JOJAPS

eISSN 2504-8457

Journal Online Jaringan Pengajian Seni Bina (JOJAPS)

Development of Tilt-Rotor Unmanned Aerial Vehicle (UAV): Conceptual Design

Mohamad Firdaus Bin Saharudin[1] & Mohd Zulfazli Bin Raub Khan[2]

[1,2] *Jabatan Penyenggaraan Pesawat*
Politeknik Banting Selangor
firdaus.saha@polibanting.edu.my & zulfazlipbs@gmail.com

Abstract

This project research presents the conceptual design of a Tilt-rotor Unmanned Aerial Vehicle (UAV), which can perform vertical take-off and landing as well as cruise by utilizing appropriate tilt angle of the rotor. A remote control will be used to command the maneuver of the aircraft. In addition, this research is focusing on designing the structure part of the UAV, which covers the tilt-rotor UAV based on maximum load maneuver as required by NATO STANAG 4671. This design approach is based on the configuration of V/STOL (Vertical or Short Takeoff and Landing). In conceptual design phase, it basically starts by setting a few specifications for a new aircraft. Every designer has their own approach and angle to set their own basis in developing their conceptual design. However, the conceptual design of the UAV include some vital and significant criteria such as design requirement, estimation of the weight of aircraft, identify some critical performance parameters, type of configuration, performance analysis and optimization. These needs and potential applications provide the motivation for this design project, in the anticipation of designing and building a model VTOL. Improvement and recommendation of new ideas for the success of the UAV are also discussed.

Key-word: - tilt-rotor, unmaned aerial vehicle & conceptual design

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 research has been throughout the world and among those are aerial mapping, unmanned aerial vehicle (UAV) etc. The search for an aircraft type with Vertical Take-off and Landing (VTOL) capabilities triggered the imagination of designers and inventors to produce numerous configurations using a wide variety of lifting and propulsion devices[3]. A summary of these configurations is shown in the V/STOL (Vertical or Short Take-off and Landing) concepts illustration prepared by the McDonnell Aircraft Company in the 1960s [6]. For the various aircraft types considered, one of the key distinguishing features is associated with the device used for providing the vertical. The development of VTOL is very important as it has many importance and usage such as in the field of safety and rescue, military application and even commercial application [2]. The usage of VTOL cuts the runaway distance making it easy to take-off and land on aircraft carrier as well as other constraint areas where the paved runaway or space is limited. The development of VTOL is very important as it has many importance and usage such as in the field of safety and rescue, military application and even commercial application. The usage of VTOL cuts the runaway distance making it easy to take-off and land on aircraft carrier as well as other constraint areas where the paved runaway or space is limited. Throughout their long history UAV have played such an important role whether in warfare or surveillance. The military and aeronautic companies have been racing to develop such UAV to be surveillance purposes. These provide very important intelligence information to the military or for civilian protection purpose out of any danger.

The idea of unmanned is to control a machined digitally and replace the needs of human intelligence on-board and 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 to 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 project is to design and fabricate a remote controlled aircraft which is also known as Tilt-Rotor unmanned aerial-vehicle (UAV) which can take-off and landing vertically. Besides, to identify the material selection for UAV and demonstrate 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. However, the research paper carried out the problem about material selection and structural analysis on the wing design. This is because the UAV is the aircraft like model, so there are many things and parts need to consider because the plane have two tilting rotors at both side; left and right.

Thus, the flying wing suffers from being unstable and difficult to control. Besides that, another problem is in findings the dimension of wing which can support the thrust produce by the two rotors. The primary objectives of this project are collecting information about the Unmanned Aerial Vehicles (UAV) and the preliminary dimensions and the mass of the Tilt-Rotor Unmanned Aerial Vehicles (UAV). Finally, the goal is giving several design trade-off with a favourable solution. Therefore, the objectives of this research are:

I. To design of Vertical Take-off and Landing (VTOL) of Tilt-Rotor Unmanned Aerial Vehicles (UAV) by surveying the material selection.
II. To perform conceptual design and structural analysis to determine the sizing of wing

