

Josh Evans Assignment

by Joshua Evans

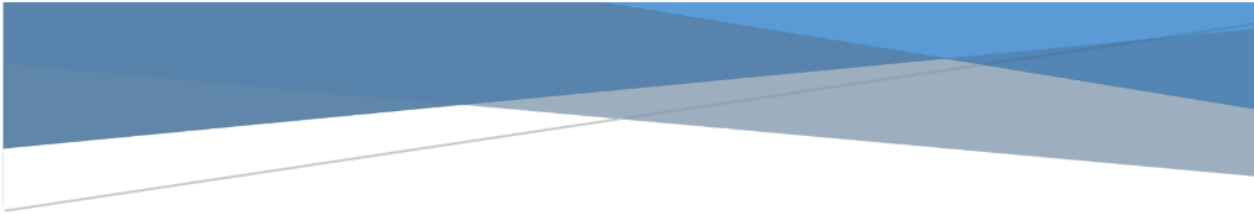
Submission date: 17-Nov-2019 09:48PM (UTC+0000)

Submission ID: 113634852

File name: 2854_Joshua_Evans_Josh_Evans_Assignment_216460_1464500774.docx (2.69M)

Word count: 3935

Character count: 21522



BENG – MANUFACTURING SYSTEMS ENGINEERING

Assessment of a Helicopter Tail Rotor

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1.0 EXECUTIVE SUMMARY

The aim of this report is to give the reader an understanding of how the tail rotor of an Apache helicopter works, along with the conditions that must be considered when carrying out finite element analysis on the model of a rotor.

To carry out analysis effectively, there are various assumptions and calculations that need to be made in relation to the forces acting on the blade, operating conditions and mesh sizes. Frequency analysis is then used to give an idea of the natural frequencies associated with the rotor and how they may relate or differ to an actual rotor blade. A static study will then be conducted and analysed using the calculations and information obtained from a variety of sources to simulate the rotor operating against the various forces that may act upon it in operation; lift, drag and centrifugal.

The report then includes a conclusion that will justify any decisions and assumptions made, along with recommendations that may be useful for future projects.



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4.0 INTRODUCTION

The AH-64 Apache Helicopter is a high-tech military vehicle that is used primarily by the U.S. Army. It is regarded as “the worlds most advanced multi-role combat helicopter” with more than 2,200 being produced since its release in 1984 (Boeing, 2019). The Apache is considered as a “revolutionary development in the history of war” due to its impressive durability, toughness and firepower. What makes the Apache different to other heavy combat vehicles is the way it can manoeuvre almost effortlessly, despite being the size of a small tank (Harris, 2019).

Rotor blades are the most important part of a helicopter, so it is essential that they are designed to the highest standard. If not for the tail rotor, the helicopter would start to spin along with the main rotors as the rotation force exerted, along with the resistance from the rotor bearings would cause the helicopter to spin along with the rotors (Harris, 2019) & (Lake, 2019). The Apache helicopter is unique compare to other helicopters as the tail blades are not loaded at 90° . Instead, the blades are spaced at 55° and 125° angles as it was discovered that this formation significantly reduces noise. It should also be noted that the tail rotor turns at 1411rpm with a tip speed of 221.62 m/s as these values will be used for various calculations throughout the report (Swopes, 2016).



5.0 ASSUMPTIONS

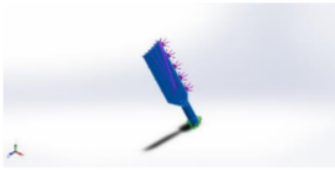
5.1 MATERIAL

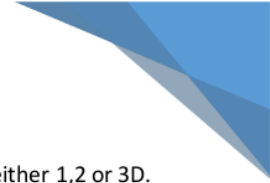
Helicopter rotor blades are very well designed and constructed components that consist of various spars and a honeycomb structure to increase strength and durability whilst minimising weight. Apache helicopters encounter tough terrain, meaning that blades will be exposed to minor obstacles such as tree branches. Blades will also encounter desert environments in which sand will hit the moving surface of the blades and cause erosion over time (Browne, 2004). To ensure that these blades can withstand such conditions, the leading edge is made from titanium, whilst the trailing edge is covered with a graphite composite material (Harris, 2019). This ensures that blades are strong enough to withstand wear and light enough to enable pilots to perform fast manoeuvres.

Titanium and graphite composites are used along with and carbon fibre to construct the blade (Harris, 2019), however due to the limitations of Solidworks simulation, the rotor in this report is being assumed as a solid titanium component. (Table.1) shows the material properties of titanium as listed on Solidworks, displaying high yield and tensile strengths as well as very high elastic and shear moduli, making it a suitable material for the purpose of the study.

