SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in
Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

Investigation of Empennage Location Effect to the Unmanned Aerial Vehicle (UAV) Structure Characteristic

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ARTICLE INFO

Article history:
Received 29 August 2023
Received in revised form 31 October 2023
Accepted 17 November 2023
Available online 25 December 2023

Keywords:
UAV; SolidWorks; simulation; empennage; composite; structure

ABSTRACT

Over the past few decades, unmanned aerial vehicles, commonly known as UAVs, have been widely used in a number of consumer and military applications, such as surveillance, tracking, monitoring, and aerial photography. Fixed-wing and rotary UAVs are the two primary categories in UAV. Interestingly, the hybridization of fixed-wing and rotary UAV gives better performance in terms of energy consumption and the needs of runaway. Designing new hybrid fixed wing-rotary UAV or hybrid vertical take-off and landing (VTOL) is challenging especially to identify the critical location in the UAV and material selection. Therefore, the objective of this research is to study the effect of empennage location and material selection on the structural strength of a hybrid VTOL UAV. The SolidWorks software was employed to design a 3D model of the UAV with different empennage locations, as well as perform a simulation of the structural strength of fibre glass, carbon fibre and kenaf for the hybrid VTOL UAV. The simulation analysis presents stress (Von Mises). The results show that the fibre glass (4.342 N/m^2) at top empennage gives the best performance as compared to other parameters. In conclusion, this study is necessary to give a better picture of structural strength of composite materials and best design location in hybrid VTOL UAV for future research.

1. Introduction

Unmanned Aerial Vehicles (UAV) are aircraft that do not carry humans on board and have recently gained popularity as a result of the diverse array of applications that are being found for them. Numerous studies have focused on the progression of technology and extensive development in order to improve the UAV's operational experience.

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https://doi.org/10.37934/aram.113.1.112

UAVs are now used for a wide variety of purposes, including surveillance, logistics, airway transportation, agricultural, and military aerial vehicles [1-3]. UAV also reported fly as a monitoring patrol on durian orchards with thermal and RGB digital cameras embedded on the UAV [4]. UAVs can be categorised into two primary categories: multirotor and fixed wing [2]. Every type of UAV comes with its own set of benefits and drawbacks. Fixed-wing UAVs are a conventional category of aircraft that feature more straightforward mechanical designs and the ability to hover over great distances while travelling at high speeds [5].

However, to take off and land, fixed-wing UAVs require either a particularly long runway or a specialised launch system. Unlike with fixed wings UAV, multirotor UAVs can perform vertical take-off and landing (VTOL), despite the fact that they have a slower cruising speed and a smaller cargo capacity [1,6]. VTOL UAV are capable of vertical take-off and landing even in the absence of a runway or launch system [6]. The VTOL UAVs have a finite lifespan as far as their operational capabilities are concerned and structural design [7-10].

As a direct consequence of this, hybrid UAVs have been developed to address these concerns and expand the capabilities of UAVs. The limitations of both VTOL and fixed wing UAVs inspired the development of hybrid VTOL UAVs. Because they can switch between two distinct flight modes, hybrid UAVs are quickly becoming increasingly popular. Several researchers were explored the enhancement of the hybrid VTOL UAV design [10-22]. A wingtip designs for a Quad+Tilt configuration with different control principles were proposed and gain of 3% improvement in cruise endurance for a 5 kg Quad+Tilt UAV [12]. There are also several studies related to tilt concept that improve in attitude stabilization [17] and the effectiveness of the flight control system [18-20] The designs enhancement was conducted may focusing on several factors as well such as wind condition during landing and take-off [11] aerodynamics load at the “tail-aft on booms” shaped configuration [14] and morphing wing design [10,15,16]. The new concept of tri-copters produces better performance in term reduce mechanical requirement [21] control surface flight performance [19], and employed less components [22].