MATERIALS AND METHODS

This project focuses on the development of multi Tilt-rotor of 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:

I. Reviewing the previous related Vertical Take-off and Landing (VTOL) of UAV projects.
II. 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 basically focused on selecting the suitable material to fabricate the Tilt-rotor UAV and adhesive needed for this project. The definition of suitable is basically defined based on several criteria and some justification has been made. Some reference reading is made based on:

I. Material selection for the main body such fuselage, wing and tail.
II. type of propeller
III. type of adhesive
IV. type of motor

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 which 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. 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 we put at the tip of the wing. The thrust must be at the *cg* location to make it more stabilize. When the aircraft is experienced the gust load during the 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.

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, the strong adhesive connection must be used to make sure the aircraft do not broken when VTOL.

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 part needs to be mounted, the glue gun will be the best solution due to low operating cost and availability. Last but not least, for the propulsion part, electric motor is chosen as it is very cheap to purchase, very environmental friendly and easy to operate.

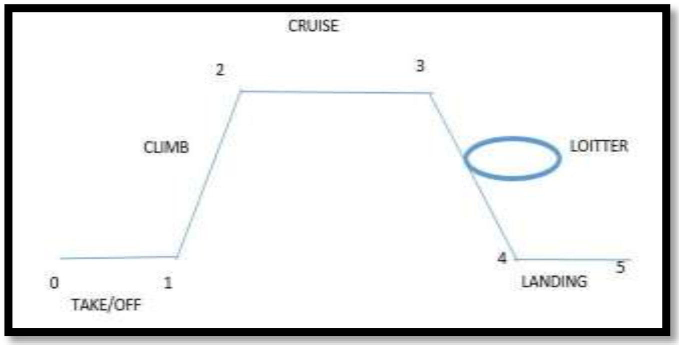
2.2 Conceptual design of Tilt-rotor UAV

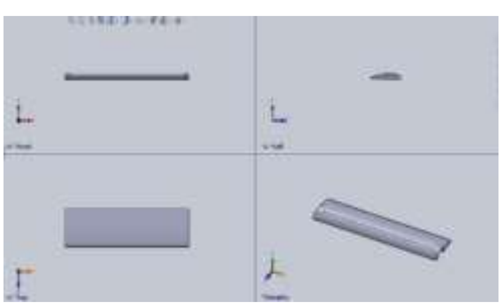
Aircraft design is basically a combination of science and art together in producing a beautiful machine. In the design phase, whether for normal configuration like in civilian aircraft or new configuration, there are few steps need to be followed in order to build an aircraft. These design phases are in chronological order, conceptual design, preliminary design, and detail design. In conceptual design phase, it basically starts by setting a few specifications for a new aircraft. Every designer has their own approach and angle to set their own basis in developing their conceptual design. However, there are some basic guidelines which will be vital and significant for conceptual design. Those are:-

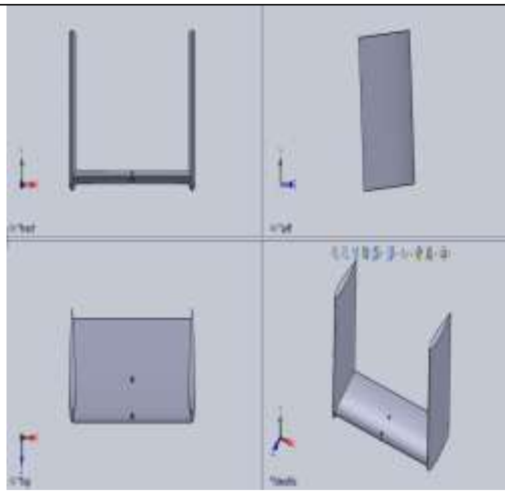
I. Design requirement
II. Estimation of the weight of aircraft
III. Identify some critical performance parameters
IV. Type of configuration
V. Performance analysis
VI. Optimization

