

Advanced computational method assignment

by Elizabeth May Roberts

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Assessment of a Helicopter Tail Rotor

Advanced computational methods
BEng Mechanical and Manufacturing Engineering

University of Wales Trinity Saint David
Faculty of Engineering

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Executive Summary:



The following document is a finite element analysis report on an apache tail rotor blade. Extensive research was undertaken to determine the rotor blades material. There are Several types of materials which are predominately used in the production of tail rotor blades, however due to assuming the component is a solid body only titanium was applicable during simulation. The Loading conditions for the tail rotor blade were researched and hand calculated for validation, to ensure the stress, strain, displacement, fatigue and frequency studies were accurate and reliable. A considerable amount of analysis and simulation was involved in obtaining an optimum mesh size, and was evidently determined by elements, nodes and run time. All results obtained from solid works, were analysed to assess their reliability and validity for determining whether the tail rotor blade was fit for purpose. All subsequent findings were critically analysed and concluded with recommendations, for future design developments and software analysis.

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Introduction:

The aim of the report:



The following report has been undertaken to research and establish, how a tail rotor blade should be finite element analysed (FEA) within solid works to obtain results on stress, strain, displacement and fatigue. The component will be critically appraised and analysed through the use of hand calculations and FEA results. Conclusions and recommendations will be based on the results analysis obtained from solid works.

The model:

The tail rotor blade mentioned is modelled on an apache helicopter, the full tail rotor assembly was exported into a new document and one tail rotor blade extracted from the assembly for analysis. The apache model however, has not been modelled to scale.

What is a tail rotor?

The tail rotor is a crucial component on all helicopters and is designed to efficiently attain power at the indicated velocity with optimum efficiency (Shabudin, 2016). The model of the tail rotor has four blades attached to it, two of the blades are rotated to 55 ° and the opposite two blades are rotated to 125°. This allows the blades enough clearance to flap and feather during flight (Donald, 2009). The rotor is mounted vertically to the end of the helicopters tail and is positioned the correct distance from the centre of gravity to allow it to attain thrust in the same direction as the main rotor, which enables the tail rotor to act as a counter to the torque created by the main rotor (Wiesner, 1974). In other words, the tail rotor ensures that the helicopter simply doesn't fly in circles. The tail rotor is also responsible for manoeuvring the aircraft by changing the angle and acceleration of the blades, which allow the pilot to steer and guide the helicopter.

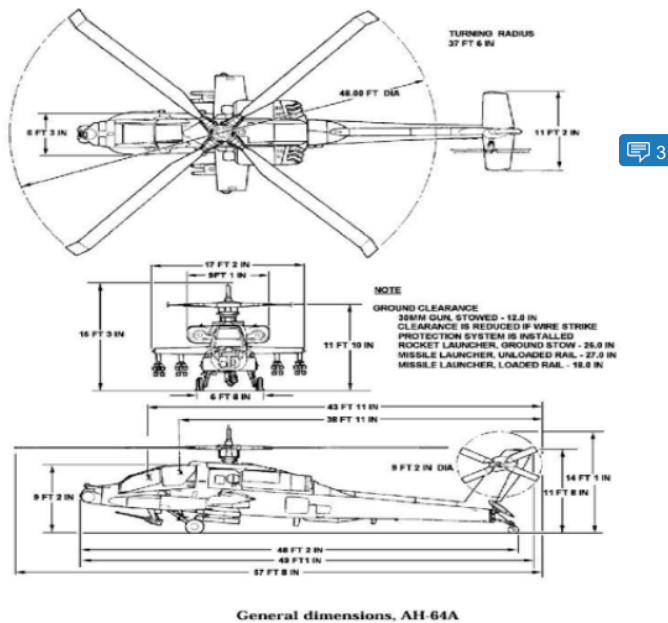


Figure 1: Image of Apache Helicopter. (Network, n.d.).

What is Finite Element Analysis (FEA)?

Finite Element Analysis is the simulation equivalent of the finite element method. It breaks down the component into smaller elements to simulate the stresses within the component. It is utilised to optimise component designs in its development stage and identify any potential failures before manufacturing (Bathe, 2014).

Considerations and Assumptions:

The following considerations and assumptions were made prior to the analysis:

- The tail rotor mode is not to scale and is in fact scaled down to a 1:3.4 ratio.
- The Apache helicopter assumed was AH-64.
- The traditional design of the tail rotor is 5 metal spars with a hollow honeycomb case, however it has been modelled as a solid body, so a solid body was assumed.
- Solid works does not allow a carbon fibre material for a solid body so a typical titanium was selected.
- Its Assumed that the tail rotor was modelled correctly.
- The format of my report was adapted from an FEA report by Penne college (Bursh, 2016)

5. Narrative(-)

Methods:

Material Selection and Properties:

Extensive research suggested two potential materials for the material of a tail rotor blade; Carbon fibre epoxy (Rasuo, 2011) and Titanium alloy (Ti-6AL-4V) (Pederson, 2002) . A typical helicopter, design is made up of five stainless steel spars and surrounded by a carbon fibre casing. Due to the modelling of the rotor blade, a solid body must be assumed. During analysis Solid works brings up an error message when carbon fibre is applied as the material. Therefore, titanium Ti-6Al- 4V alloy is utilised, due to its extensive applications within aerospace and aviation industry (Newkirk, 2007). A tabulated list of material properties is shown below in table 1:

Table 1 : Material Properties of Ti-6Al-4V (Roberts, n.d.).

Property	Value	Units
Elastic Modulus	1.0480031e+11	N/m ²
Poisson's Ratio	0.31	N/A
Shear Modulus	4.1023807e+10	N/m ²
Mass Density	4428.784	kg/m ³
Tensile Strength	1050000000	N/m ²
Compressive Strength		N/m ²
Yield Strength	827370880	N/m ²
Thermal Expansion Coefficient	9e-06	/K

Fixtures:

In order to simulate and analyse the component, a fixed geometry needed to be selected. The component however, had been altered to a length of 326mm, in order for accurate simulation it was extended to its initial size of 366mm, this was done by extending the end of the tail rotor by 40mm.

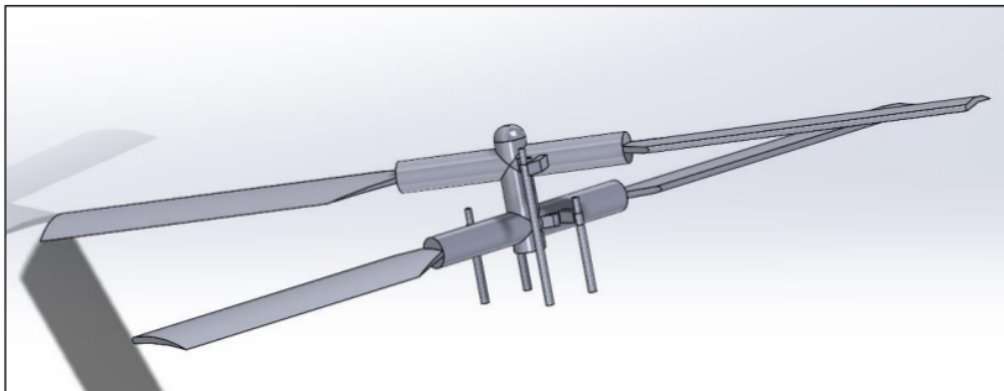


Figure 2: Full scale tail rotor, (Lake, 2019).