The aerodynamics influence on the UAV also conducted and presented in Table 1. It is crucial to understand the effect of flexible wing as compared to rigid wing [23], airfoil type (as shown in Figure 1) [24] and gust's effect on the wing root bending moment [25]. Besides that, response surface methodology is viable to study the design characteristic [26]. Furthermore, the selection of propeller type may influence the performance of UAV in term of thrust force produced [27] In terms of parachute design, an annular parachute canopy produced a higher drag coefficient (1.03) than a cruciform parachute canopy (0.91) hence assists the UAV on the recovery phase. All the information above gives clear insight on the importance of aerodynamics analysis. However, the new hybrid VTOL UAV need a structural analysis as well to give better structure sustainability.

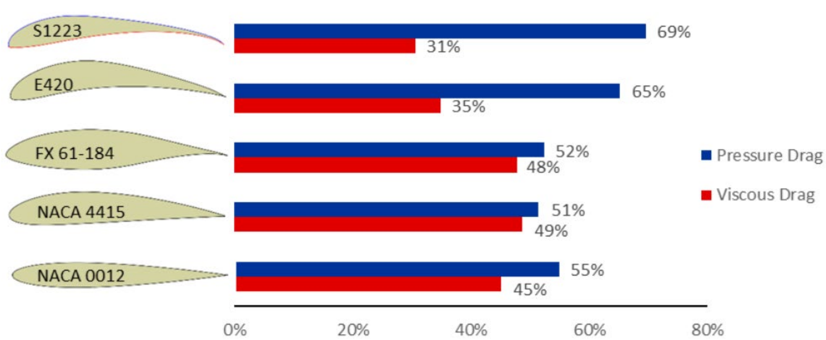


Fig. 1. The Drag composition in terms of percentage of total drag at $\alpha_{(L/D\ max)}$ with S1223 at Re: 0.3×10^6 and all other airfoils at Re: 1.0×10^6 [24]

Table 1
The review analysis on the aerodynamics effect to the UAV

No.	Objective	Output	Author
1	This article describes the lift coefficient profile of an MAV that imitates a dragonfly at a frequency of 11 Hz, three different Reynolds numbers, and varied AoA for tandem arrangements with flexible wings.	The results also demonstrated that, with the exception of the Reynolds number of 14000, the lift coefficient of flexible wing skin was greater than that of rigid wing skin for attack angles of 10° and below.	[23]
2	By examining the variance in pressure drag and its distribution with regard to the kind of airfoil geometry, angle of attack, and the contribution of pressure towards the overall drag at low Reynolds numbers	Concave airfoils, like the E420 and S1223, stand out in the group for providing high lift at the expense of an increase in drag. L/D ratio analysis by itself can be underestimating their potential.	[24]
3	To reduce the gust's effect on the wing root bending moment.	It is discovered that the wing dihedral angle has a negligible impact on the wing root bending moment brought on by the gust load. The wing root bending moment, however, is significantly altered by the wing sweep angle. The best swept back design for the current configuration, with a sweep angle of 45° and the best composite lay-up, resulted in an average 12% reduction in the bending moment over the frequency range of 0 to 100 Hz.	[25]
4	The response surface methodology (RSM) has been used to examine the effects of design characteristics including camber, velocity, and frequency of the flapping wing.	The research demonstrated the significance of RSM in enhancing the aerodynamic characteristics of flapping wing mechanisms.	[26]
5	To compare the thrust produced by a regular propeller with a serrated propeller.	Particularly when both propellers are operating at high speeds between 6000 and 7000 rpm, the conventional propeller's thrust force is greater than that of the serrated trailing edge propeller. When the propeller reaches 7000 rpm, the conventional propeller's thrust force increases by three times that of the serrated propeller.	[27]
6	in order to choose the optimal canopy design that can produce more drag throughout the recovery phase by analysing an aerodynamic performance.	An annular parachute canopy produced a higher drag coefficient (1.03) than a cruciform parachute canopy (0.91) according to computational results with an effective grid analysis. The results also showed how important separation and recirculating flows were behind the investigated geometries, which in turn contributed to the drag.	[4]

