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Development of tilt-rotor unmanned aerial vehicle (UAV): material selection and structural analysis on wing design

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Development of tilt-rotor unmanned aerial vehicle (UAV): material selection and structural analysis on wing design

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Abstract. This paper presents the design of a tilting rotor unmanned aerial vehicle (UAV), evaluation of flight loads based on the standard requirement, structural analysis to determine stress and sizing of the wing, and flight test of the UAV. The main objective is to perform structural analysis to size the UAV's wing section. The analysis shows that the structure design of the wing is safe to be used.

1. Introduction

Aeronautic industries have long begun and have been growing over decades with newer inventions, technologies as well as rapid research in this promising field [1]. There are a lot of researches have been made throughout the world including aerial mapping, unmanned aerial vehicle (UAV), etc. The search for an aircraft type with vertical take-off and landing (VTOL) capabilities has triggered the imagination of designers and inventors to produce numerous configurations using a wide variety of lifting and propulsion devices [3]. A summary of some of these configurations is available in the V/STOL (Vertical or Short Take-off and Landing) concepts illustration prepared by the McDonnell Aircraft Company in the 1960s [6]. For various aircraft types considered, one of the key distinguishing features is associated with the device used for providing the vertical lift. The development of VTOL is very important as it has many usage such as in the field of safe and rescue, military application and even some commercial applications [2]. The usage of VTOL cuts the runaway distance, making it easy to take-off and land on aircraft carrier as well as other constrained areas where the paved runaway or space is limited.

Throughout their long history, UAVs have played such an important role whether in warfare or surveillance. The idea of unmanned is to control a machine digitally and replace the needs of human intelligence on-board, saving the human capital for much better use. When compared to manned aerial vehicles, UAVs are believed to provide two vital benefits – they are cost effective and reduce the risk to a pilot's life [4]. However, accident rates in today's UAVs are over 100 times compared manned aircraft. Therefore, improved safety and reliability are still required. The requirement of this research is to design and fabricate a remote controlled aircraft, which is also known as Tilt-Rotor UAV, that can take-off and land vertically. Besides, the study also done to identify the material selection for the UAV and demonstrate the analysis on the wing design of the UAV. In order to achieve the whole benefits and purposes out of Tilt-Rotor UAV, there are a lot of obstacles need to be overcome. Since the rotors can be configured to be more efficient for propulsion (e.g. with root-tip twist) and it avoids a helicopter's issues of retreating blade stall, the tilt-rotor can achieve higher speeds than helicopters. A tilt-rotor aircraft differs from a tilt-wing in that only the rotor pivots rather than the entire wing. This method trades off efficiency in vertical flight for efficiency in STOL/STOVL operations.

Nevertheless, the scope of this research paper is limited to material selection and structural analysis on the wing design. The primary objectives of this project are to design VTOL of Tilt-Rotor UAV by surveying the material selection and to perform structural analysis to determine the sizing of wing.

2. Materials and methods

This study is focused on the development of multi tilt-rotor UAV by concentrating on the structure and design analysis. The information obtained will guide the UAV to move at tilting concept mechanism towards the respective object of interest. In accomplishing the outlined objectives, several guidelines have been observed: reviewing the previous related VTOL UAV projects and performing a standard structural analysis by several methods in aircraft structural analysis design concept.

2.1. Material selection and conceptual design

In this part, it is basically focused on selecting the suitable material to fabricate the tilt-rotor UAV and adhesive needed for this project. Some reference reading is made based on material selection for the main body such fuselage, wing and tail, type of propeller, type of adhesive and type of motor. Table 1 highlights some of the optional materials that can be selected for the main body of the UAV.