Table 1 – Material properties of titanium (SWReport, 2019).



Model Reference	Properties
	Name: Model type: Default failure criterion: Yield strength: Tensile strength: Elastic modulus: Poisson's ratio: Mass density: Shear modulus: Thermal expansion coefficient: Titanium Linear Elastic Isotropic Unknown 1.4e+08 N/m^2 2.35e+08 N/m^2 1.1e+11 N/m^2 0.3 4600 kg/m^3 4.3e+10 N/m^2 9e-06 /Kelvin



5.2 MESH SIZING

Meshing is a crucial tool used in FEA to approximate the geometry of a component in either 1,2 or 3D. A beam mesh is used for a one-dimensional shape and a shell mesh can be used for a two-dimensional shape. For this analysis, a solid mesh is used as the area undergoing analysis is a three-dimensional shape. Meshing is critical as it determines the quality of the results that are obtained from a study as it will have an effect on the number of elements present, which directly effects the computational time (Gohlke, 2015).

Selecting the appropriate mesh size can be achieved numerous ways. Solidworks software automatically suggested applying a mesh the same size as the thickness of the blade at 4.8mm. Dividing the thickness by a factor of 3 will also provide a valid mesh size of 1.8mm (Lake, 2019). The mean of the two mesh sizes at 3mm was also selected as an option. The characteristics of each mesh are shown in Table XX  2

Table 2 – Data regarding the mesh sizes that were used during analysis (Solidworks, 2019).



Mesh Size	No. of Nodes	No. of Elements	No. of DOF	Total solution time
1.8mm	177502	113025	530625	00:00:24
3mm	46515	27570	138795	00:00:11
4.2mm	21333	12115	63630	00:00:03

The 1.8mm mesh was selected for this study as despite the longer solution time, the higher number of nodes and elements gives far greater accuracy with results (SWHelp, 2017).



Table 3 – Properties of the 1.8mm mesh used for analysis (Solidworks, 2019).

Total Nodes	177502
Total Elements	113025
Maximum Aspect Ratio	9.6116
% of elements with Aspect Ratio < 3	98.7
% of elements with Aspect Ratio > 10	0
% of distorted elements (Jacobian)	0
Time to complete mesh (hh:mm:ss):	00:00:08



Figure 1 – 1.8mm Mesh (Solidworks, 2019).

5.3 LOADING CONDITIONS

To ensure that results are as accurate as they can be, given the circumstances, real life forces must be applied to the tail rotor. The three forces that apply to nearly all aerodynamic systems are weight, drag and lift (Wilde, 2013). Due to how the rotor is being simulated in isolation to the rest of the helicopter, the forces in relation to weight are not considered. The third force included for the study is centrifugal force (Table.5). A fixture was also used on the base of the shaft to simulate the idea of the blade being attached to the other three rotors (Table.4).

3. BCs (-)

Table 4 – Fixture details and resultant forces (SWReport, 2019).

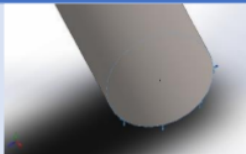
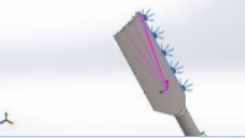
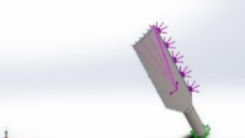
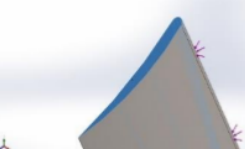
Fixture name	Fixture Image	Fixture Details			
Fixed-1		Entities:	1 face(s)		
		Type:	Fixed Geometry		
Resultant Forces					
Components		X	Y	Z	Resultant
Reaction force(N)		-40.866	-713.865	-1502.09	1663.6
Reaction Moment (N.m)		0	0	0	0

Table 5 – Forces applies to component for analysis (SWReport, 2019).

Load name	Load Image	Load Details			
Drag Force		Entities:	1 face(s)		
		Type:	Apply normal force		
		Value:	0.1488 N		
Lift Force		Entities:	1 face(s)		
		Type:	Apply normal force		
		Value:	41.019 N		
Remote Load – Centrifugal Force		Entities:	1 face(s)		
		Type:	Load (Direct transfer)		
		Coordinate System:	Global cartesian coordinates		
		Force Values:	---, 714.86, 1500 N		
		Reference coordinates:	139.63 761.76 - 1114.76 mm		
		Components transferred:	Force		



The following section is a breakdown of the values shown in (Table.5), showing the calculations used to obtain the values.

5.3.1 DRAG

This force is the resistant force that is applied to the blade due to the air resistance exerted on the rotor during operation. Due to the size and aerodynamic design of helicopter rotors, this figure is expected to be low (BCCampus, 2019).