The investigation on the structure analysis were conducted rigorously. One of the aerospace industry's challenges is ensuring the efficiency and quality of aircraft structural parts [28]. Akshayraj *et al.,* [13] investigated new design of tail sitter for VTOL UAV and application of composite as the structure material. The result reported that the UAV weight was reduced by 44.17% as compared to aluminium. Composites are fiber-reinforced "matrix" materials. These materials have high weight-adjusted specific values. Despite the matrix diluting properties. A composite's characteristics are affected by both its components and the fiber-resin interactions at its interfaces [29]. The goal of developing composites with a range of reinforcing materials is to increase performance, weight, and cost [13,30]. Generally, there are several researchers conducted analysis on the UAV' structure material such as aluminium [31], fibre glass [13], carbon fibre [13], 3D printed multi-material composite [28,32], Jute fibre composite [33], sandwich composite materials [9], and composite skin for UAV [15]. The study on flax fibre and hybrid fibre presented the filling time using simulation hence assists any future researchers to fabricate the using respective materials [34]. Natural fibre application has gain serious attention in the recent engineering trends due to green concept composite. The strength of the natural fibre may depend on the fibre volume fraction of the composite, fibre length and chemical treatment. The fibre volume fraction and fibre length in the composites may influence formation of void or bubble. The principal access to the penetrating water becomes the cross-section of the fibre [35]. Therefore, swelling within the matrix occurs when hydrophilic fibre is reinforced with hydrophobic resin fibre [35].

From the discussion of previous researchers, the hybrid VTOL UAV's motor positioning, material selection and empennage location may need to be thoroughly investigated. Furthermore, there is a lack of study in terms of the natural fibre composite material used for the empennage hybrid VTOL UAV. Therefore, the goal of this project is to investigate the structural strength of kenaf, carbon fibre, and glass for the hybrid VTOL UAV at three empennage positions by using the SolidWorks software.

2. Methodology

Work breakdown structure (WBS) was employed as a guideline for this research management implementation. A WBS chart was developed with the help of the tasks, that must be completed to ensure that the objective of the study was achieved. Table 2 shows the main activities and tasks throughout this project to accomplish the objective.

Figure 2 displays the hybrid VTOL UAV which currently under research and development phase located in Research Centre for Unmanned Vehicle (ReCUV), Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM). This model formed the foundation for further development in this study.

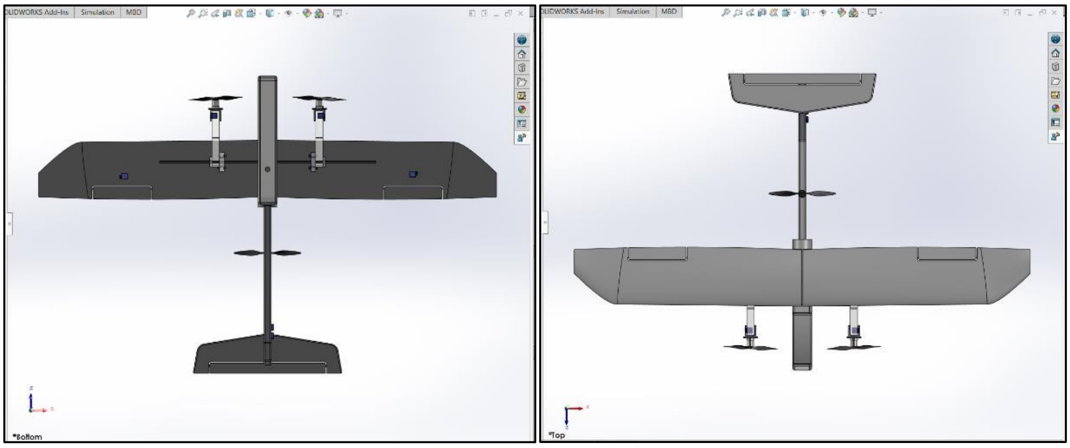
Table 2
Work breakdown structure (WBS) of the research project

Main Activity 1	Task
3D model design of hybrid UAV	Task 1: Design 3D model parts of hybrid UAV.
	Task 2: Assemble designed parts.
	Task 3: Design three separate empennage location.
3D simulation of hybrid UAV	Task 4: Apply three different materials for three different simulation tests.
	Task 5: Perform static study and simulation report.
Structural material strength	Task 6: Apply correct material.
	Task 7: Analyse material's reaction to forces.
Analyse data	Task 8: Analyse stress value from the simulation report.
Empennage location	Task 9: Apply material for each location design.
	Task 10: Run simulation for each location.
Analyse data	Task 11: Analyse stress value from the simulation report.

