STRUCTURAL ANALYSIS OF HYBRID VTOL CONFIGURATION

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Abstract

Maximizing flying qualities of a UAV is not a new topic in the aeronautical branch. Therefore, there is a significant amount of growing interest shown by researchers to integrate the flying mechanism of both conventional fixed wing UAV and rotorcraft UAV and thus, results in the birth of hybrid VTOL UAV. This paper investigates the difference in wing deflection of a hybrid VTOL UAV, a quadrotor fixed-wing with two independent propulsion systems and a conventional fixed wing. Quantitative method is chosen throughout this study where data collected are mainly from experiments and literature study. Firstly, the general wing specification is determined. To achieve this, a design analysis is conducted based on theoretical calculation and data from previous researches. The most suitable wing is found to be a straight wing with 0.3m chord length and 2m wingspan. Following that, a structural analysis is done to compare the difference in wing deflection for both mentioned UAV. After fabricating the model wing spar, an experimental set up for vibration test to determine wing deflection of a quadrotor fixed-wing is being prepared and ran. At the same time, wing deflection of a fixed wing UAV is calculated by using beam deflection equation. The maximum deflection obtained is 0.0865385m and 0.0002516m respectively. The result shows that maximum deflection at wing tip for hybrid VTOL is higher than a conventional fixed wing. Factors that contributed to this finding were the concentrated upward lift force and also fluctuated force coming from vibration of the motor driven propeller.

Keywords

VTOL, Hybrid UAV, quadrotor, fixed wing, vibration

1.0 INTRODUCTION

UAV or unmanned aerial vehicle is a technology that has been around for many decades already and is extensively used in military. Apart from being used in military, we can now see UAV being used in various other industries such as agriculture, rescue operations and surveillance [1]. Conceptually, UAV is defined as an aircraft that flies without the presence of on-board pilot [2][3].

There are initially two main types of UAV which are fixed-wing UAV and rotor-wing UAV [4][5][6]. A fixed-wing UAV is capable in carrying heavy payload since the space available in its cabin or fuselage structure enables it to store more stuff [8]. However, this UAV needs long runway or spacious space for taking off and landing [5]. On the other hand the rotorcraft UAV has higher maneuverability and is capable of VTOL which makes this type of UAV more suitable to be used in various environment but has much lesser speed and lower endurance [4][6].

As a result, the high interest to develop a UAV that is capable to tackle both limitations stated earlier led to the innovation of the new generation of UAV called the hybrid VTOL UAV which assimilates the advantages of fixed-wing and rotorcraft UAV [7][8][9]. This type of UAV is categorized into two, the one with same power plant and the one with separate power [10]. Same thrust producer refers to the aircraft that uses only one set of thrust system for both hovering and forward flight such as tiltwing, tiltrotor and tailsitter [11][18].

Contrary to these three aircrafts is the famous rotor fixed wing UAV which does not need such moves of its structure for vertical flying [6][9]. This type of UAV has two independent propulsion systems to integrate both of the vertical flying mechanism of a copter and horizontal flying mechanism of a conventional aircraft [3]. Previous study found that the x-style quadrotor configuration is the most commonly used by rotor fixed wing UAV as this style serves better attitude stability [5][6]. Among the successful quadrotor fixed wing UAV invented are Arcturus JUMP by Arcturus UAV and Hybrid Quadcopter HQ-40 manufactured by Latitude Engineering [6].

Although this new generation of UAV is designed to tackle the drawbacks caused by rotorcraft and conventional fixed wing UAV, the existing designs of rotor fixed wing UAV still have their own weaknesses. The interference of airflow that occurs while switching the flying mechanism from vertical to horizontal and vice versa may cause the UAV to become unstable and resulting in the difficulty to control [6][10][12][13][14]. However, the major works to date only focuses on the previously mentioned issue and presents very little or nothing at all regarding how difference is the deflection at the tip of the wing between a hybrid VTOL and a conventional fixed wing.