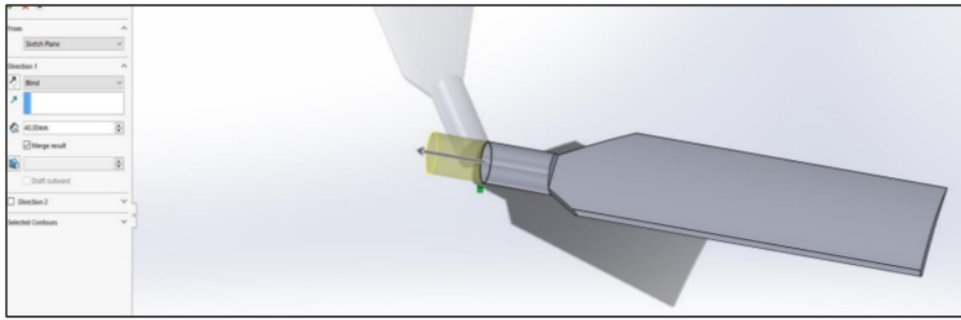


Figure 3: Amended tail rotor blade (Roberts, 2019).

The fixed geometry was then assigned to the cylindrical edge of the rotor blade, which is shown below:

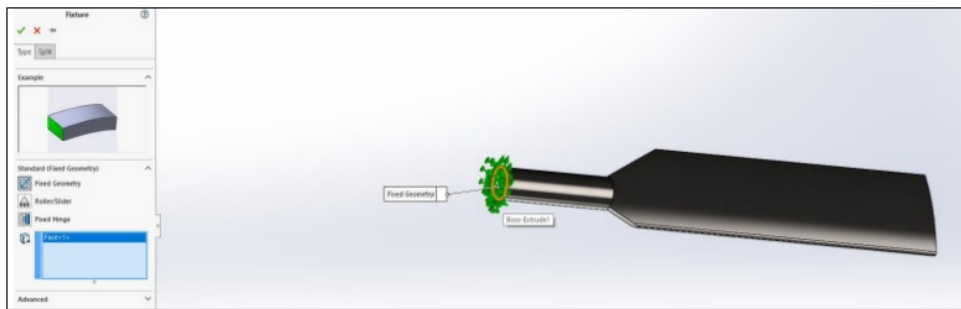


Figure 4: Fixed Geometry on Tail rotor end (Roberts, 2019).

Loading was required next.

External Loads:

(Administration, 2019) States that there are three fundamental forces acting on the tail rotor blade at one time. They are as follows; lift, drag and centrifugal force, which acts on the centre of mass. Each force is briefly explained below:

Lift:

In order for an object to be elevated, lift must be generated. This occurs when a fluid is forced to move perpendicular in the opposing direction to an object (Administration, 2019). Newtons third law states, that the air acting on the tail rotor blade must exert equal and opposite forces in order for it to successfully steer and lift the helicopter. In order to accurately simulate the tail rotor blade, the lift force is calculated. The formula is shown below (Shish, 2016):

$$F_L = \frac{1}{2} \times (C_L \times \rho \times A \times V^2)$$

Table 2: Formula values and sources for lift equation:

Sub script value:	Meaning:	Value:	Sourced from:
C_L	Coefficient of lift	1.47 approx.	(Naca, 2019). (Newkirk, 2007).
ρ	Air density- Dry air.	1.204 Kg/m ³ .	(Helmenstine, 2019)
A	Area on which force acts.	$16.24455 \times 10^{-3} \text{ m}^2$	(Works, 2019)
V^2	Velocity of component.	54.075m/s	Formula: (Helmenstine, 2019), Value from equation 1.

Therefore, the lift formula is:

$$F_L = (\frac{1}{2} \times 1.47 \times 1.204 \times (16.24455 \times 10^{-3}) \times 54.076^2)$$

$$\text{Lift Force} = 42.039 \text{ N}$$

The force was then applied to the underneath of the rotor blade.

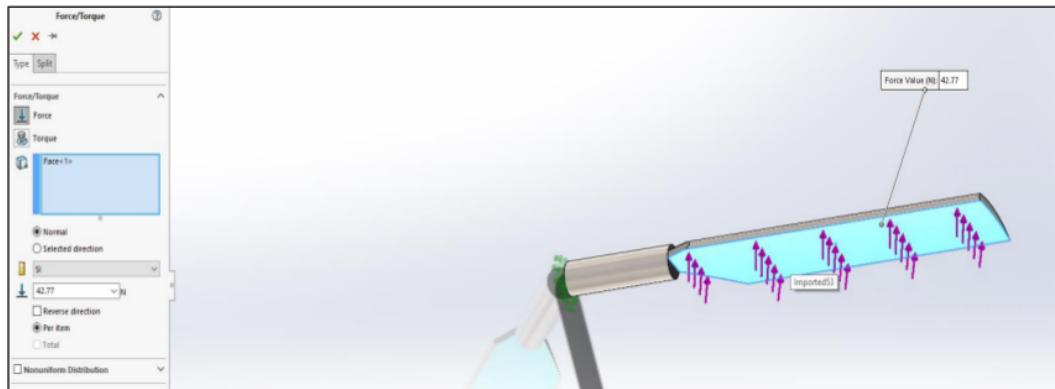


Figure 5: Application of lift force on tail rotor (Roberts, 2019).

Centrifugal Force:

Centrifugal force is the force that ensures all rotating components move away from the centre of rotation (Cantrell, 2019). According to Newton's First Law of Inertia an object typically moves in a straight line. Therefore, when a tail rotor blade is spinning, the centrifugal force acts at the centre of mass on the largest face, to ensure the blades remain straight and do not deflect to failure. This is the equal and opposite force to the lift. In order to accurately load the blade in simulation the centrifugal force must be calculated, below is the equation for centrifugal force taken from (Skills, 2019):

$$F_c = mv^2 / R$$

Table 3: Formula values and sources for centrifugal force equation:

Sub script value:	Meaning:	Value:	Sourced from:
M	Mass of Blade	461.67×10^{-3}  8	(Works., 2019)
V ²	Velocity	147.76 rad/s	(Units, 2019) (Newkirk, 2007)
R	Radius in which it rotates	158.72×10^3 mm	Equation 2.

$$F_c = mv^2 / R = 461.67 \times 10^{-3} \times 147.76^2 \times 158.72 \times 10^3$$

$$\text{Centrifugal force} = 1599.8419 \text{ N/m.} \quad \text{9}$$

The force was applied to the model as a remote load at the centre of mass. Using the centre mass function on solid works, the exact coordinates were retrieved and inputted into solid works remote load location; $x = -139.63$ $y = 761.76$ $z = -1114.76$. It was observed that the force was acting in both the y and z axis, therefore the correct translational forces were calculated using the radius of the load:

$$Y \text{ axis} = 1599.84 \times \cos 25.48 = 1444.23 \text{ N}$$

$$X \text{ axis} = 1599.84 \times \sin 25.48 = 688.24 \text{ N}$$

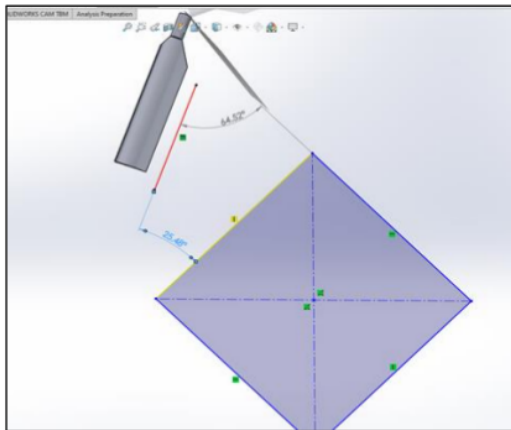


Figure 6: Calculating radius from solid works, (Roberts, 2019).