Table 1. Justification material selection for the main body [8]

Materials	Pros	Cons
Balsa wood	• Porous • Less glue required • Lightweight • Widely available • Stiff • Easy to sand	• Varying strength • Very expensive
Basswood	• Won't crush • Lightweight	• Hard to sand • Not widely available • More expensive
Depron foam	• Very lightweight • Easy to shape • Flexible • Very cheap	• Not very strong
Plastic	• Strong • Rigid	• Rigid • Hard to work with • Expensive • Relatively heavy
Metal	• Very strong • Rigid	• Very heavy • Expensive • Hard to work with • Not widely available
Fibre glass	• Very strong • Very lightweight	• Very expensive • No previous experience • Not widely available

Depron foam was chosen as the base frame material due its low cost and easy fabrication properties, despite Fiber Glass having a significant strength to weight advantage. The aluminum box are put in the wing for tilt rotor and the body is covered by fibre glass composite. Table 2 tabulates some of pros and cons of alternatives for the propellers.

Table 2. Justification for propeller selection [8]

Propellers	Pros	Cons
Dual Blade	• Easily available • Very efficient • Easy to use • Fairly cheap	• Larger diameter
Multi Blade	• Smaller diameter	• Less available • Less efficient
Wood Blade	• Very rigid • Efficient • Light	• Breaks easily
APC Blade (Metal)	• Don't break as easily • Efficient	• Heavy

For this tilt-rotor VTOL UAV, the location of the propeller is placed at the tip of the wing. The thrust must be at the *cg* location to make it more stable. When the aircraft experience gust load during hover, the tail rotor will produce thrust to make it stable. It was decided to use two-blade propellers as compared to three-bladed system used by the real V-22 Osprey [2]. This is due to increased efficiency of the two-bladed propellers over the three-bladed propellers. Moreover, justification for the adhesive selection can be seen in Table 3.

Table 3. Justification for adhesive selection [8]

Adhesives	Pros	Cons
Wood Glue (Urea)	• Easiest to use • Low cost • Light color	• Poor heat resistance • Poor moisture resistance • Bond not very strong
Hot Glue	• Quick cooling time • Relatively easy to use • Low cost	• Bond not strong • Leaves residue • Visible on plane
Gorilla Glue	• Very light • Expands while setting • Best for wood than other materials • Waterproof	• Hard to work with • Contains air bubbles • Somewhat expensive
Pro-bond Glue	• Expands when dry • Less glue required • Cheap • Water-resistant	• Heavy
Rubber Cement	• Strong flexible bond • Easy to peel off • Not brittle	• Flammable • Highly toxic • Expensive
Super Glue	• Very strong bond • Often used for model aircraft • Versatile • Water resistant	• Expensive • Can become brittle • Long cure times

To make the aircraft in stable and solid form, a strong adhesive connection must be used to ensure that the aircraft does not broken during flight or VTOL. On the other hand, some considerations for the motor selection is presented in Table 4.

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Table 4. Justification for motor selection [8]

Motors	Pros	Cons
Electric	• Cheap • Easy to run • Clean • Doesn't require gasoline • Lightweight	• Low power / torque
Nitro	• Relatively cheap • Wide availability • High torque and power	• Special mixture of fuel • Heavy
Gas	• High torque and power	• Not as available • Heavy • Special mixture of fuel • Expensive
Jet	• Extreme power	• Extremely expensive • Not as available

Based on the above justification, the main body will be made from depron foam board due its flexibility, easy to shape, price tag and light in weight. For the propeller, the dual propeller is chosen due to its availability, efficiency and price tag. As there are a lot of parts that needs to be mounted, the glue will be the best solution due to the low operating cost and high availability. Last but not least, for the propulsion part, electric motor is chosen as it is very cheap to purchase, environmental friendly and easy to operate.

2.2. Conceptual design of tilt-rotor UAV

Aircraft design is basically a combination of science and art together in producing a beautiful machine. In the design phase, whether for normal configuration like the common civilian transport aircraft or for new configuration, there are few steps that need to be followed in order to design and build an aircraft. These design phases are in chronological order: conceptual design, preliminary design, detail design. In conceptual design phase, it basically starts by setting a few specifications for the new aircraft. Every designer has their own approach in developing their conceptual design. However, there are some basic guidelines that are vital and significant for conceptual design. They are design requirement, estimation of the weight of aircraft, identification of some critical performance parameters, type of configuration, performance analysis and optimization. For this study, the mission specifications of the tilt-rotor UAV are presented in Table 5. Some initial conceptual design estimations are then presented in Table 6.