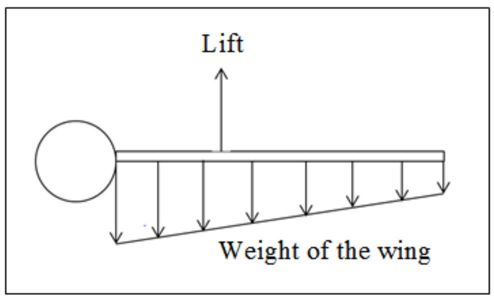

Figure 1: Weight of the wing and lift produced by rotor acting on wing spar

According to Figure 1, during vertical takeoff, the weight of the wing is acting downwards as distributed force. At the same time, thrust produced by lifting rotors is acting downwards. Due to the significant difference between the sizes of the wing surface area with are of rotation of the propeller blade, therefore the lift force is considered as a concentrated force. This case is different from a fixed-wing aircraft because wing of a hybrid VTOL does not generate lift during taking off but a fixed wing does. The difference in these forces will eventually cause the tip of the wing to experience deflection. However it is important to remember that in real life application, the force coming from the rotor is not a static force. There will be fluctuation in the amount of forces acting on the wing.

2.0 MATERIALS AND METHOD

Quantitative methodology had been chosen to investigate the difference in wing deflection between a rotor fixed wing and a conventional fixed wing. Data were collected from experiment and calculations that were based on existing related studies. To achieve this, the MTOW of the rotor fixed wing was estimated. After that, the new wing dimension was determined. Following that, a thrust test was conducted to identify thrust available during vertical takeoff. At the same time, the deflection at wing tip was calculated for the fixed wing mode. Lastly, a vibration test was conducted to identify the deflection at wing tip of a rotor fixed wing. The two results were then being compared and a conclusion was drawn out of it.

2.1 Wing Specification

The structure of the wings used in this project is made of EPS foam. However for both main spar and aft spar, they are made of aluminium bar. The important parameters for the wing are listed in Table 1. Then, to find suitable wingspan, the MTOW of the UAV was estimated. The reason why this was done was because the amount of lift needed by a UAV depended on its MTOW.

Table 1: General Wing Specification

Type of Wing	Straight Wing
Airfoil Type	E205
Chord	0.310 m

During a straight and level flight, lift needs to be equal to weight, and drag is equal to thrust for creating an equilibrium condition. Supposing this equilibrium is violated; when lift is larger than weight, then the aircraft will fly upwards and when the lift is smaller than weight, then the aircraft will fly downwards. Therefore, to ensure the aircraft to fly upwards, a certain amount of lift-to-weight ratio was determined beforehand. Once the ratio had been determined, the value of L was substituted into lift equation as shown below. The suitable value of C_l during cruising could be identified by using graph C_l/C_d against angle of attack, α and C_l against α. However, the discussed C_l referred to the 2D or infinite wing theory. In the case of real life application, it is a finite wing (3D). Therefore, the C_L should have a 30% reduction of C_l due to the occurring of induced drag [15].

$$L = C_L \frac{1}{2} \rho v^2 S \quad (1.1)$$

2.2 Thrust Test

The purpose of thrust test was to identify amount of thrust needed for takeoff. Therefore, a thrust test was conducted to collect data on thrust and power of the motors. In this study, the thrust stand used was calibrated first in order to prove its reliability in producing thrust measurement. The setup of the experiment was as shown in Figure 2.

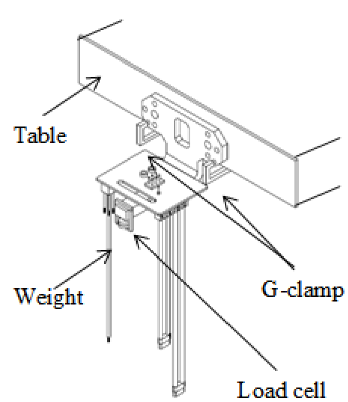

Figure 2: Setup for thrust calibration

For both experiment, Dynamometer Series1520 from RCbenchmark was used together with its software as the thrust stand. Since the thrust sensor only worked horizontally, therefore, to imitate the weight of objects that always acted downwards, the dynamometer was clamped vertically by using a G-clamp. Motor mounting part was purposely removed from load cell since its presence served as additional weight to the load cell and would affect the measurement later. The average tare thrust was taken as -0.01267 gf. Then, the weights that had been prepared beforehand were added and the corresponding average thrust reading was taken.

Following that, the thrust stand was clamped horizontally for thrust test as illustrated in Figure 3. However, due to limited time, the test was conducted on one motor only and it was assumed that other motors perform exactly the same as the motor used for the test. The experiment was run for 10 times and the data for each trial were recorded.