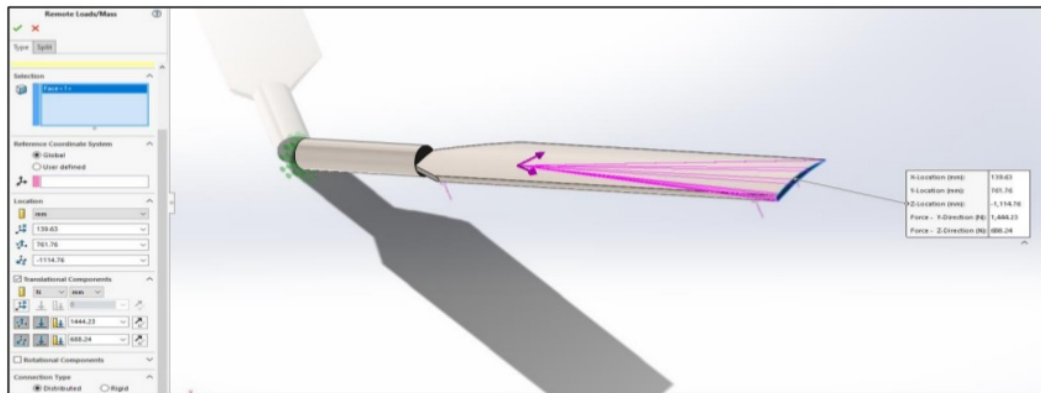


Figure 7: Tail rotor remote loading in y and z axis. (Roberts, 2019).

Drag:

In the case of a tail rotor blade, the drag acting on it is the air resistance which is acting the opposite direction to its rotation. The drag is proportional to the squared velocity for a turbulent flow. This also needed to be calculated, the formula is shown below (Shish, 2016):

$$F_D = \frac{1}{2} (C_D \times \rho \times A \times V^2)$$

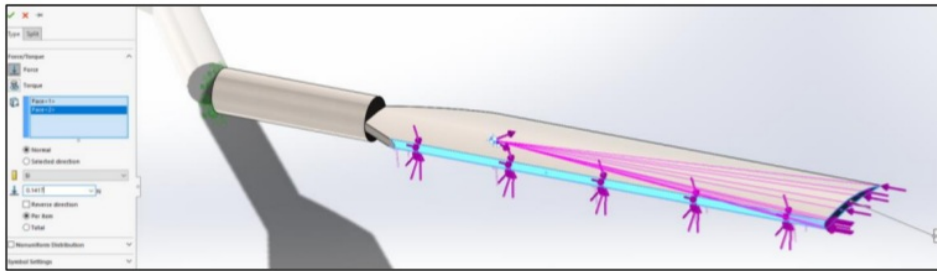
Table 4: Formula and values for drag force:

Sub script value:	Meaning:	Value:	Sourced from:
CD	Coefficient of drag.	0.04 	(Bengstonm, 2019)
ρ	Air density – Dry air.	1.204 Kg/m ³	(Helmenstine, 2019)
A	Area in which it acts.	2.01361 x 10 ⁻³	(Works., 2019)
V ²	Velocity Blade is spinning.	54.076 ² m/s	Formula (Helmenstine, 2019), taken from equation 1.

$$F_D = \frac{1}{2} (0.04 \times 1.204 \times (2.01361 \times 10^{-3}) \times 54.076^2)$$

$$\text{Drag force} = 0.1417 \text{ N}$$

The drag force when then applied to the back edge of the blade to simulate real life drag.



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Figure 8:Applying drag force to blade, (Roberts, 2019).

Mesh Selection and Application:

During analysis, the ideal mesh for a component should be 1/3 of the total material thickness. However, due to the inconsistency of material thickness on the tail rotor, the thickest area on the blade has been selected, which is 5mm thick. The correct size mesh for the tail rotor is approximately 1.67mm, and can be seen in the below table A 1.67mm mesh provides more element and node data compared to the solid works suggested 4.7mm mesh.

Table 5: Mesh information:

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Mesh Size (mm):	No. of Nodes:	No. of elements:	No. of DOF:	Solve time (seconds):
4.7	14769	8093	43944	5
2.2	106307	66142	317700	13
1.93	150765	95555	450699	25
1.93- h-adaptive	241945	158696	724235	41
1.67	212564	136146	635586	33

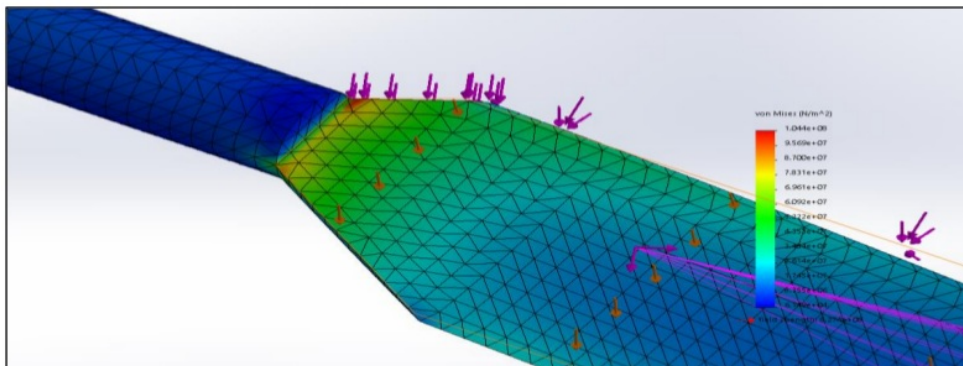


Figure 9: Deflected area using 4.7mm, (Roberts, 2019).

As you can see from the image, the elements are large and there is no transitional colouring between elements. It is a one element mesh in the thicker areas and no elements in other areas. A 3-element mesh is preferred for accurate and reliable results.

The mesh was reduced to 2.2mm, where a significant improvement can be seen to element sizing, this time, 2 elements are present in the larger areas and 1 element in the smaller areas. The stress concentrated areas are also more refined.

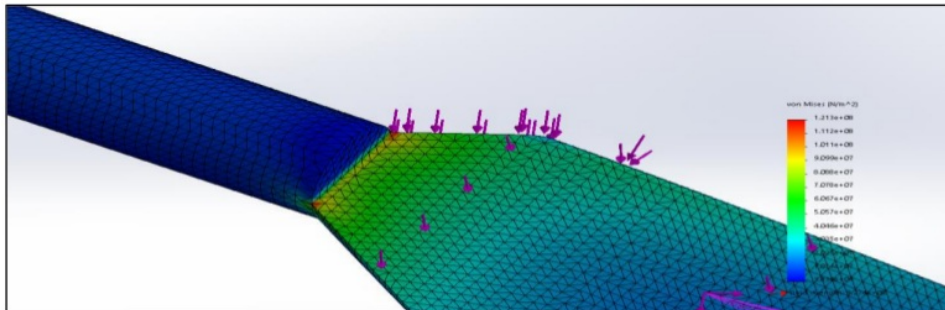


Figure 10: Deflected area using 2.2mm mesh. (Roberts, 2019).