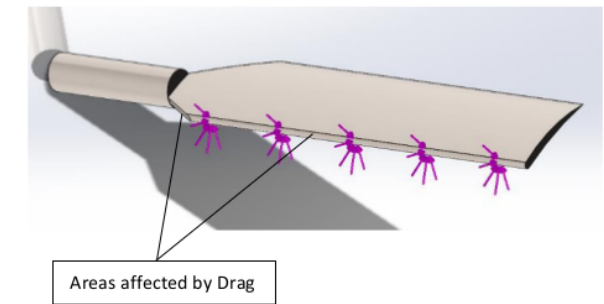
Table.1 shows the values required to calculate the drag force. See Appendix 1 for calculations for these values.

Table 6 – Values required to calculate drag force

Values	
Air density (ρ)	1.19 kg/m ³
Drag Coefficient (C_D)	0.04 
Surface area at edge of blade (A_2)	0.0020136m ²
Linear velocity (v)	54.1 m/s ²

Table 7 – Drag force equation (Beck, 2019).

Equation	
Drag Force (F_D)	$F_D = \frac{1}{2} \cdot C_L \cdot \rho \cdot v^2 \cdot A$ $F_D = \frac{1}{2} \cdot 0.04 \cdot 1.19 \cdot 54.1^2 \cdot 0.002136$ $F_D = 0.1488N$



 6

Figure 2 – Drag forces applied to rotor (Solidworks, 2019).

5.3.2 LIFT

The lift force is the force that would be applied to the tail rotor due to how the helicopter is trying to rotate along with the main rotor. It acts on the underside of the rotor blade and was calculated using the values in (Table.8). (Fig.3) shows the area in which the calculated forces apply.

Table 8 – Values required to calculate lift force (See Appendix).

Values	
Air density (ρ)	1.19 kg/m ³
Drag Coefficient (C_D)	1.45
Surface area at edge of blade (A_2)	0.016244m ²
Linear velocity (v)	54.1 m/s ²

Table 9 – Lift force equation (EngineersEdge, 2019).

Equation	
Lift Force (F_L)	$F_L = \frac{1}{2} \cdot C_L \cdot \rho \cdot v^2 \cdot A$ $F_L = \frac{1}{2} \cdot 1.45 \cdot 1.19 \cdot 54.1^2 \cdot 0.016244$ $F_L = 41.019N$

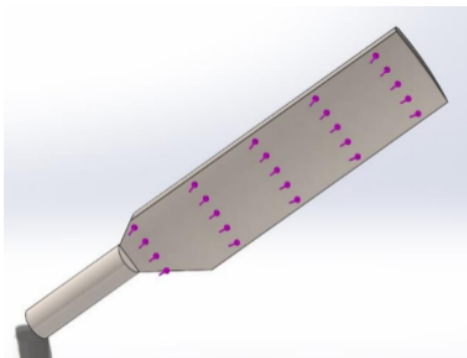


Figure 3 – Area in which the lift force applies to the rotor (Solidworks, 2019).



5.3.3 CENTRIFUGAL

The centrifugal forces act outwards from the centre of gravity of the component to the tip of the blade.

The values and equations required to find the centrifugal forces that apply to the rotor can be found in the tables below. (Fig.4) shows the area in which these forces apply to the rotor.

Table 10 - Values required to calculate centrifugal force (See Appendix).

Values	
Radius (r)	0.15872m
Angular velocity (ω)	147.76 rad/s
Mass (m)	0.47952 kg

Table 11 – Centrifugal force equations (EngineersEdge, 2019).

Equations	
Centrifugal Force (F_C)	$F_C = \frac{mv^2}{r}$ $F_C = \frac{0.47952 \times 147.76^2}{0.15872}$ $F_C = 1661.7N$
Centrifugal Force on Y axis (F_{Cy})	$F_{Cy} = 1661.7 \cos 25.48$ $F_{Cy} = 1500N$
Centrifugal Force on X axis (F_{Cx})	$F_{Cx} = 1661.7 \sin 25.48$ $F_{Cx} = 714.86N$

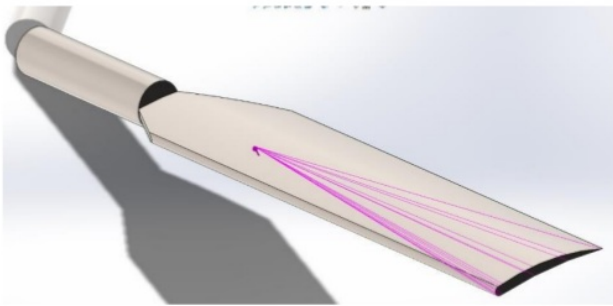


Figure 5 - Area in which the centrifugal forces apply to the rotor (Solidworks, 2019).