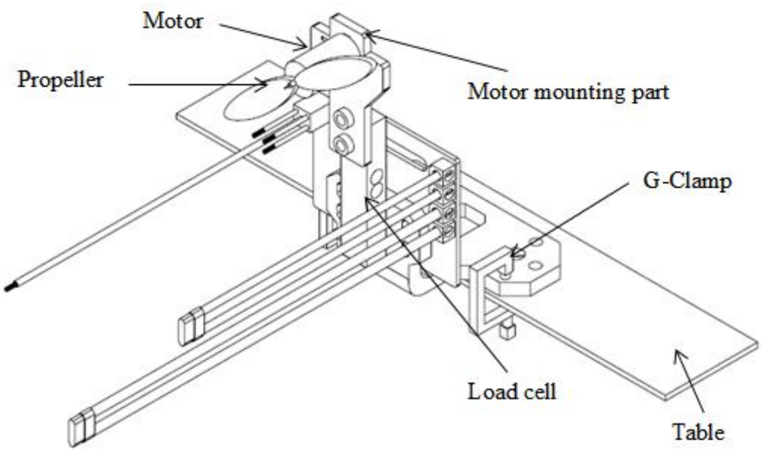

Figure 3: Setup for thrust test

2.3 Wing Deflection on Fixed Wing

To find the deflection of wing of a fixed wing UAV that would be compared later with a hybrid VTOL, the beam deflection equation was used and expressed as below.

$$y = \frac{Wx^2}{24EI}(x^2 + 6l^2 - 4lx) \tag{1.2}$$

E value of the aluminium bar was taken as 69GPa [16] while value of I was calculated from equation (1.3). However, since the shape involved was not a square but an airfoil shape, therefore the airfoil shape must be simplified into a rectangle by using the efficient chord and maximum thickness of camber. After that, by using equation (1.2), values of y by varying x from 92cm to 100 cm were found.

$$I = \frac{bd^3}{12} \tag{1.3}$$

2.4 Vibration Test

There were significant difference between flexural strength of an EPS foam and a pure aluminium. The flexural strength of EPS foam was around 0.1% from the aluminium's as stated in previous section. This value was relatively small that EPS foam could be considered to have zero contribution on supporting any forces acting on the wing. As a result, the experimental setup for vibration analysis involved only aluminium bars that acted as wing spar rather than the wing as a whole since foam was used only to give the wing airfoil shape as needed and due to its lightweight criteria. The objective of this experiment was to identify the amount of displacement experienced by the tip of the wing during vertical takeoff.

The experimental setup was arranged as shown in Figure 4. Firstly, aluminium was measured and cut according to the dimension of the new wing and propeller arms that had been calculated earlier. Then, four pieces of small plates was prepared as mounting part between motor and aluminium bar. Pixhawk flight controller was used as a sensor in this experiment. The reason why it was used instead of an accelerometer was because it consisted of Invensense MPU 6000 3-axis accelerometer/gyroscope and could measure static forces of acceleration which is gravity and also dynamic forces such as vibration. Following that, an Arduino board was connected to the laptop and sensor. Then, the Arduino software was ran for data collection. To read acceleration data provided by the sensor, the serial output on the top right corner of the software was used. The data measured was collected and integrated with respect to time.

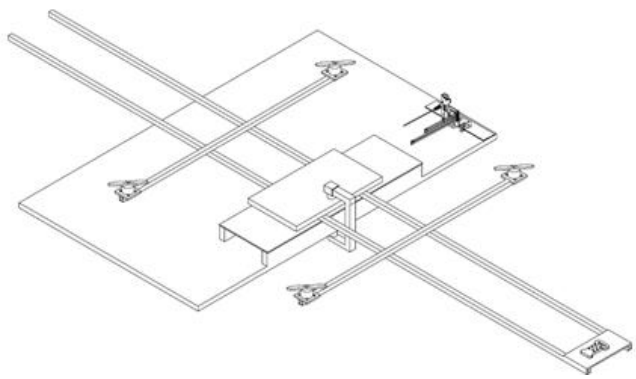

Figure 4: Setup for vibration test

3.0 RESULT AND DISCUSSION

3.1 Wing Specification

The total weight was found as 3.54kg. To simplify further analysis, this value was rounded off to 3.5kg. Therefore, the weight of the UAV was estimated to be as ±3.5kg. The value of Re was acceptable as a mini UAV that weighed below 10kg should fly in the range of 10^4<Re<10^5 [19].