Table 5. Preliminary mission specifications of the present UAV [7 – 8]

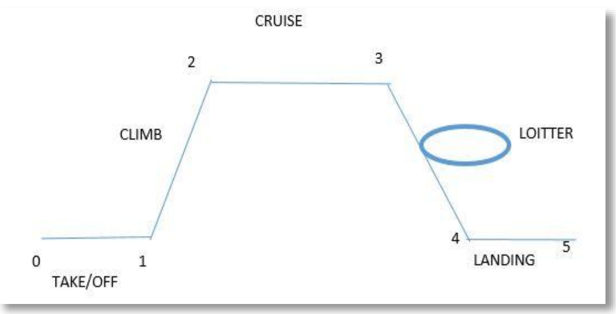
<table>
<tr><th>Mission Specifications</th><th>Mission Profile</th></tr>
<tr><td>V_{max} = 30 m/s
V_{climb} = 49 ft/s
Rate of climb = 10 ft/s
V_{stall} = 39 ft/s
V_{cruise} = 69 ft/s
Range = 10000 ft
Altitude = 1000 ft
Endurance = 20 min
Rho (sls) = 0.00238 slug/ft^3
Rho (cruise) = 0.002308 slug/ft^3</td><td>
</td></tr>
</table>

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Table 6. Design calculations

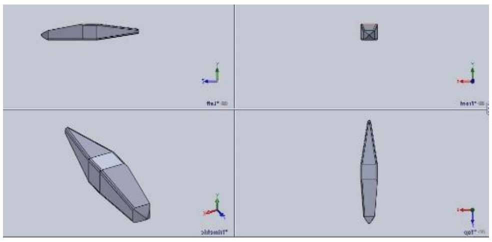
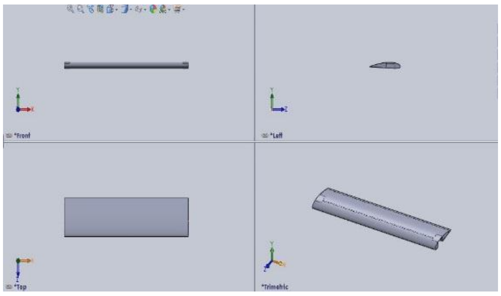
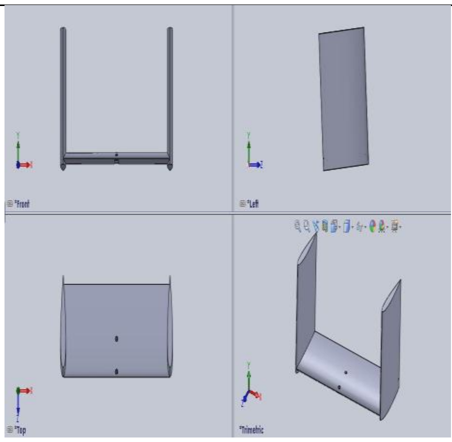
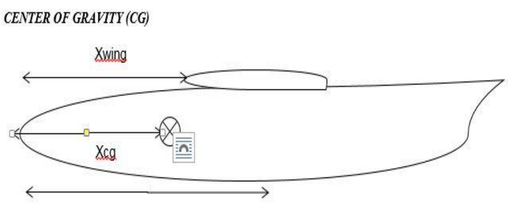
	FORMULA/DESIGN	CALCULATION VALUE
MAXIMUM TAKE OFF WEIGHT	STALL: $\frac{W}{S} \ll \frac{1}{2}.\rho.Vstall^2.C_{lmax}$ TAKE-OFF: $\frac{W}{S} \ll TOP.\sigma.C_{lTO}.\frac{Hp}{w}$ CLIMB: $\frac{w}{s} = \frac{\left(\frac{T}{W} - G\right) \pm \sqrt{\left(\frac{T}{W} - G\right)^2 - (\frac{4Cdo}{\pi e})}}{2/q\pi Ae}$ CRUISE: $\frac{W}{S} = q\sqrt{\pi AeCdo}$	STALL: $\frac{W}{S} \ll 1.79\ lb/ft2$ TAKE-OFF: $\frac{W}{S} \ll 1.411\ lb/ft2$ CLIMB: $\frac{W}{S} = 39.896\ lb/ft2$ CRUISE: $\frac{W}{S} = 1.582\ lb/ft2$
WING LOADING	The lowest wing loading is the one to be selected.	$\frac{W}{S} = 1.411\ lb/ft2$
FUSELAGE SIZING	$L = aWo^c$  **Figure 1.** Fuselage sizing	$L = 2.31ft = 700\ mm$
WING SIZING	 **Figure 2.** Wing Sizing	$\frac{Wo}{s} = 1.411, s = \frac{Wo}{1.411} = 1.79\ ft2$ $b = \sqrt{A \times S} = 3.3\ ft$ $Cr = \frac{2S}{b(1+\lambda)} = 0.54$ $\bar{c} = \frac{2}{3}.Cr.\left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right) = 0.54$ $Ct = \lambda Cr = 0.54\ ft,$ $\bar{y} = \frac{b}{6}\left(\frac{1+2\lambda}{1+\lambda}\right) = 0.82$
TAIL SIZING	 **Figure 3.** Tail Sizing	<u>VERTICAL TAIL</u> $Cvtnew = 0.95(0.04) = 0.038$ $Svt = \frac{Cvtnew.bw.sw}{Lvt} = 0.162ft$ $Lvt = \frac{60}{100}L = 1.386ft$ $b = \sqrt{A \times S} = 0.44ft$ $Cr = \frac{2S}{b(1+\lambda)} = 0.368ft$ $Ct = \lambda Cr = 0.368\ ft$ $\bar{c} = \frac{2}{3}.Cr.\left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right) = 0.368ft$ $\bar{y} = \frac{b}{6}\left(\frac{1+2\lambda}{1+\lambda}\right) = 0.11\ ft$