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

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



	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 we need considered in our calculation.	$$\frac{W}{S} = 1.411\ lb/ft2$$
FUSELAGE SIZING	$$L = aWo^c$$  **Figure 1.** Fuselage sizing	$$L = 2.31ft = 700\ mm$$
WING SIZING	 **Figure 2.** Wing Sizing	$$\frac{Wo}{s} = 1.411$$ $$s = \frac{Wo}{1.411} = 1.79\ ft2$$ $$b = \sqrt{A \times S} = 3.3\ ft$$ $$Cr = \frac{2S}{b(1+\lambda)} = 0.54$$ $$\bar{c} = \frac{2}{3}.\text{Cr}.\left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right) = 0.54$$ $$Ct = \lambda Cr = 0.54\ ft,$$

<table>
<tr><td></td><td></td><td>$\bar{y}=\frac{b}{6}\left(\frac{1+2\lambda}{1+\lambda}\right)=0.82$</td></tr>
<tr><td>TAIL SIZING</td><td>
Figure 3. Tail Sizing</td><td>
<table>
<tr><th>***VERTICAL***</th><th>***HORIZONTAL***</th></tr>
<tr><td>$Cvtnew=0.95(0.04)=0.038$

$Svt=\frac{Cvtnew.bw.sw}{Lvt}=0.162ft$

$Lvt=\frac{60}{100}L=1.386ft$

$b=\sqrt{A\times S}=0.44ft$</td><td>$Chtnew=0.95(0.5)=0.475$

$Sht=\frac{Chtnew.Cw.sw}{Lvt}=0.361ft$

$Lvt=\frac{30}{100}L=0.693ft$

$b=\sqrt{A\times S}=1.46ft$</td></tr>
<tr><td>$Cr=\frac{2S}{b(1+\lambda)}=0.368ft$

$Ct=\lambda Cr=0.368\ ft$</td><td>$Cr=\frac{2S}{b(1+\lambda)}=0.38ft$

$Ct=\lambda Cr=0.114ft$</td></tr>
<tr><td>$\bar{c}=\frac{2}{3}.Cr.\left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right)=0.368ft$

$\bar{y}=\frac{b}{6}\left(\frac{1+2\lambda}{1+\lambda}\right)=0.11\ ft$</td><td>$\bar{c}=\frac{2}{3}.Cr.\left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right)=0.27ft$

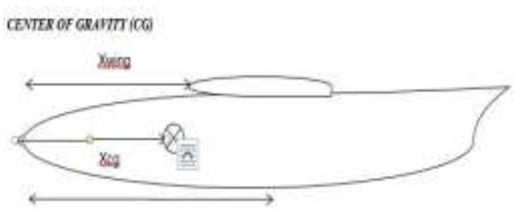
$\bar{y}=\frac{b}{6}\left(\frac{1+2\lambda}{1+\lambda}\right)=0.27\ ft$</td></tr>
</table>
</td></tr>
<tr><td>CENTRE OF GRAVITY</td><td>

Figure 4. Centre of gravity</td><td>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 :
$Xcg=\frac{0.20(0.9)+0.4(0.3)+0.25(2)+0.25(0.941+0.135)}{0.2+0.4+0.25+0.25}=0.97\ ft$

$Xcg=0.97ft\simeq 296\ mm$

$static\ margin=\frac{(Xn-Xcg)}{c}=0.1$

$0.1=\frac{Xn-0.97}{0.54}=Xn=1.024$

$Xac=Xn-Xvt=0.794\ ft$</td></tr>
</table>

Figure 5. These two figures justify layout and 3D view of the UAV design after achieved the design requirement.