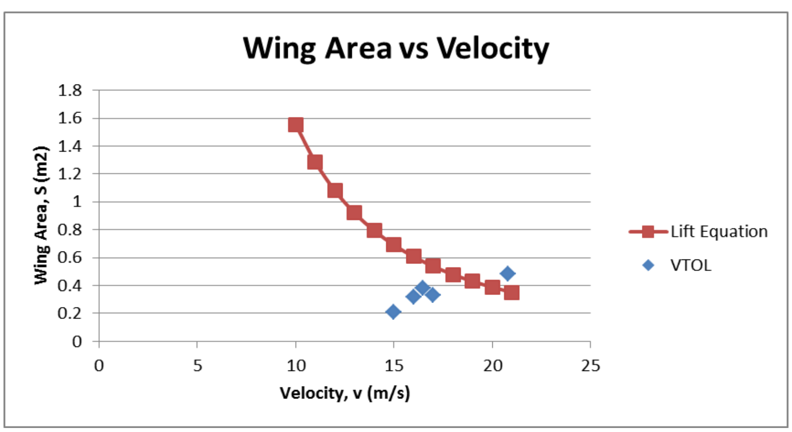

Figure 5: Graph of wing area against velocity

A comparison of the two results revealed that at the range of 15m/s to 20m/s, the wing area data collected from existing VTOL had lower values from the calculated values. It was decided that the best method to adopt for this investigation was by referring to wing area calculated from lift equation. Presumably that the optimum cruising speed would be around 16m/s, hence the corresponding wing area was 0.607415 m^2. By maintaining the chord of the wing as before which was 0.31m, the new wing span should be 1.96 m in which was taken as 2 m for this study. By substituting the new wing area into equation (3.2) again, the amount of lift force required to fly a ± 3.5 kg rotor fixed wing was 70.093 N.

3.2 Thrust Test

Simple linear regression analysis is a statistical modeling approach that was used for predicting the relationship between one dependent variable and one independent variable [17]. To investigate the reliability of thrust measured from the calibration test, firstly a graph of thrust against load was plotted as shown in Figure 1(a) and an estimated simple linear regression line was produced from it by using least squares method. The result displays that thrust measured from the calibration test lies in the range of 0 to 3500gf and is similar to the weight of the loads. The mean ± standard deviation of thrust obtained for each load were: -0.0001 N ± 0.0033 N (load = 0 g), 4.9358 N ± 0.0019 N (load = 503 g), 9.8274 N ± 0.0038 N (load = 1002 g), 14.7361 N ± 0.0031 N (load = 1503 g), 19.6336 N ± 0.0047 N (load = 2001 g), 24.5369 N ± 0.0034 N (load = 2502 g) and 29.4744 N ± 0.0048 N (load = 3005 g). In all cases, the difference between the average of thrust measured with the actual load was only around ± 0.01 N, which was very small. The data points also have low dispersion level since they were very close to the mean (stay in the range of not more than ± 0.0050 N).

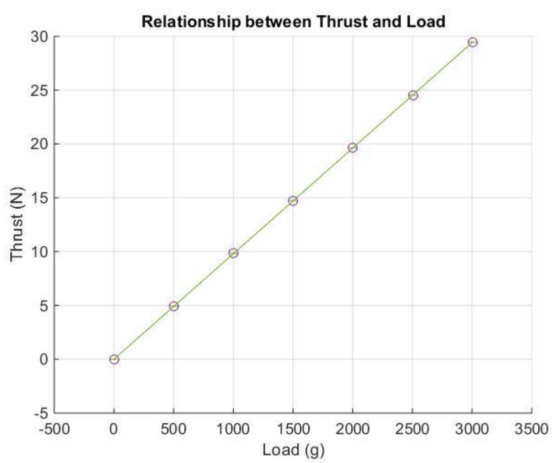

Figure 5: Graph of thrust against load

To further determine whether or not previously mentioned finding is acceptable, the regression line (y = 1.0002x + 0.028795) obtained was being fully utilized. The y in the linear regression function denotes thrust as a dependent variable, 1.0002 as regression coefficient, x represents load as independent variable and 0.028795 as constant. This finding states that the thrust measured will increase by an average of 1.0002gf for every additional unit of load which in this case it is very close to 1 and can be considered as thrust measured $\approx$ load. This value is also relatively small and does not affect the experimental data collected as a whole. In short, the result shows that the thrust stand produce consistent thrust measurement with high accuracy and therefore it is reliable to be used for next experiment.

