft in Longitudinal Plane During Landing', *IEEE Transactions on Aerospace and Electronic Systems*, vol. 49, no. 2, pp. 1338-1350, 2013.
- [22] N. Lungu, R. Lungu and D. Tutunea, 'Control of Aircraft Landing using the Dynamic Inversion and the H-inf Control', *Proceedings of 17th International Carpathian Control Conference*, High Tatras, Slovakia, 29 May-1 June 2016.
- [23] J. Che and D. Chen, 'Automatic Landing Control using H/sub/spl infin// Control and Stable Inversion', *Proceedings of the IEEE Conference on Decision and Control*, Orlando, USA, 4-7 December 2001.
- [24] A. Ashraf, W. Mei, L. Gaoyuan, M. M. Kamal and A. Mutahir, 'Linear Feedback and LQR Controller Design for Aircraft Pitch Control', *Proceedings of 4th International Conference on Control Science and Systems Engineering*, Wuhan, China, 21-23 August 2018.
- [25] J. G. Juang and J. Z. Chio, 'Fuzzy Modelling Control for Aircraft Automatic Landing System', *International Journal of Systems Science*, vol. 36, no. 2, pp. 77-87, 2005.

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