Fig. 2. The hybrid VTOL UAV for research and development in UTHM

2.1 3D Model Design of Hybrid UAV

The 3D model and simulation of hybrid VTOL UAV was conducted using SolidWorks software. The wing was designed following S7055 aerofoil type. The same design was employed to the tailed. The complete assembly model design for this research is presented in Figure 3. The empennage part is shown in Figure 4. The effect of material and empennage location variation on the hybrid VTOL UAV body is investigated and experimental details is tabulated in Table 3. Figure 5 shows the location of empennage to the main body structure for investigation. The mechanical properties of the materials are tabulated in Table 4.



(a) (b)

Fig. 3. The assembly design of hybrid UAV (a) bottom view (b) Top view

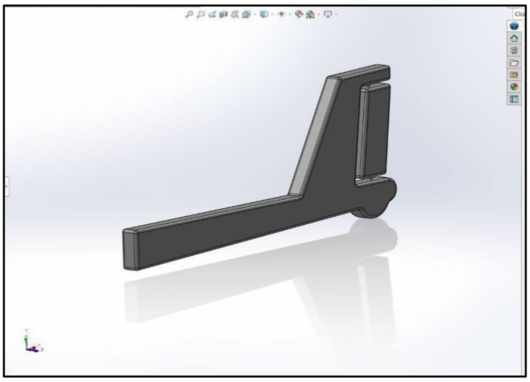
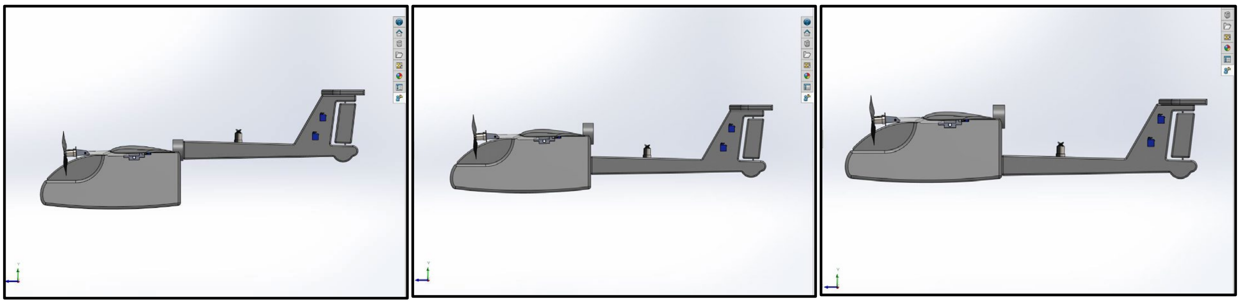


Fig. 4. The empennage design for the UAV



(a) (b) (c)

Fig. 5. The location of empennage to the main body structure for investigation (a) Top location (b) Middle location (c) Bottom location

Table 3
The experimental parameters for stress analysis

Factor	Experimental condition levels		
	1	2	3
A – Structural material	Fibre glass	Carbon fibre	Kenaf Fibre
B – Empennage location	Top	Centre	Bottom

Table 4
The meshing condition and mechanical properties in simulation

No	Item	Fibre glass	Carbon fibre	Kenaf fibre
1	Mesh type/ mesher	Solid mesh/ Blended curvature-based mesh		
2	Tensile strength	2.05×10^9 N/m^2	4.00×10^9 N/m^2	1.3×10^9 N/m^2
3	Density	2250 kg/m^3 [36]	1776 kg/m^3 [36]	1220 kg/m^3 [37]
4	Torque applied	40 N.m to each load point		

2.2 3D Model Simulation of Hybrid UAV

In simulation, the crucial part of this step is applying the external load and parts to the model. The application must be precise to avoid miscalculation in the simulation and avoid any error when meshing it. The design of the beam is the topology configuration that will give a huge impact in the result. The meshing condition and properties are tabulated in Table 4. First, apply fixed geometry to the structure to restraint the structure from moving. Then, determine the load point (as shown in Figure 6) which are the propeller of the hybrid VTOL UAV and apply torque as stated in Table 4. The SolidWorks software was simulated the analysis and the Von Misses stress result on the UAV structure was recorded. The highest Von misses stress indicates the best performance of the design.