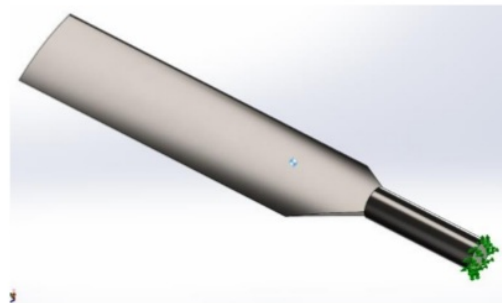


Figure 4 – Centre of mass used to apply centrifugal forces.



6.0 FINITE ELEMENT ANALYSIS

For this simulation, the tail rotor is being simulated in isolation so that any forces exerted from the main rotor are not considered in the results. The lift force that was calculated and applied horizontally in the simulation has been added to simulate the idea of the tail rotor working against the torque exerted by the main rotors.

6.1 MODAL ANALYSIS – FREQUENCY STUDY

This type of analysis is carried out to observe the natural frequencies of the rotor, showing how the component will react while subjected to different levels of frequency. For this study, the rotor will be fixed in place, without any other forces applied to it (SWHelp, 2019). When different frequencies are applied to the blade, the vibrations will cause it to seemingly deform into a mode shape associated with this type of design (He & Fu, 2001).

$$\begin{aligned}\text{Frequency of the rotor} &= \frac{Rpm}{60} \\ &= \frac{1411}{60} \\ &= 23.52\text{Hz}\end{aligned}$$

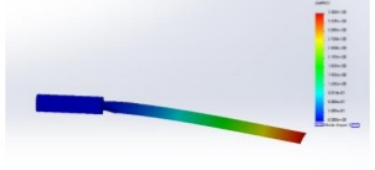
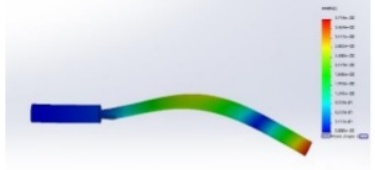
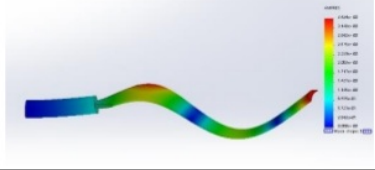


From this calculation, a frequency of 23.5Hz is obtained to be what the natural frequency of the rotor should be. The frequency from the first mode is high and should be a lot closer to 23.5Hz. This could factor from the way in which the rotor has been fixed for the study and the fixture may increase the stiffness element (De, 2019).

(Table.12) shows the different mode shapes that occur at different frequencies throughout the frequency analysis. Despite not being able to achieve a figure closer to 23.5Hz for the 1st mode, it can still be concluded that the component will operate properly. The results at 45.724Hz show a natural resonance reaction that looks reasonable and considering that this study is vibrating at a higher rate than reality, it should work perfectly at 23.5Hz (Irvine, 2003).



Table 12 – Mode shapes experienced during frequency analysis (Solidworks, 2019).

Mode		Frequency (Hz)
1		45.724
3		293.23
5		794.77

List Modes			
Study name: Frequency 1			
Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	285.03	45.364	0.022044
2	1,030	163.93	0.0061003
3	1,818	289.34	0.0034561
4	2,639.6	420.1	0.0023804
5	4,869.6	775.02	0.0012903
6	7,824.2	1,245.3	0.00080305
7	8,478.9	1,349.5	0.00074104
8	8,746.8	1,392.1	0.00071834
9	12,098	1,925.5	0.00051934
10	13,782	2,193.5	0.0004559

Figure 6 – Resonant frequencies given from the frequency study. 1-6 Translation modes, 7-10 construction modes e.g. 1st and 2nd order (Solidworks, 2019).

6.2 STATIC ANALYSIS

6.2.1 STRESS

For this analysis, Solidworks uses von Mises' theory to determine if the ductile metal rotor will yield or fracture (SimWiki, 2019). The  10 es that the component is displaying in (Fig.8) exceeds the yield strength of the material at $3.876 \times 10^8 \text{ N/m}^2$ (see Fig.7), leading to the failure of the component as it will either snap or be permanently deformed as it will not return to its original state as the elastic limit of the titanium rotor has been exceeded (Hosch, 2019). This could be due to a poor design of the component as there is a slight gap between the edge of the blade and the shaft. This seems to have caused a high stress concentration that has led to the failure. This could possibly be avoided by adding a fillet or by eliminating the gap by redesigning the rotor (Thomas, 2019).