Table 6. Design calculations (continued)

	FORMULA/DESIGN	CALCULATION VALUE
TAIL SIZING		HORIZONTAL TAIL $Chtnew = 0.95(0.5) = 0.475$ $Sht = \frac{Chtnew.Cw.sw}{Lvt} = 0.361ft$ $Lvt = \frac{30}{100}L = 0.693ft$ $b = \sqrt{A \times S} = 1.46ft$ $Cr = \frac{2S}{b(1+\lambda)} = 0.38ft$ $Ct = \lambda Cr = 0.114ft$ $\bar{c} = \frac{2}{3}.Cr.\left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right) = 0.27ft$ $\bar{y} = \frac{b}{6}\left(\frac{1+2\lambda}{1+\lambda}\right) = 0.27\ ft$
CENTRE OF GRAVITY	 **Figure 4.** Centre of gravity	Weight distribution : Wo= 2.52 lb , Wwing= 0.25 kg , Wengine=0.20 kg, Wpl = 0.4 kg , Wtail= 0.25 kg $\sum Mcg = \sum Mle$ without wing : $x = \frac{0.20(0.9) + 0.4(0.3) + 0.25(2)}{0.2 + 0.4 + 0.25} = 0.941\ ft$ with wing : $Xcg = 0.97\ ft$ $Xcg = 0.97ft \simeq 296\ mm$ $static\ margin = \frac{(Xn - Xcg)}{c} = 0.1$ $0.1 = \frac{Xn - 0.97}{0.54} = Xn = 1.024$ $Xac = Xn - Xvt = 0.794\ ft$

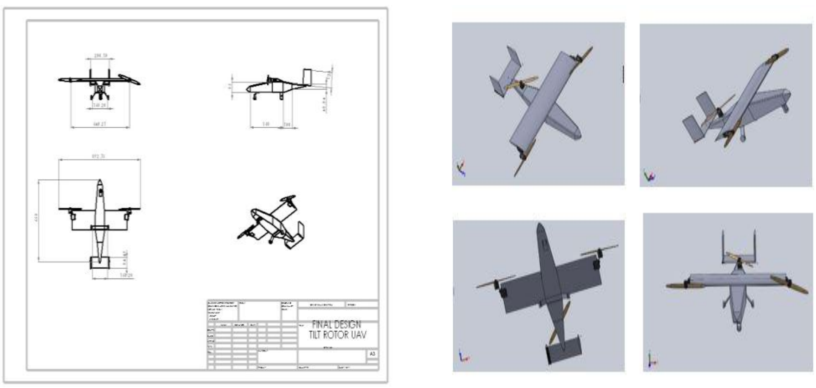


Figure 5. Layout and 3D view of the UAV design after achieved the design requirements