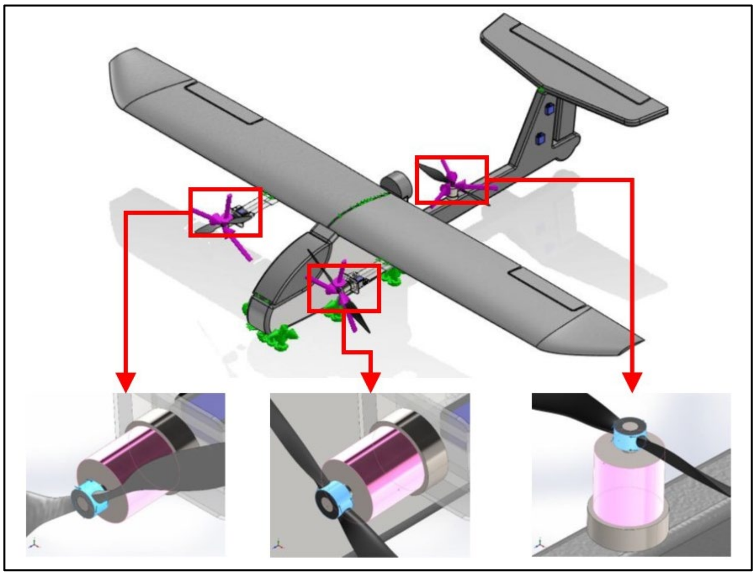


Fig. 6. The three-load point location in the simulation study

2.3 Statistical Analysis via Taguchi Method

The Taguchi methods are statistical methods initially developed by Genichi Taguchi to improve the quality of manufactured goods. More recently, the techniques have been used in scientific and engineering experiments since they allow for the analysis of many different parameters without a prohibitively high number of experiments. Many researchers now apply robust design as a tool to achieve quality engineering in many fields [38,39].

Furthermore, Taguchi offers an experimental design wholly based on statistical design as a tool which is less sensitive to noise factors. The two major tools used are: the signal to noise (S/N) ratio, which measures quality with the emphasis on variation, and orthogonal arrays, which accommodate many design factors simultaneously. The significance of the factor or multiple factors that affect the machining quality performance could be determined in a very short time when this technique is employed. The method of calculating the S/N ratio response is designed in three different modes depending on whether the quality characteristics is smaller the better, larger the better or nominal the better. In this analysis, the larger the better is preferred to perform high Von Misses Stress. The equations (Eq. (1)) for calculating the S/N ratio are for the larger the better characteristic (in dB) which is

$$\frac{S}{N} = -10\ \log\frac{1}{n}\left(\Sigma\frac{1}{{y_i}^2}\right) \qquad (1)$$

n is the number of observations and y_i is the observed data. The S/N ratio values function as a performance measurement to develop processes insensitive to noise factors. The degree of predictable performance of a product or process in the presence of noise factors could be defined from the S/N ratio values. For each type of characteristics, with the above S/N ratio, the higher the S/N ratio, the better the result. The S/N ratio was presented in response graph and response table.

The Taguchi design of experiment (DOE) for this research was L_9 orthogonal array. The DOE was selected from the fact that the investigation was conducted on two factors with three levels as shown in Table 3. Minitab software was employed to propose the DOE. Von Misses stress was considered as the output result. The simulation study was conducted in nine runs following the L_9 orthogonal array DOE. The results were further analysed via S/N ratio values and presented in Table 6 and Figure 8.

3. Results

Figure 7 shows the stress analysis view on the UAV structure due different empennage location for fibre glass material. Table 5 shows the stress value obtained in the analysis. The result shows that the highest stress obtained from the simulation analysis is at the top empennage and with fibre glass material. Condition. According to the findings, the stress simulation, the empennage is predicted to be under a marginally greater amount of stress when it is in the top position.