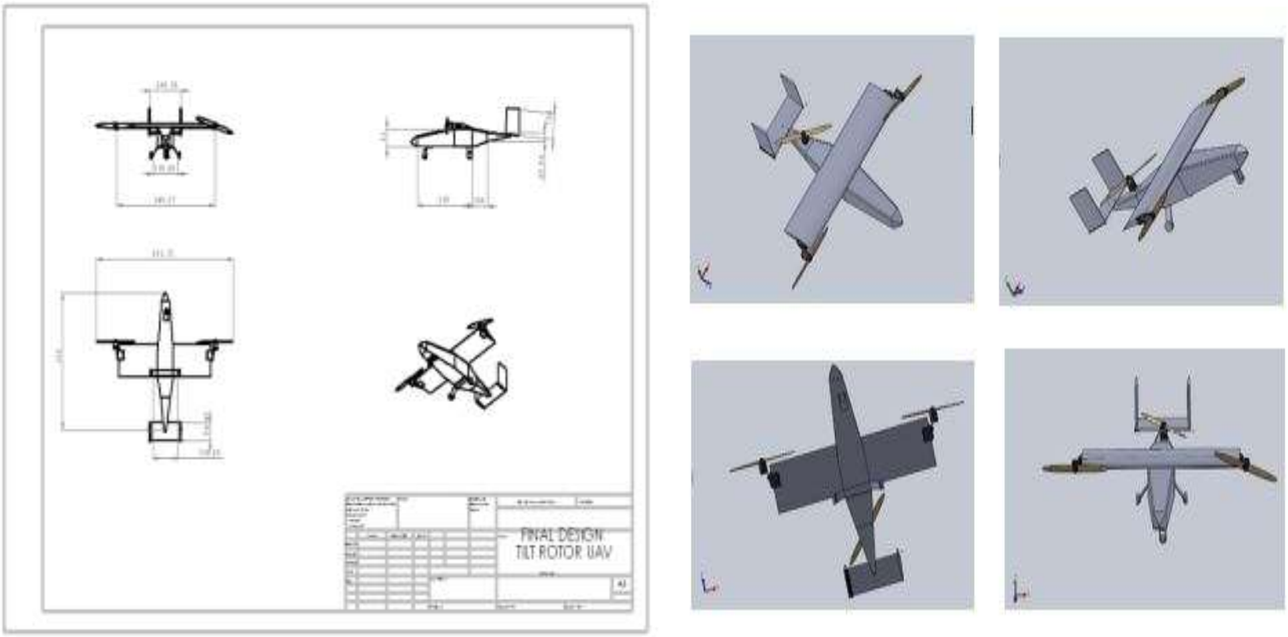


Figure 5. These two figures justify layout and 3D view of the UAV design after achieved the design requirement

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 use specific requirements for the factor of safety, 4.5 will be used as the factor of safety, which is obtained from the STANAG USAR requirement [14]. Below are the calculation parts to get the safety factor, N_z from the STANAG requirement:

Let:
W= 1.3 kg = 2.866 lb

$$Nz = 2.1 + (\frac{10900}{W + 4536})$$

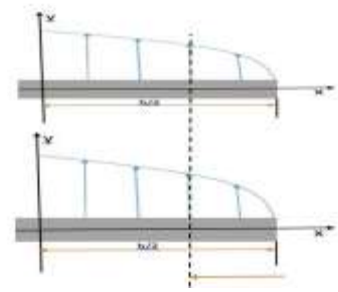
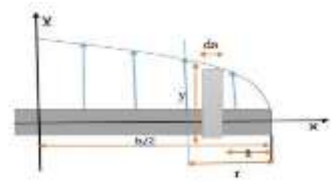
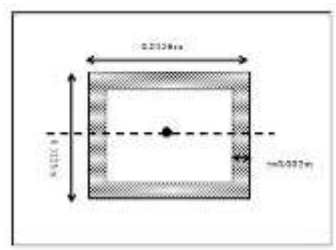
$$Nz = 2.1 + (\frac{10900}{2.866 + 4536})$$

$$Nz = 4.5$$

3.1 Structural Analysis of Wing Design.

In this section, the structural analysis is mainly about to investigate the shear force and bending moment at the wing of tilt rotor UAV. This theory will apply at the calculation part for the tilt-rotor UAVproject.

Table 6. Justification for structural analysis of wing design.