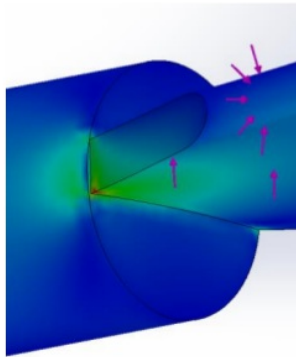


Figure 8 – Stress concentration on the tail rotor

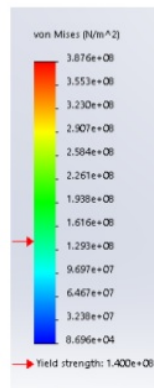


Figure 7 – Von Mises scale showing the stress value (Solidworks, 2019).

A fatigue check was used to pinpoint the areas of the component that failed due to the excess stress applied during the study. The results can be seen below in (Fig.9).

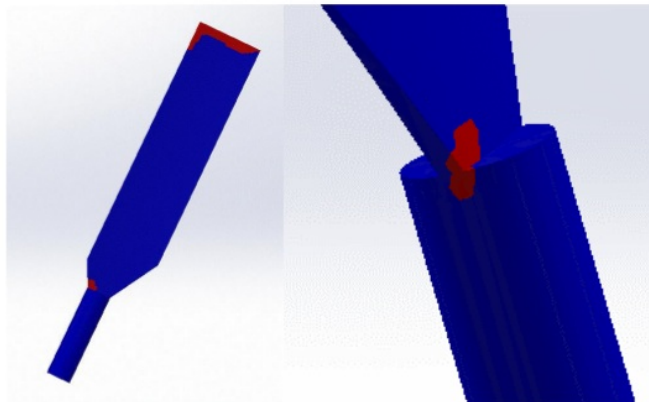


Figure 9 – Stress concentrations displayed in fatigue check (Solidworks, 2019).

High levels of stress are also noticeable in (Fig.10) from what seems to be the area of the rotor that has been fixed in place. Using the probing tool on Solidworks, the stress of the specific node that is being fixed in place is given at 1.224×10^8 . This figure almost exceeds the yield strength of the material at 1.400×10^8 and may affect the overall results of the study. This high stress value is likely because the fixing of the component has increased the stiffness present in the material. The inclusion of a bracket or holster could be introduced to apply boundary conditions to the component and reduce stiffness (De, 2019). However due to how this report is based on a single part study, the inclusion of another component is not available, so the stiffness effects of the fixture are to be neglected for simulation purposes.

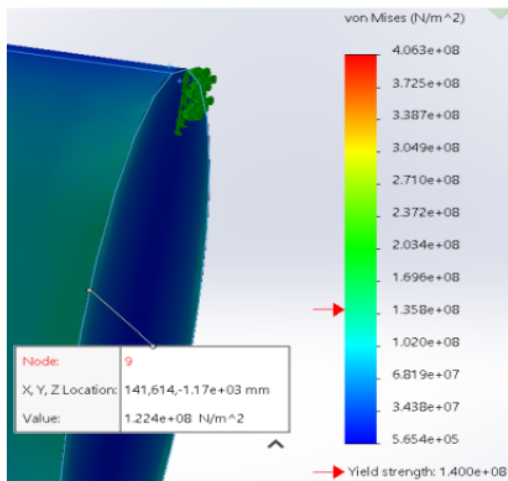


Figure 10 – High stress due to stiffness in relation to fixture (Solidworks, 2019).

6.2.2 DISPLACEMENT

These results show how much the rotor has displaced when subjected to the forces calculated in section.... (Fig 11) shows that the maximum displacement of the rotor is 4.029mm and has unsurprisingly occurred towards the tip of the blade. This was expected due to several factor including how it is the furthest point from fixture, the design of the rotor and the centrifugal forces that have been applied for the study. This displacement is also the result of the effect that airfoil has on the underside of the rotor (Weltner, 2019).

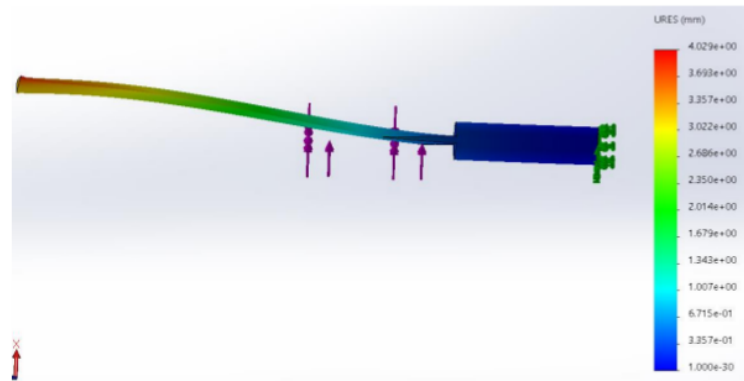


Figure 11 – Displacement analysis (Solidworks, 2019).