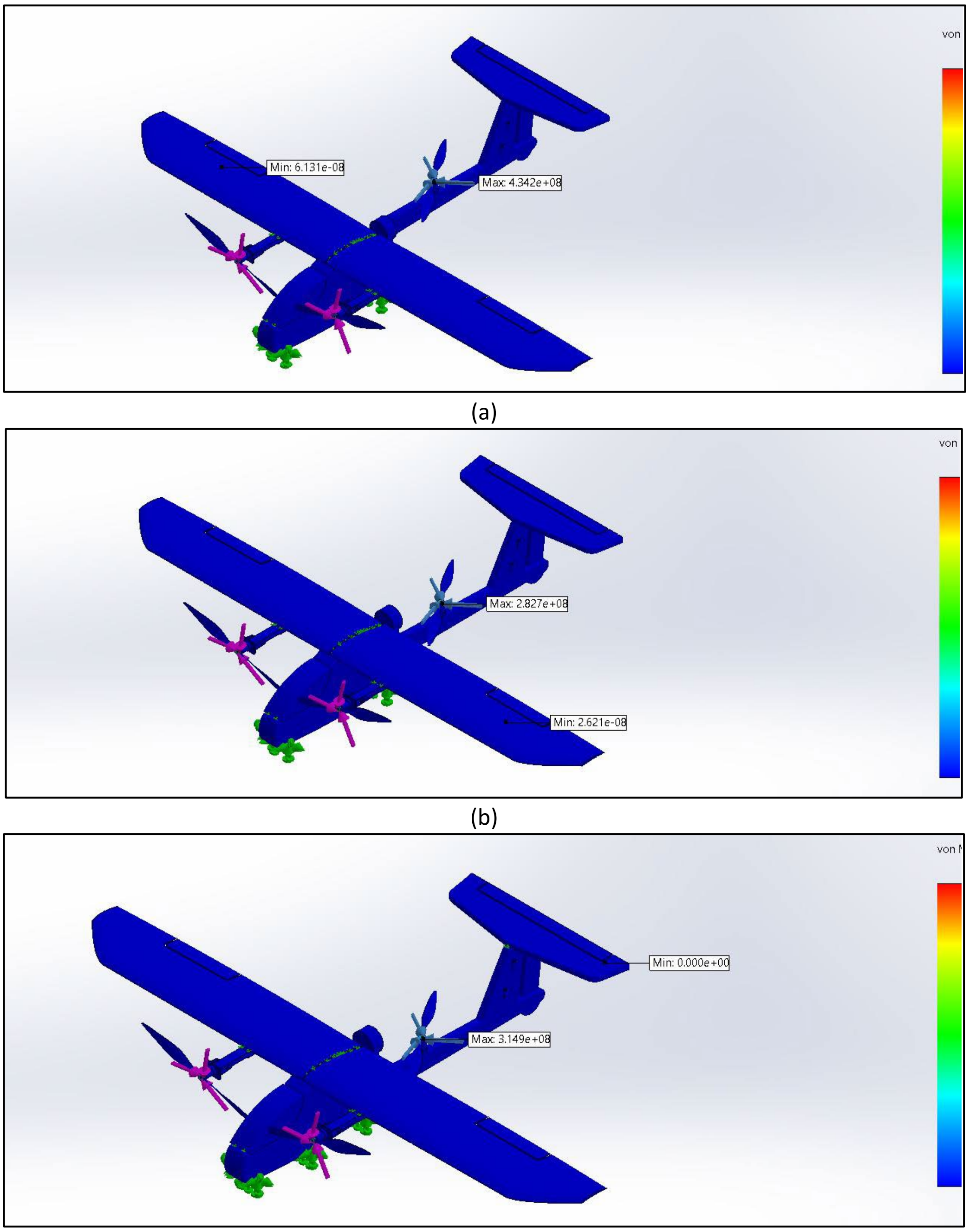


Fig. 7. The sample of stress view simulation on Fibre Glass (a) Top empennage design (b) Centre empennage design (c) Bottom empennage design

Table 5
Von Misses Stress values

	Stress, N/m² (max)		
Material/Location	Top	Centre	Bottom
Fibre Glass	4.342	2.827	3.149
Carbon Fibre	2.285	2.199	2.080
Kenaf	2.796	2.160	2.559

The theory to explain this is the stresses on the wings and fuselage of the UAV are tension, compression, shear, bending, and torsion. These stresses are absorbed by each component of the wing structure and transmitted to the fuselage structure. The empennage (tail section) absorbs the same stresses and transmits them to the fuselage. These stresses are known as loads, and the study of loads is called a stress analysis. Stresses are analysed and considered when an UAV is designed [15]. For material analysis, fibre glass was shown to be able to sustain the maximum amount of stress, followed by kenaf, and then carbon fibre.