The mesh at 1.67mm is very refined, pointing the exact areas of stress and potential failure.

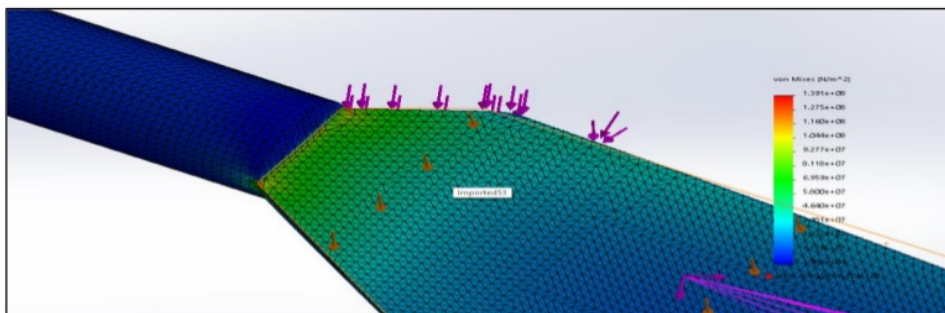


Figure 11: Deflected area using 1.67 mm mesh, (Roberts, 2019).

The no. of nodes significantly increased from 4.7mm to 1.67mm and the no of elements increased also, the degrees of freedom also increased creating an increased solve time. For extra mesh refinement the h-adaptive mesh function on solid works was utilised for a 1.93mm middle ground mesh with 5 runs being selected, the mesh was much more refined in the stress concentrated areas only, and the stresses significantly increased, providing more accurate results, in terms of increased nodes and elements.

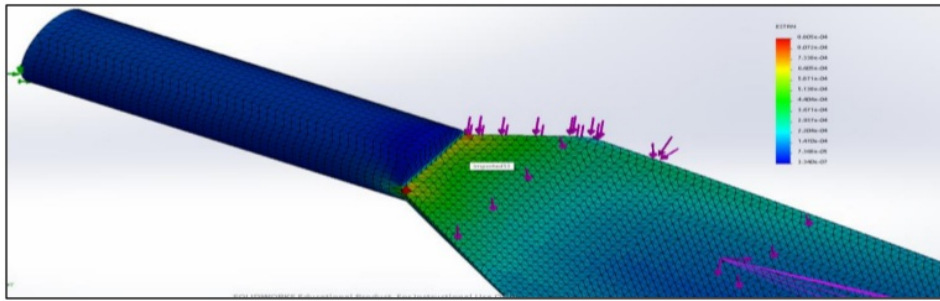


Figure 12: Deflected area using 1.93mm mesh, (Roberts, 2019).

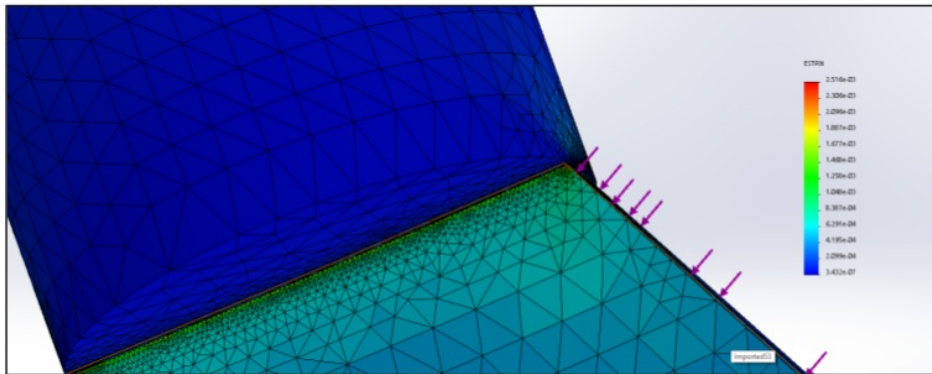


Figure 13: H-adaptive 1.93mm mesh result, (Roberts, 2019).



Results and Analysis:

The finite element analysis for the structural analysis of tail rotor blade is carried out using solid works simulation. Static, fatigue and frequency studies are carried out on the blade to obtain data on the following assessments; stress, strain, displacement, natural frequency, first order and second order of torsion and bending. The results are displayed and analysed below:

Static Analysis:

Static analysis is utilised for assessing if a component will meet the required working conditions. The analysis in this report is carried out using solid works linear static simulation. Linear static analysis examines the relationship between applied forces and displacements (Femto, 2017). The tail rotor has been fixed and loaded as described previously, the results for stress, strain and displacement are shown below:

Stress Results:

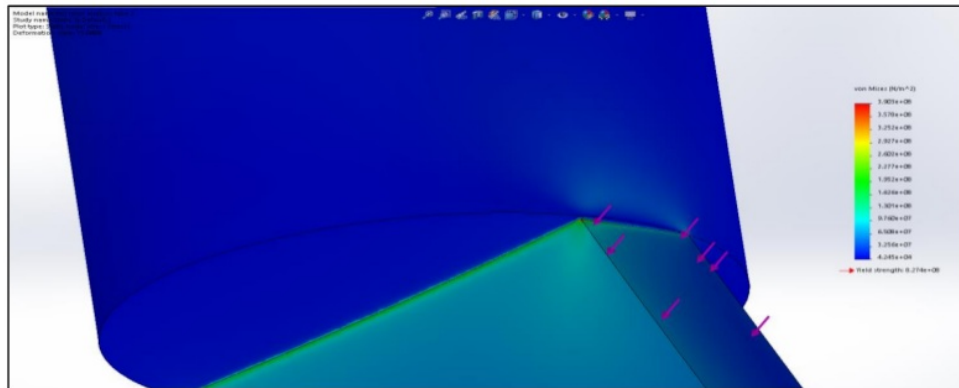


Figure 14: Underside Right side view of stress results of tail rotor, (Roberts, 2019).

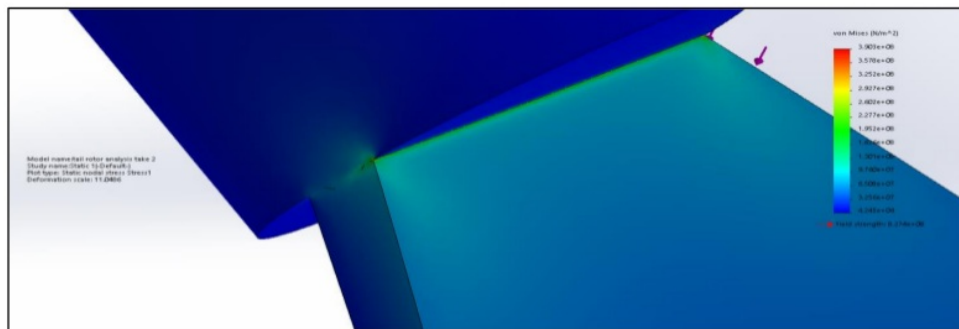


Figure 15: Bottom view of stress results of tail rotor, (Roberts, 2019).