NO	ITEM ANALYSIS	RESULT	FIGURE
1	Load Factor	$Nz = 4.5$	
2	Shear force $Va\ (aerodynamic\ shear\ force)$ $Vp\ (propeller\ shear\ force)$ $V(Total)$	 $Va = 0.2088\ N$ $Va = 7.505N$ $V = 7.7138N$	
3	Bending moment $Ma\ (aerodynamic\ moment)$ $Mp\ (propeller\ moment)$ $M(Total)$	 $Ma = 0.02724\ N.m$ $Mp = 1.3133\ N.m$ $M = 1.34054$ N. m	
4	Moment of Inertia	$I = 2.62083 \times 10^{-9}$	
5	Shear Stress	$\tau = 344.91\ KPa$	
6	Bending stress	$\sigma = 4.260\ MPa$	$\sigma_x = -\frac{M_z y}{I_{zz}} + \frac{M_y z}{I_{yy}}$

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

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

$$\sigma = 4.260\ MPa < 276\ MPa$$

Where σ is 4.260 MPa
This shows the wing bending stress is less than bending stress yield, even though it is very small but may increase the weight later.
Shear stress formula:

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

Where τ is 344.91KPa, V is 7.7138N, 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]. According to the *V-n* diagram below:

Since the airspeed is no more than 25 kts, a load factor of 1.5 is given. So the max stress is 276 MPa. For aluminum, the stress strain curve is shown below. According to the calculation, the maximum stress is 4.118 MPa is far smaller than the upper yield point for aluminum, so this aluminum is safe to use.

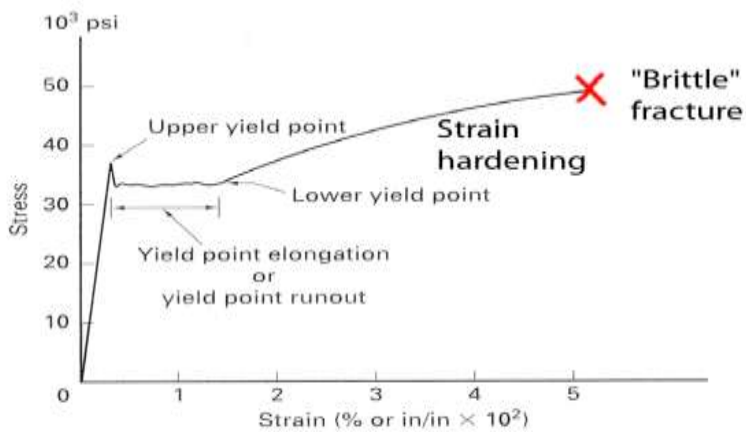


Figure 6.Stress-strain curve diagram [8]

3.2 Wing Design Simulation Analysis

After the theoretical structural analysis has been performed by proving design requirement calculation and mechanical structure on the wing parts, Solidworks and Catia V5 software have been used to design and simulation for this research.

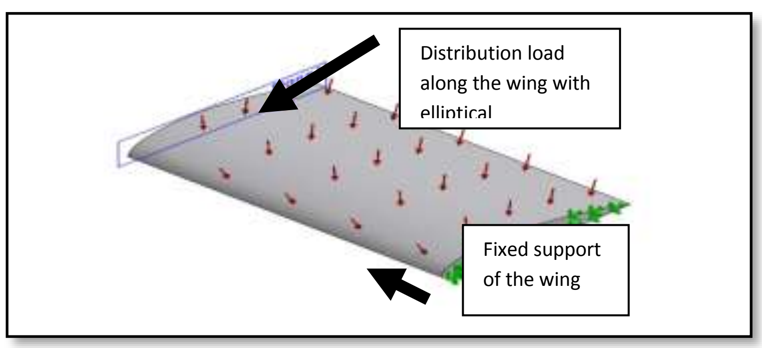


Figure 7. Load distribution applied along the wing

The load distribution is assume to be elliptical and the fixed support at the edge of the wing. 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 the tensile strength is 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.