6.2.3 STRAIN

(Fig.13) shows that the positions that the strain occurs in this study is similar to the location of the stress results (Fig.11). This is likely to do with the linear relationship between the two entities (Fig.12) in relation to Young's Modulus (BirminghamUni, 2019).

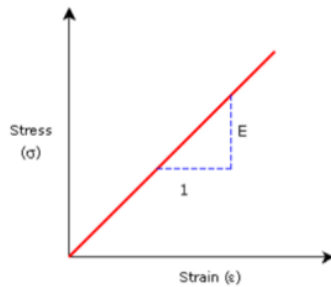


Figure 12 – Correlation between stress and strain (Solidworks, 2019).

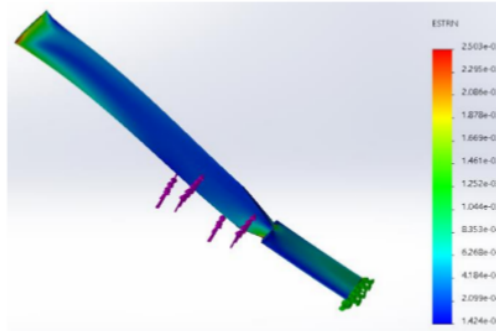


Figure 13 – Areas of rotor in which strain is acting (Solidworks, 2019).

The Young's Modulus values of the component according to this analysis in $1.55 \times 10^{11} \text{ N/m}^2$, which exceeds the Young's Modulus of the titanium used for the rotor in (Table.1) at $1.1 \times 10^{11} \text{ N/m}^2$. Once the YM value has been reached then the material has reached its limit of proportionality and will experience permanent deformation and most likely fracture (Fig.14) (EngineeringToolbox, 2019).

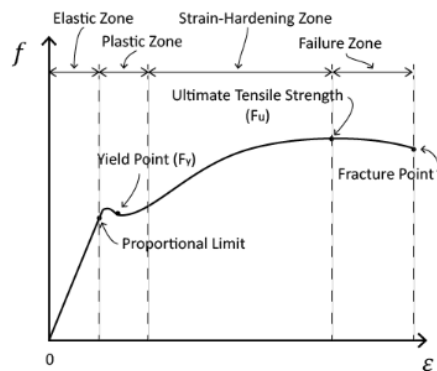


Figure 14 – Modulus of Elasticity diagram (SAFAS, 2019).

6.3 STATIC ANALYSIS – TO SCALE

This part of the report aims to briefly describe the effects that scaling down the forces exerted on the rotor so that they are proportional to the rotor size to see how they will affect the overall analysis.

6.3.1 LOADING CONDITIONS

It is possible that the component has failed due to the forces being applied not being to scale, as they were calculated using figures of a full-sized helicopter. Using the length of the rotor 366.13mm in (Fig.15) and the radius of the full sized rotor 1.27m (Swopes, 2016), a ratio of 1:3.5 is obtained (RatioCalculator, 2019).

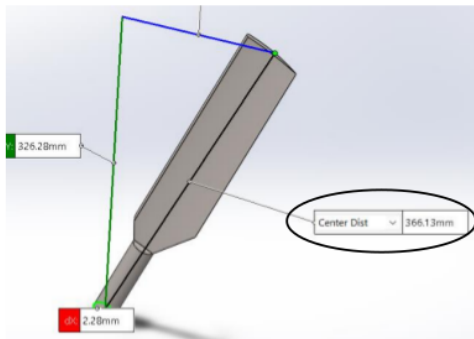
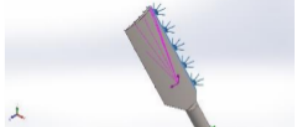
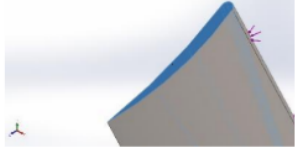


Figure 15 – Using measuring feature to measure rotor (Solidworks, 2019).

For this study, all values that were exerted on the rotor in the previous section have been scaled down by a factor of 3.5 to attempt to give a more accurate result and to see if the failure is resolved. (Table 13) shows the updated forces that have now been applied to the static study.

Table 13 – Scaled down figures (SWReport, 2019).

Load name	Load Image	Load Details	
Drag Force		Entities: Type: Value:	1 face(s) Apply normal force 0.05 N
Lift Force		Entities: Type: Value:	1 face(s) Apply normal force 11.72 N
Remote Load – Centrifugal Force		Entities: Type: Coordinate System: Force Values: Reference coordinates:	1 face(s) Load (Direct transfer) Global cartesian coordinates ---, 204.25, 428.6 N 139.63 761.76 -1114.76 mm

6.3.2 STRESS – TO SCALE

From this new study (Fig.16), the stress points are similar to the analysis in (Section 6.2.1) however in this case, the values are not as severe. The highest von Mises stress value for this study is below the yield strength of the material at 1.161×10^8 meaning that the component has not failed. This is further proven by another fatigue check which can be observed in (Fig.17).