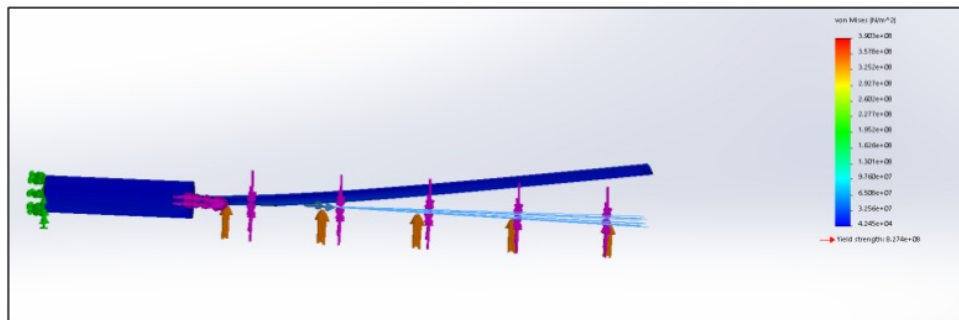


Figure 16: Side view of deflection on stress results of tail rotor, (Roberts, 2019).

What is seen from the stress results is two stress concentrated areas found on the corners joining the blade to the shaft. The maximum Von-mises stress is 390.3 MN/m^2 and the yield stress is 827.4 MN/m^2 , the stresses found in the component are under half of the yield stress, which gives confidence that this component will reach its component life without catastrophic failure, due to its minimal concentrations.

Displacement Results:

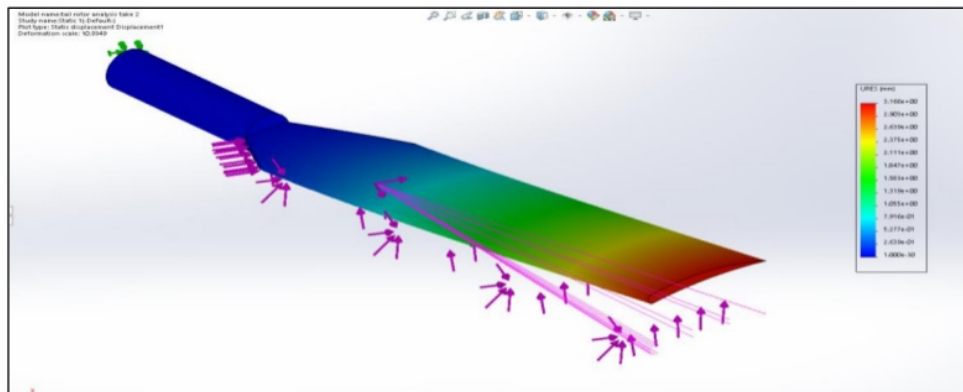


Figure 17: Top view of displacement results of tail rotor, (Roberts, 2019).

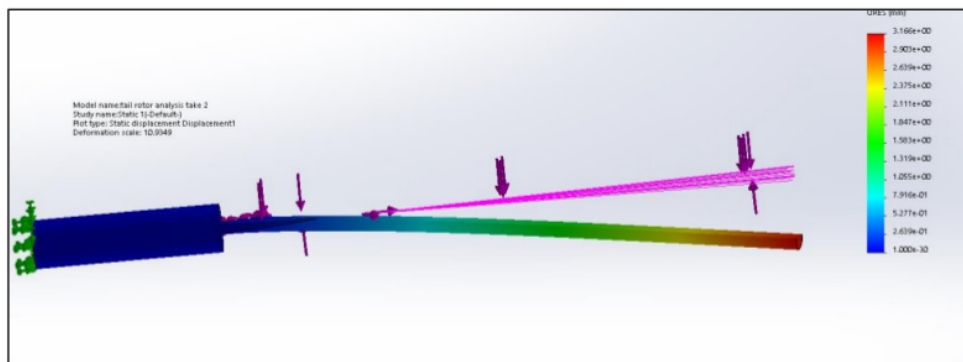


Figure 18: Side view of displacement results of tail rotor, (Roberts, 2019).

The results recorded, show a 3.166mm displacement. The displacement seen decreases from the blade root to the blade tip, with the largest displacement occurring from the remote load region to the tip of the blade. The largest displacement (3.166mm) is concentrated around the end of the blade, which is potentially due to the reduction in material thickness, lack of support and extensive loading. The smallest displacement of 1mm occurs in the stress concentrated region, which is a positive result in terms of component failure. When the dimensions and the displacement of the blade are considered together, a 3.166mm displacement across a 366mm blade is an average result.

Strain Results:

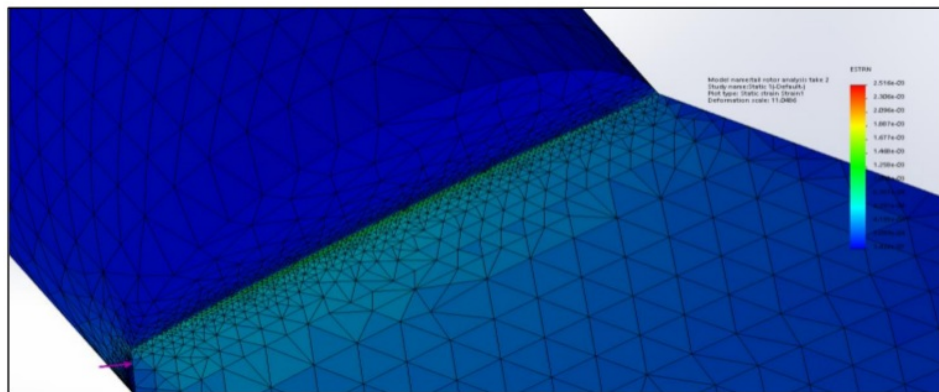


Figure 19: Top view of Strain results of tail rotor, (Roberts, 2019).

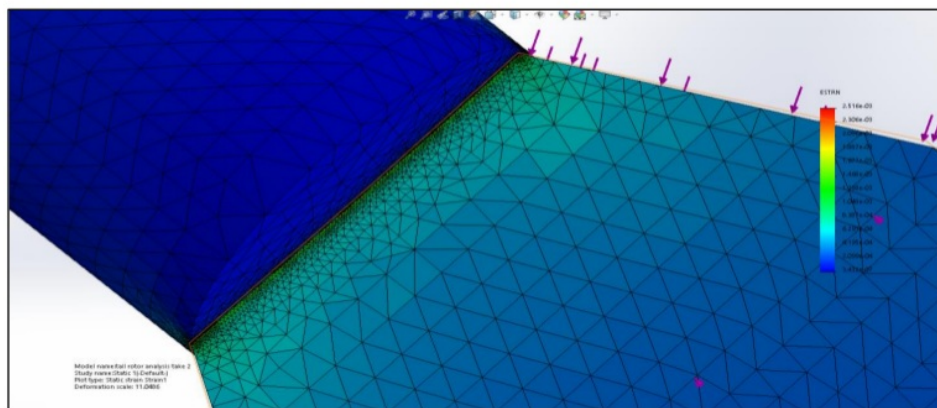


Figure 20: Bottom view of strain results of tail rotor, (Roberts, 2019).