To determine amount of thrust and power available to perform vertical takeoff, a graph of thrust, power and current against percentage of throttle was plotted by using data measured from thrust test on MATLAB. However, the data was collected only until $\pm 55\%$ throttle due to the thrust stand's limited capability. Since data was only collected until ±55% throttle, therefore the thrust, power and current required for percentage of throttle that went beyond 55% was predicted by using regression analysis

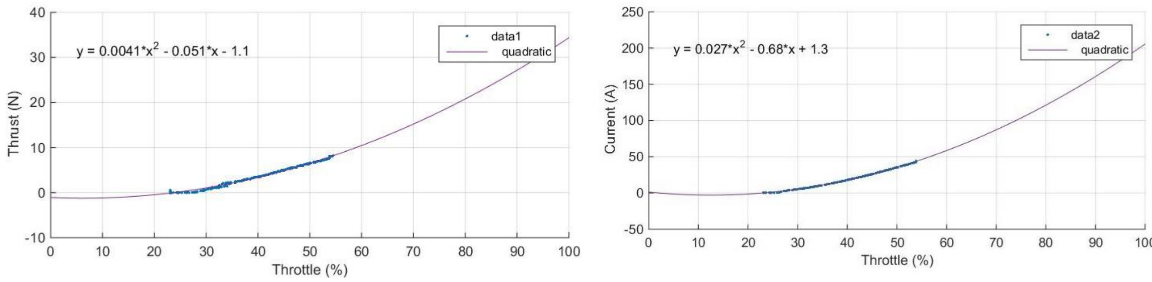

Figure 6: Graph of thrust and current against percentage of throttle

Based on Figure 6, for graph of thrust against throttle, the regression function obtained was $y = 0.0041x^2 - 0.051x - 1.1$. This expression denotes that as the percentage of throttle increased, the amount of thrust produced would also increase accordingly. The evidence showed that the thrust produced lied at the range of 0 N to ±35 N. As calculated previously, the motors were required to produce 70.093 N of lift. Since there were four lifting rotors, then each motor must be able to yield 17.52 N of upwards thrust therefore the UAV would be able to perform vertical takeoff only if the motors rotated at 70% to 79% of throttle. For graph of current against throttle, the regression function presented was $y = 0.027x^2 - 0.68x + 1.3$. According to the function, the current would probably reach 200A at 100% throttle. However, by referring to the datasheet supplied from manufacturer, the ESC used was only capable to supply continuous current only up to 80A and a burst current of 100A. As discussed earlier, the UAV was capable to fly at 70% to 79% throttle. The finding above showed that at 70% to 75% throttle, the current was predicted to reach at somewhere less than 100A therefore, this ESC had been proved to be suitable.

3.3 Vibration Test

The raw data obtained from Arduino Serial Output were in g unit and in the direction of x, y and z-axis. The data was converted into acceleration unit, m/s^2. It was then integrated until the value of displacement was obtained. From Figure 4.6, the highest amplitude for graph of displacement on z-axis against time was recorded as not more than +0.1 m and not less than -0.05 m. The mean ± standard deviation of displacement obtained were 0.000986 m ± 0.01144816 m. The difference between mean and standard deviation was quite large which means the dataset had high dispersion level and scattered more randomly rather than gathered around one range of values.

Both displacement and deflection were vector quantities since they came with magnitude and direction. However, displacement is the magnitude of deflection [20]. Therefore, the displacement on z-axis obtained from vibration test was being compared with deflection calculated to see which one between them displayed larger deflection at wing tip during takeoff.

Table 2: Comparison between deflection at wingtip of a hybrid VTOL and fixed wing

	Mean	Standard Deviation	Max. Deflection
Hybrid VTOL	0.000986	0.01144816	0.0865385
Fixed Wing	0.000238	0.00000789	0.0002516

4.0 CONCLUSION

As a conclusion, all research objectives have been achieved. This thesis has presented a detailed design process on wing of a hybrid VTOL UAV that covers from estimating MTOW of the UAV to fabricating the wing spar model together with limitations faced during executing it. The structural analysis done on the wing spar has also been recorded thoroughly for future use. Both thrust test and vibration test conducted has provided the results as expected.

The result shows that maximum deflection at wing tip for hybrid VTOL is higher than a conventional fixed wing. Factors that contributed to this finding were the concentrated upward lift force and also fluctuated force coming from vibration of the motor driven propeller. The difference is relatively high which is about 75%. In addition to that, dataset of hybrid VTOL were randomly spread data than fixed wing. This is understandable since dataset of hybrid VTOL is collected from experiment while a fixed wing is measured by using theoretical calculation.

Recommendations on future work include the detailed description on the deflection of the rotor in hybrid VTOL, vibration test that involves a complete set of wing instead of only wing spars, and carry out wind tunnel testing for a more precised data on wing deflection of a fixed wing.

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