3. Results and discussion

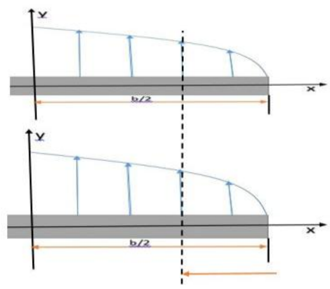
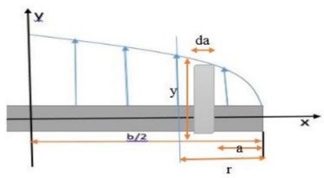
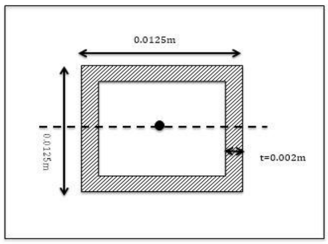
Before the structure of the wing can be designed, there is a need to determine the loads that will be imposed on the aircraft's wing. This section deals with the general issue of aircraft loads and how they are predicted in the early stages of the design process. The load factor is the multiplier used on limit load to determine the design load. In this case, since there are specific requirements for the factor of safety, 4.5 will be used as the factor of safety as obtained from the STANAG USAR requirement [14]. The safety factor, N_z from the STANAG requirement is calculated as follows, taking the weight to be 1.3 kg or 2.866 lb:

$$Nz = 2.1 + \left(\frac{10900}{W+4536}\right) = 2.1 + \left(\frac{10900}{2.866+4536}\right) = 4.5$$

3.1. Structural analysis of wing design

In this section, the structural analysis is mainly about investigation of shear force and bending moment at the wing of the tilt rotor UAV. This theory will be applied at the calculation part for the tilt-rotor UAV project.

Table 7. Justification for structural analysis of wing design

ITEM ANALYSIS	RESULT	FIGURE
Load Factor	$Nz = 4.5$	
Shear force		
Va (aerodynamic shear force)	$Va = 0.2088\ N$	
Vp (propeller shear force)	$Va = 7.505N$	
$V(Total)$	$V = 7.7138N$	
Bending moment		
Ma (aerodynamic moment)	$Ma = 0.02724\ N.m$	
Mp (propeller moment)	$Mp = 1.3133\ N.m$	
$M(Total)$	$M = 1.34054\ \mathrm{N.m}$	
Moment of Inertia	$I = 2.62083 \times 10^{-9}$	
Shear Stress	$\tau = 344.91\ KPa$	
Bending stress	$\sigma = 4.260\ MPa$	$\sigma_x = -\frac{M_z y}{I_{zz}} + \frac{M_y z}{I_{yy}}$

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Aluminium 2014-T6 was used as the reference, which σy = 414 MPa. To compare it :

$$\sigma = 4.260\ MPa < \frac{414}{1.5} \quad \rightarrow \sigma = 4.260\ MPa < 276\ MPa$$

where σ is 4.260 MPa. This shows that the wing bending stress is less than bending stress yield, even though it is very small but may increase the weight later. For the shear stress:

$$\tau = \frac{VQ}{It} = 344.91\ KPa$$

where τ is 344.91 kPa, V is 7.7138 N , Q is $2.34375X10^{-7}$, I is 2.62083×10^{-9} and t is 0.002. In aircraft structure design, one of the most important factors is load factor. Each design of aircraft has its own *V-n* diagram. Here the *V-n* diagram is the same as RV-9 [8]. Since the airspeed is no more than 25 kts, a load factor of 1.5 is given, so the maximum stress is 276 MPa. For aluminum, the stress strain curve is shown in Figure 6. According to the calculation, the maximum stress is 4.118 MPa, which is far smaller than the upper yield point for aluminum, hence aluminum is safe to use.