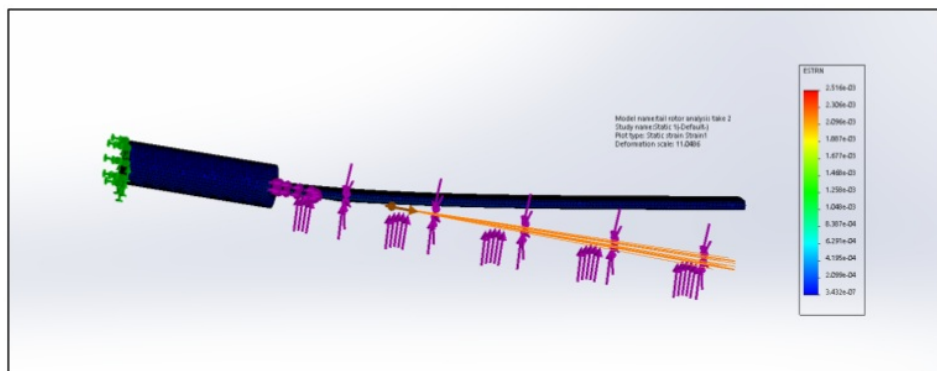


Figure 21: Side view of strain results of tail rotor, (Roberts, 2019).

The results show a max 'ESTRN' of 2.516×10^{-3} , which is equivalent to the actual strain. The strained areas remain in the same place as the stressed areas, confirming the previous results. The change in length was also calculated to check the severity of the displacement, the equation is as follows:

Strain = Change in length / Original length which is transposed to:

$$\text{Change in length} = \text{Strain} \times \text{original length} = 2.516 \times 10^{-3} \times 366\text{mm} = 0.920856\text{mm}.$$

The result shows a small displacement, which affirms the previous assumption of a minimal displacement within the tail rotor. To gain further insight into the results, the young's modulus was calculated and compared to the tail rotors material elastic modulus. The equation is shown below:

$$\text{Youngs modulus: Stress / Strain} = 3.908 \times 10^8 / 2.516 \times 10^{-3} = 155.3259141 \text{ MN/m}^2.$$

The elastic modulus of titanium Ti-6AL-4V is: 104.80031 MN/m².

5. Proof Read

The young's modulus of the component is 155.3259141 MN/m², indicating that there may be an error within the previous results, as the component should fail at 104.80031 MN/m². This means either the forces are incorrect or the software is not calculating the results as required.

Fatigue Results:

A fatigue study was run to check how many life cyclical loadings it can take before the component fails.

The results are shown below:

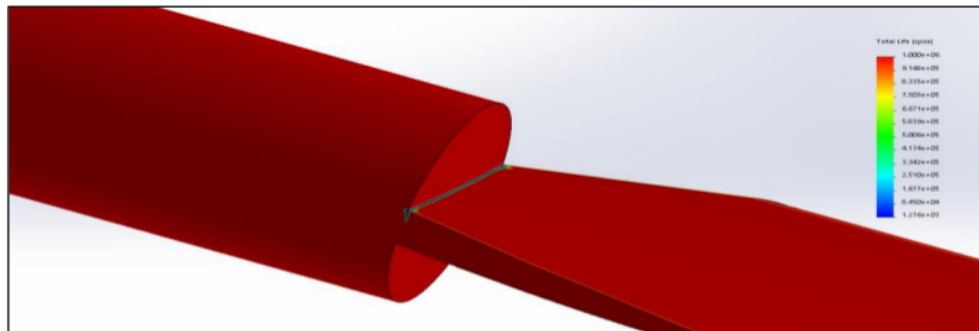


Figure 22: Fatigue crack propagation on bottom left side tail rotor blade, (Roberts, 2019).

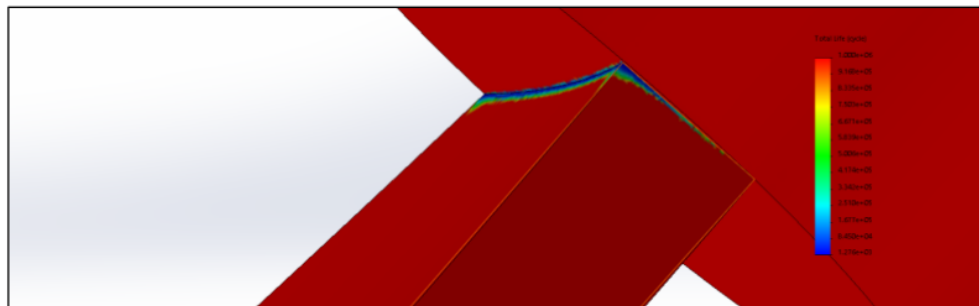


Figure 23: Fatigue crack propagation on bottom right side tail rotor blade, (Roberts, 2019).

The results show that after 1,276 cycles the component will fail, if 1 cycle = 1 trip then after 1,276 flights the component will fail. Therefore, it is suggested that the component be replaced after 1000 flights as a safe fail. These results further back up the assumption, that the previous results may be inaccurate or carrying an error forward.

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Frequency analysis:

Frequency analysis enables an individual to investigate the designs of loaded and unloaded natural frequencies within a component. Every component has a set of preferred vibration and resonant frequencies, “which are characterised by specific shapes of vibration” (Solidworks, 2012). Frequency analysis aids in determining potential failures within a component leading to preventative measures being taken. Below are the results from the tail rotor frequency study:

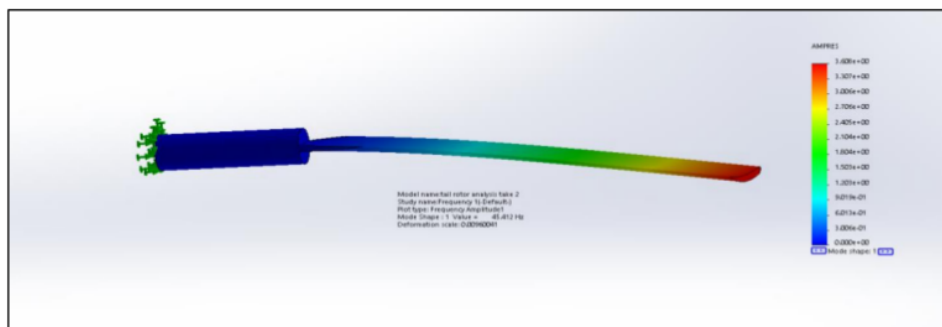


Figure 24: Image of Mode 1 on frequency study of tail rotor, (Roberts, 2019).

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The purpose of this assignment is to analyse whether this component is fit for purpose; therefore, the first mode will be predominately analysed, alongside comments about the additional nine modes. In order to efficiently analyse the first mode, the frequency in which the rotor blade spins were calculated. The formula can be seen below:

$$1 \text{ Hz} = 60 \text{ rpm therefore, } 1,411 \text{ rpm} / 60 = 23.516 \text{ Hz.}$$

The results show the component vibrates at a natural frequency of 45.412 Hz and the in-service tail rotor vibrates at a 23.516 Hz frequency when rotating at 1,411 rpm. The tail rotor blade does not vibrate at the same Hz as the natural frequency, potentially due to the forces acting on it, such as centrifugal force which ensures the blade remains parallel during flight. The results provide a positive analysis, the preferred frequency for the tail rotor should always lower than its natural frequency.

Within frequency analysis, there are 10 modes which are most commonly used. There are the first six modes, which are classed as the six degrees of freedom within a component and then the last four modes are the four constructional modes which are known as: the first order of torsion, the first order of

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bending, the second order of bending and the second order of torsion. The results for the remaining nine modes are displayed below:

Study name: Frequency 1			
Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	285.33	45.412	0.022021
2	1,079.3	171.78	0.0058213
3	1,831.2	291.45	0.0034312
4	2,638.9	419.99	0.002381
5	4,964.8	790.17	0.0012656
6	7,893.7	1,256.3	0.00079598
7	8,838.6	1,406.7	0.00071088
8	9,199.2	1,464.1	0.00068302
9	12,500	1,989.4	0.00050266
10	13,837	2,202.1	0.0004541

Figure 25: List of frequency values from study, (Roberts, 2019).