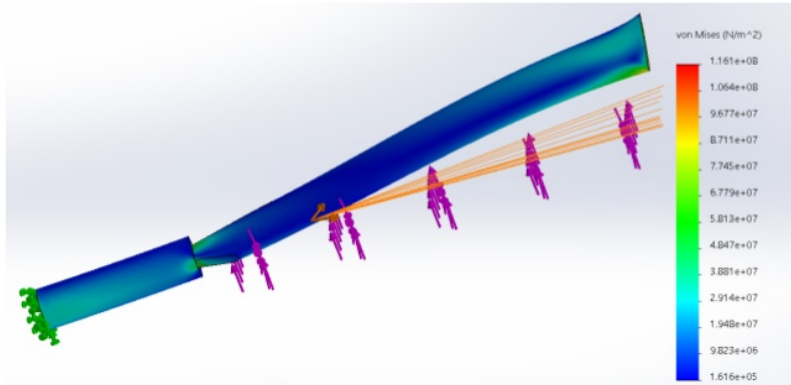


Figure 16 – Stress analysis scaled at 1:3.5 (Solidworks, 2019).

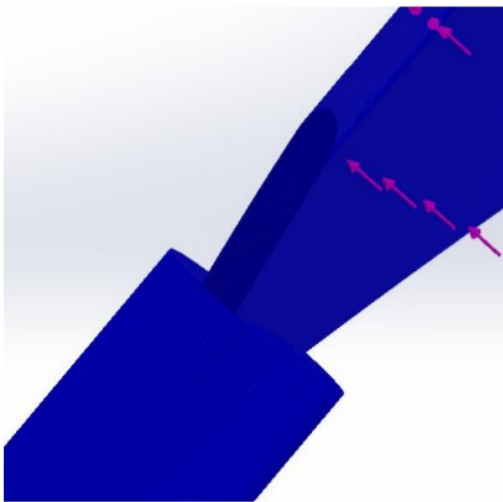


Figure 17 Fatigue check showing no signs of failure- (Solidworks, 2019).

6.3.3 STRAIN – TO SCALE

Similar to the stress results, the strain points are similar to the analysis carried out in (Section 6.2.3) with no points of failure.

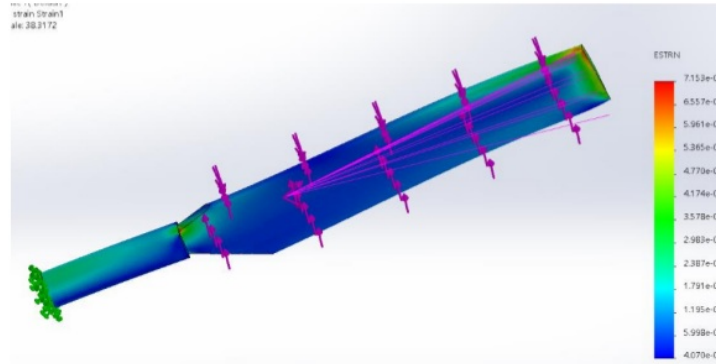


Figure 18 – Strain values when forces have been scaled to 1:3.5 (Solidworks, 2019).

6.3.4 DISPLACEMENT – SCALED AT 1:3.5

These new results show how much the rotor has displaced when subjected to the scaled down forces that have been recalculated and applied. The effect on the rotor is roughly the same, acting in the same areas as (Section 6.2.2). However, when scaled down, (Fig 19) shows that the maximum displacement of the rotor has now been reduced to 1.151mm.

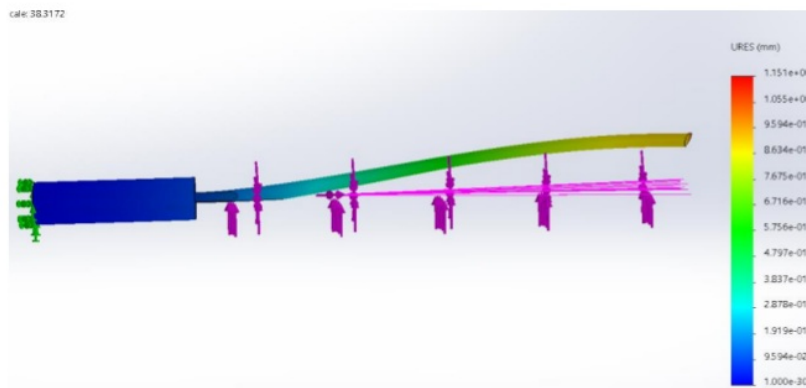


Figure 19 – Displacement values when forces have been scaled to 1:3.5 (Solidworks, 2019).