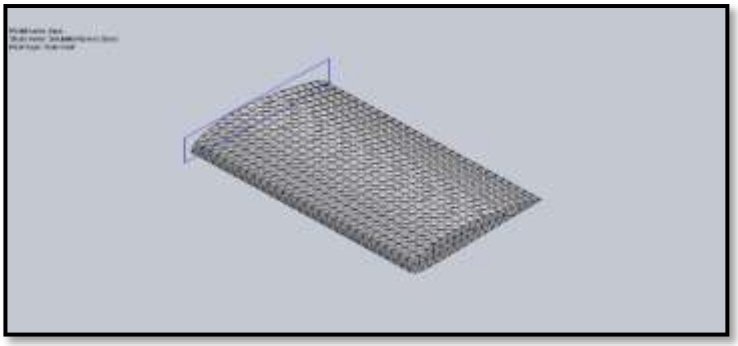


Figure 8. The Mesh generation for wing

Mesh analysis on the wing is observed to get the grid solid region on the wing and to justify the structural wing design for doing further element structural analysis. Its shows that the value of the bending stress of the wing using this software simulation is 5.42 MPa. The diagram shows that the structure is safe because the most of the region at the wing is blue which not critical condition. The wing is safe to use in our 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, its shows that the bending stress is 5.42 MPa while by doing manually calculation, the bending stress by theoretically is $4.260\ MPa$. The result shows that there was small difference with approximately 10% between the both values. So, the wing is safely to be used on the UAV.

Conclusion

In this paper we have outlined the details of conceptual design, material selection and structural analysis on the wing of rotor UAV platform. After material selection process has been done, the designed Tiltrotor UAV is economical, moderately functional, and is an excellent platform for academic research purpose. In contrast to military UAV users, which undertake highly specialized missions with highly accurate and reliable instruments. By perform the structural analysis of the model, meshing and stiffness of the model and we also applying the loads on the prototype to analyse the von-mises stresses and displacements. Tiltrotors, however, are typically as loud as equally sized helicopters in hovering flight. After all, the objective of this project is achieved and there is some improvements for any aspects of UAV and ready to fabricate and flight test.

References

Boeing(2006).http://www.boeing.com/rotorcraft/military/v22

V-22 osprey tiltrotor aircraft. URL https://commons.wikimedia.org/wiki/File:V-22_Osprey_tiltrotor_aircraft.jpg.

Panther UAS. (2011). Retrieved from http://www.unmanned.co.uk/ autonomous-unmanned-vehicles/uav-data-specifications-factsheets/panther-uas-specifications/

E. Cetinsoy, S. Dikyar, C. Hancer, K.T. Oner, E. Sirimoglu, M. Unel,and M.F. Aksit. Design and construction of a novel quad tilt-wing {UAV}. *Mechatronics*, 22(6):723 – 745, 2012.URL http://www.sciencedirect.com/science/article/pii/S095741581200044X.

Holsten J, Ostermann T and Moormann D. Design and wind tunnel tests of a tiltwing UAV. CEAS Aeronautical Journal, Springer Wien, Vol. 2 pp. 69-79, 2011

Liebeck, H. R. 2005, NASA/ McDonnell Douglas Blended-Wing-Body, Aircraf Organisation, http://www.aircrash.org/burnelli/bwb.htm, 2005

McCormick, B. W. Aerodynamics, Aeronautics, and Flight Mechanics, 2nd edition, Wiley, New York,1995.

Raymer, D. P. Aircraft Design: A Conceptual Approach. 3rd edition, AIAA Education Series,1999.

Landolfo, Aerodynamic And Structural Design Of A Small Nonplanar Wing UAV, Dayton, Ohio May 2008.

M. Miletic, A. Arnold. Euler-Bernoulli Beam with Boundary Control: Stability and FEM. Proceedings in Applied Mathematics and Mechanics, 11, No. 1, pp. 681–682, (2011).

O'Connell, R. F., "Design, Development and Implementation of an Active Control System for Load Alleviation for a Commercial Transport Airplane", AGARD-R-683.

E. Rauscher, "Structural flight load measurement – Demonstration of structural integrity", Structural and Materials Panel – Specialist Meeting I, Siena, 1-6 April, 1984.

Nonami, K. & Kendoul, F. & Suzuki, S. & Wang, W. & Nakazawa, D. (2012) Introduction. *Autonomous Flying Robots, Unmanned Aerial Vehicles and Micro Aerial Vehicles.* Springer, pp.1-14

NATO(2009).http://nsa.hq.nato.int