S/N ratio stress analysis is reported in Figure 8 and Table 6. Further analysis was conducted using the response table of the S/N ratio and the response graph of the S/N ratio to identify the most influential factor and the optimum level in each factor to obtain a higher Von Misses Stress.

Table 6 shows that the material is proposed as the most influential factor, as compared to the empennage location. This result refers to the delta item. Delta is the difference between the minimum and maximum S/N ratio for each of the factors. The higher value means that it is considered as the most influential factor above the others. Rank refers to the order of the influencing factor in each analysis. Number one is considered as the most influential factor followed by number two.

Table 6
Response table for S/N ratio in Von Misses stress analysis

Level	Factors	
	Material	Location
1	10.581	10.506
2	6.794	8.622
3	10.869	9.117
Delta	4.074	1.884
Rank	1	2

The optimum level is identified from the highest S/N ratio value in each factor. For the material type factor, level 3 (which is kenaf fibre) is proposed as the optimum level. While for empennage location type, level 1 (which is the top location) is proposed as the optimum level. Figure 8 depicts that the optimum parameters necessary to achieve the highest Von Misses Stress is a combination of kenaf fibre and top empennage design.

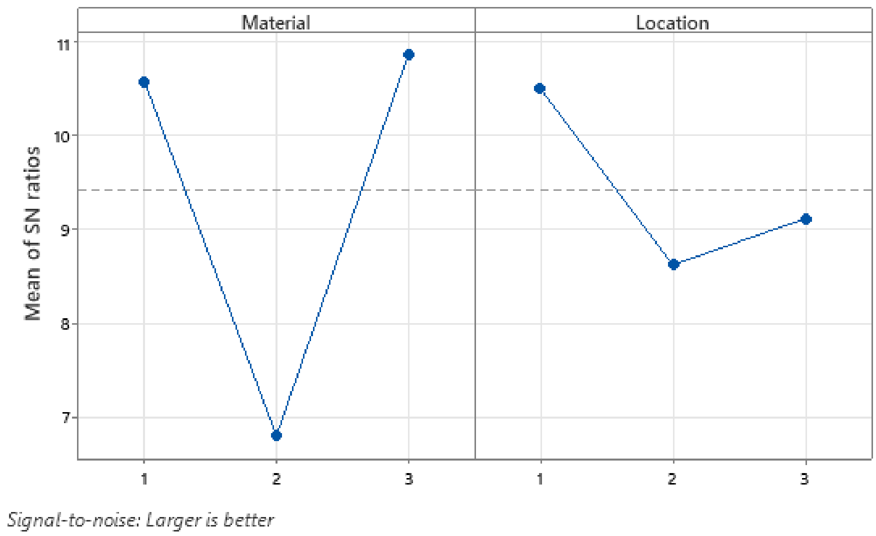


Fig. 8. Response graph for S/N ratio in Von Misses stress analysis

4. Conclusions

The objective of this research is to investigate the structural strength of kenaf, carbon fibre and glass fibre composite and three different empennage location. The simulation process via Solidwork software propose fibre glass material (4.342 N/m^2) at the top empennage as the best combination parameters. The structural analysis via Taguchi Method propose that material's type factor influences significant effect to the strength performance as compared to the location of empennage. Furthermore, Kenaf fibre and top empennage design are the optimize parameter required to obtain the maximum Von Misses Stress via Taguchi method. The future researchers may obtain a beneficial insight on the hybrid VTOL UAV fabrication process and material selection.

Acknowledgement
The authors would like to thank the Universiti Tun Hussein Onn Malaysia for supporting the research activity through research grant TIER 1: Q498

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