7.0 CONCLUSION

To conclude this report, it is to be noted that the simulation would differ massively in real life circumstances as many assumptions had to be made for this analysis. These assumptions include that the tail rotor will be in a state of isolation from the main rotors and other forces. Also, in real life circumstances, other factors like air humidity would change depending on the environment that the helicopter is operating in e.g. deserts = less humid – less air resistance, UK = more humid - more air resistance. The analysis was also conducted in an isolated state from other contributing factors like forces from the main rotor and any other changes like wind, height and speed.

It should also be noted that Solidworks is not capable of displaying the actual affects of what would happen if the limits of the material were breached due to how it is a linear solver. This means that the user would likely be unaware of the extent of the results if they were inexperienced with using FEA software.

Good

However, when the acting forces were scaled down, it did obviously enhance the accuracy of the results. The scaling issue was taken into account initially, but analysis was still carried out to see what the results would be before and after altering the scale of the acting forces.

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8.0 APPENDIX

Equations	
Angular velocity at tip of the blade	$\omega = rpm \times \frac{2\pi}{60}$ $\omega = 1411 \times \frac{2\pi}{60}$ $\omega = 147.76 \text{ rad/s}$
Linear velocity (v)	$v = \omega r$ $v = 147.76 \times 0.366125$ $v = 54.1 \text{ m/s}^2$

Values	
Air density (ρ)	$1.225 - 0.035 = 1.19 \text{ kg/m}^3*$
Lift Coefficient (C_L)	1.45 (Sciencing, 2019)
Drag Coefficient (C_D)	0.04 (Fig.20) 21
Surface area underneath blade (A_1)	0.016244 m^2 (Solidworks, 2019)
Surface area at edge of blade (A_2)	$0.00188543 \text{ m}^2 + 0.012818 \text{ m}^2 = 0.0020136 \text{ m}^2$ (Solidworks, 2019)

* The value for air pressure is at 1000ft, so 0.035 is subtracted from the original value of 1.225 (EngineeringToolbox, 2019)



Figure 20 – Apache dimensions (Swopes, 2016).

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Shape		Drag Coefficient
Sphere	→ 	0.47
Half-sphere	→ 	0.42
Cone	→ 	0.50
Cube	→ 	1.05
Angled Cube	→ 	0.80
Long Cylinder	→ 	0.82
Short Cylinder	→ 	1.15
Streamlined Body	→ 	0.04
Streamlined Half-body	→ 	0.09

Measured Drag Coefficients

Figure 21 – Drag coefficients



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Josh Evans Assignment

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

63/100

PAGE 1

PAGE 2

PAGE 3

QM

5. Presentation(+)

Generally your presentation is good

PAGE 4

PAGE 5

PAGE 6



Comment 1

Using an Isotropic material is a reasonable assumption - but why have you chose Titanium - what grade is this? Why?

PAGE 7



Comment 2

proof read your work! - Table 2.



Comment 3

Solution time to do what? How did the results differ?



Comment 4

You are starting to discuss mesh quality - where were these elements? Were they of concern?



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



Comment 5

Where have you got this coefficient from?



Comment 6

This would act in one direction which is opposite to the direction of travel.



Comment 7

These calculations assume the blade is in laminar air flow - is this correct?



Comment 8

where does this angle come from? You need to justify and back-up all your calculations.



Comment 9

Surly you want to avoid this frequency?



Comment 10

387MPa



Comment 11

good suggestion



Comment 12

when showing images such as this, the mesh should be visible so that the influence on the results can be assessed by the reader.



Comment 13

scale? what does red/blue mean?

PAGE 16



Comment 14

units?

PAGE 17



Comment 15

?

PAGE 18



Comment 16

155GPa



Comment 17

is



Comment 18

define any acronyms before you use them

PAGE 19

PAGE 20



Comment 19

units?



Good



Comment 20

What element order did you use? Why?



Comment 21

You need to make it clear in the main report where you got these figures from.



5. Resolution(-)

Make sure that any images that you take from other sources are of good enough resolution to be clear in your report



Comment 22

Units should be converted to SI



Comment 23

?

GRADING FORM: APACHE ACM

**JOSHUA
EVANS**

62.70

RESEARCH INFORMED LIT



12.6

KNOWLEDGE & UNDERSTANDING



12.8

ANALYSIS



18

PRACT APP & DEPLOYMENT



12.6

SKILLS FOR PROF PRAC



6.7