3.2. Wing design simulation analysis

After the theoretical structural analysis has been performed by proving design requirement calculation and mechanical structure on wing parts, Solidworks and Catia V5 software have been used to design and simulation for this research. The load distribution is assume to be elliptical and the fixed support is at the edge of the wing, as shown in Figure 7. The wing is arranged as high wing location. The load distribution pressure is 7.784 N/m^2 as calculated by using area under the elliptical graph at the wing. The material of the wing is fixed foam, which has tensile strength of 7 lbs/sq.in. The properties of the material are 1.2 lb/ft^3 of the weight and the density of the foam is 1.2 lbs/cu.ft.

Mesh analysis on the wing is done to get the grid solid region on the wing and to justify structural wing design for doing further element structural analysis. This is shown in Figure 8. Figure 9 shows that the value of bending stress of the wing using this software simulation is 5.42 MPa. The diagram shows that the structure is safe because most region of the wing is blue, which not in critical condition. The wing is safe to use in the UAV after doing structural analysis. The UAV wing span is 1.96 ft and the chord length is 0.54 ft. After doing simulation by using Solidworks 2014 software, it shows that the bending stress is 5.42 MPa. From manual calculation, the theoretical bending stress is found to be 4.26 MPa. There is a small difference with approximately 10% between both values.

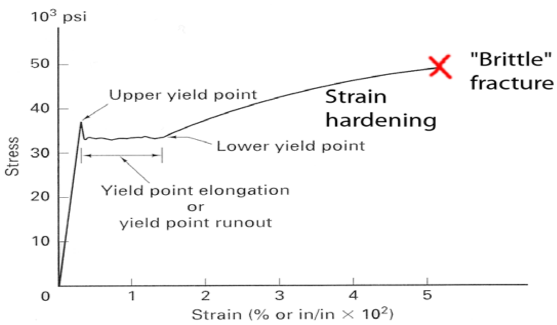

Figure 6. Stress-strain curve diagram [8]

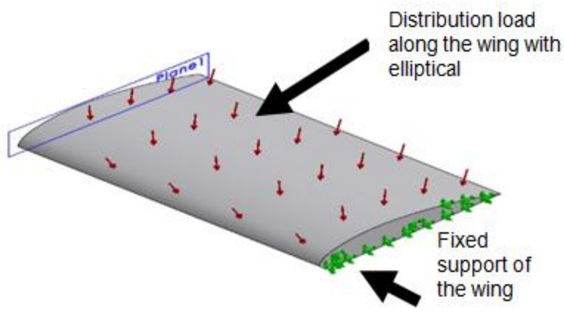

Figure 7. Load distribution applied along the wing

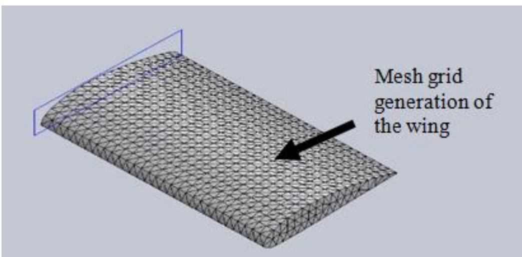

Figure 8. Mesh generation for wing

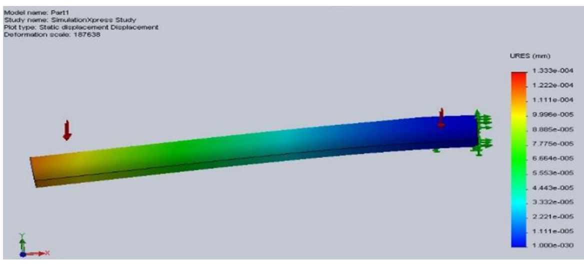

Figure 9. Von Mises stress analysis for wing

4. Conclusion

In this paper, the details of design, material selection and structural analysis on the wing of rotor UAV platform have been outlined. The designed Tiltrotor UAV is economical, moderately functional and an excellent platform for academic research purpose. By performing the structural analysis of the model, the results show that the design is safe for use. All in all, the objective of this project is achieved and it is ready to be fabricated for a flight test.

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