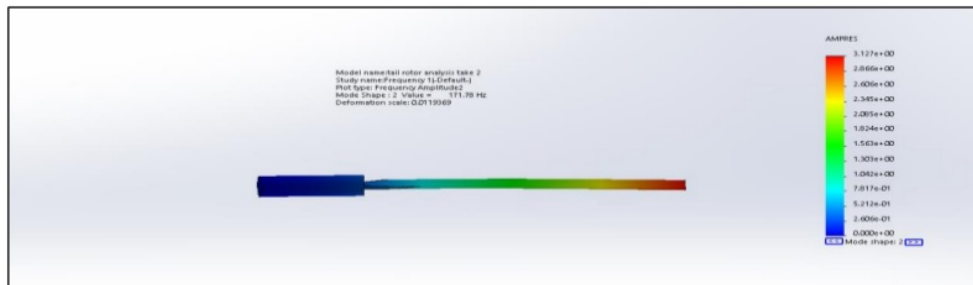


Figure 26: Mode 2 from frequency study, (Roberts, 2019).

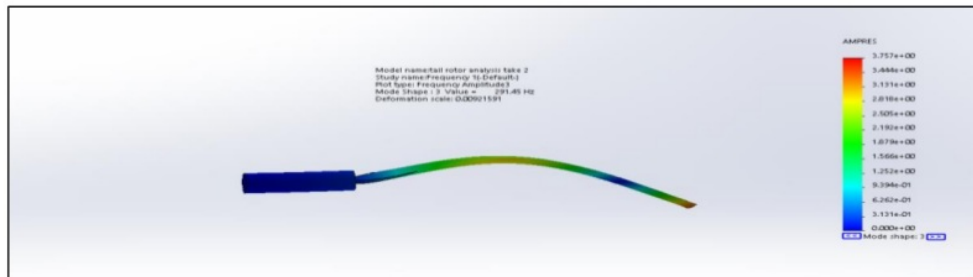


Figure 27: Mode 3 from frequency study, (Roberts, 2019).

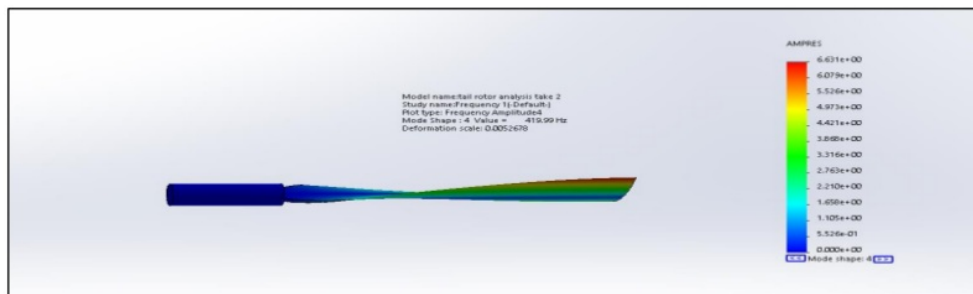


Figure 28: Mode 4 from frequency study, (Roberts, 2019).

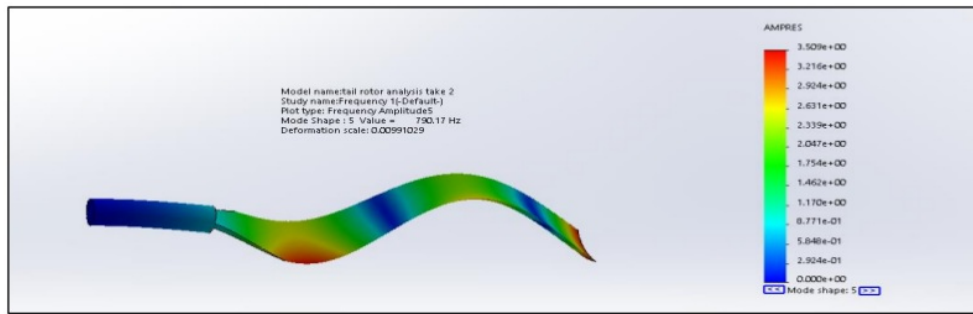


Figure 29: Mode 5 from frequency study, (Roberts, 2019).

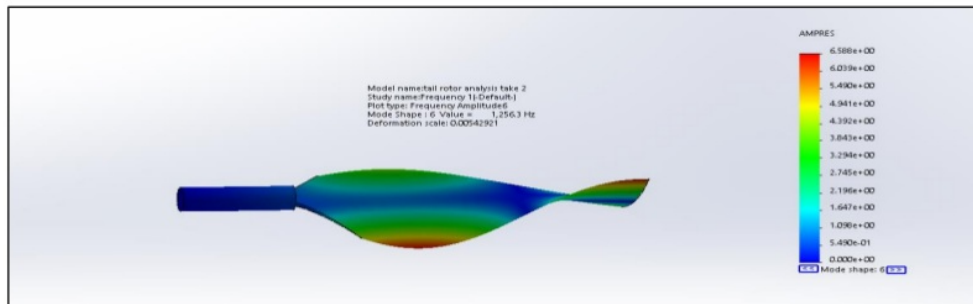


Figure 30: Mode 6 from frequency study, (Roberts, 2019).

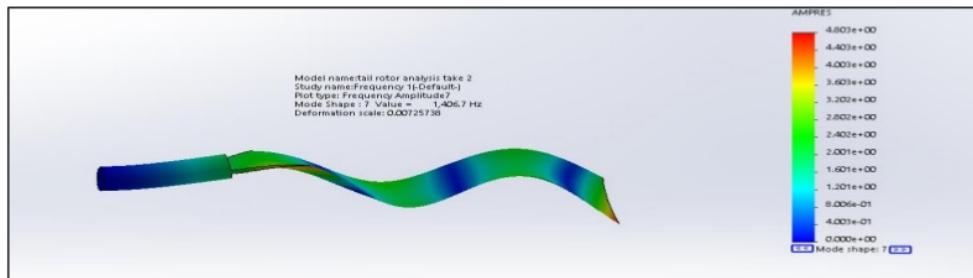


Figure 31: Mode 7 from frequency study, (Roberts, 2019).

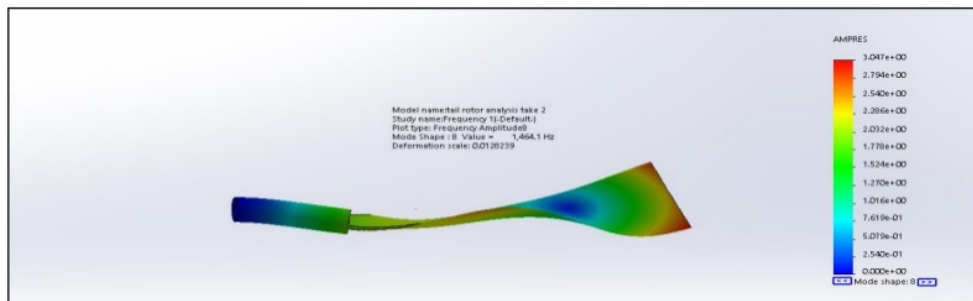


Figure 32: Mode 8 from frequency study, (Roberts, 2019).

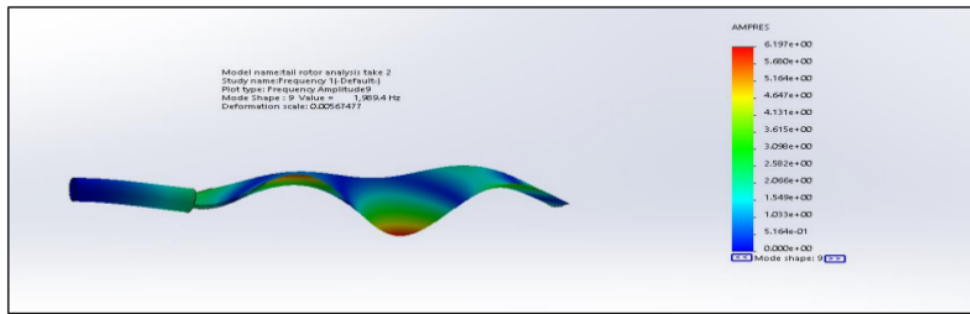


Figure 33: Mode 9 from frequency study, (Roberts, 2019).

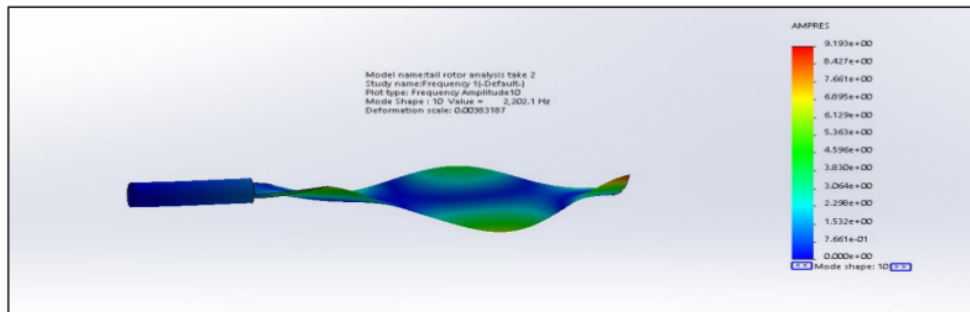


Figure 34: Mode 10 from frequency study, (Roberts, 2019).

The images above show the extent in which the tail rotor blade could deform and vibrate if the natural frequency is exceeded. The results however, do not take into consideration additional vibrations from different components on the helicopter, such as the engines and main rotor. Therefore, the results are not 100% accurate and could actually be considered as an approximation.

Critical Comments:

The information collected for this report provides data on the size and design of an apache tail rotor blade. It is apparent that the blade has not been modelled correctly, in terms of design and size. If this study was carried out on a fully scaled rotor blade, the displacement results would be much more realistic and accurate. Due to the component being modelled as a solid body, only one material could be selected and further issues with solid works material selection, meant carbon fibre could not be selected for the study and titanium was used instead.

Solid works is a linear solver meaning it does not take into consideration anything in and above the plastic deformation region. From this error all the results calculated in the static study, do not show any component failure. However, when the young's modulus was calculated, it surpassed the elastic modulus for the material, indicating the component should have failed. This theory is then backed up

by the fatigue study results which clearly show component failure, therefore leaving the results questionable and suggesting the component is therefore not fit for its intended purpose.

The timescale and word count on the report was not realistic and would require more analysis and research in order to accurately calculate whether the component is safe for use.

Conclusions:

To conclude the report, a critical comparison of the results and model have been made. The results from the static study show two stress concentrated areas on the rotor blade, which is to be expected. However, no subsequent failure is displayed. The calculations and comparison of the fatigue study and young's modulus of the material and component have conflicting results. Both variables display component failure, this leads to the assumption that either the model, software or hand calculations are incorrect. Therefore, it can be concluded that the results obtained from solid works are invalid, and potential changes would need to be made in terms of model design, due to the model not being fit for purpose. Additional changes would also need to be made for alternative software, and the changes would therefore allow an accurate nonlinear study to be carried out on the tail rotor blade.

Recommendations:

For a more reliable results, the following recommendations have been made;

- Source a non-linear software which investigates and displays plastic deformation and failure.
- Design a fully scaled tail rotor blade, which will provide more accurate and realistic data.
- For current model improvement; introducing radiuses to the stress concentrated areas would reduce stress and potential infidel failure. Good
- For a more in-depth report, a longer research period would be required with an increased word count to provide the reader with a greater understanding of the analysis.

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Appendix:

Equation 1: Velocity

Formula to obtain value V2 in lift equation:

$$\omega = V / R :$$

$$V = \omega \times R :$$

$\omega = 1,411$ Rpm rotor speed to 147.75 rad/s and Radius of full blade = 366mm

$$V = 147.75 \times 0.366 = 54.0765 \text{ m/s}$$

Equation 2: Radius

Formula for Radius:

Length of full blade – distance to centre of mass =

$$366\text{mm} - 207.28\text{mm} = 158.72\text{mm}$$

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Advanced computational method assignment

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

68/100

PAGE 1

PAGE 2



Comment 1

Apache

PAGE 3

QM

5. Presentation(+)

Generally your presentation is good

QM

5. Automatic(-)

If you are going to use automatically generated tables (such as this) in word - make sure that they are defined correctly.

PAGE 4

PAGE 5



Comment 2

The aim of the report is not to carryout some FEA - this is a tool. The aim of the report is to assess the blade.

PAGE 6



Comment 3

You should convert imperial units to SI.



Comment 4

This is reasonable



Comment 5

Why did you use Titanium?

QM

5. Narrative(-)

Your report should be written in third person narrative.

PAGE 7

PAGE 8

QM

3. BCs (-)

The components that the blade attaches to will obviously have some flexibility which will lower the stresses, increase the fatigue life, increase the displacements and lower the natural frequency of your results

QM

5. Formatting

PAGE 9



Comment 6

What altitude is this at?



Comment 7

This is confusing/incorrect

PAGE 10



Comment 8

units?



Comment 9

N

PAGE 11



Comment 10

what shape is this for?

PAGE 12



Comment 11

Your drag force should be opposite to the direction of travel.



Comment 12

Solve time to do what? What were the results?

PAGE 13



Comment 13

This is easier to see with elemental stress displayed rather than nodal stress.



Comment 14

pin?



Comment 15

number

PAGE 14



Comment 16

What element order are these? Why?

PAGE 15



Comment 17

When showing plots such as these the mesh should be shown so that the influence of the underlying elements can be understood.

PAGE 16

PAGE 17

PAGE 18



5. Proof Read

Proof read your work before you submit it.

PAGE 19



Comment 18

Contextualise this. If the helicopter flies twice a day, the roter will need replacing after 1.4 years.



Comment 19

whether



Comment 20

But your part is constrained.

PAGE 20

PAGE 21

PAGE 22

PAGE 23



Good



Comment 21

Recommendations should be regarding the topic that the report is about - not the assignment.

PAGE 24

PAGE 25

PAGE 26

GRADING FORM: APACHE ACM

ELIZABETH MAY

67.90

ROBERTS

RESEARCH INFORMED LIT



13.6

KNOWLEDGE & UNDERSTANDING



13.4

ANALYSIS



21

PRACT APP & DEPLOYMENT



13.2

SKILLS FOR PROF PRAC



6.7