

NOVEMBER 17, 2019

ADVANCED COMPUTATIONAL METHODS (M6X00408)

ASSESSMENT OF A HELICOPTER TAIL ROTOR

ANDREW CURTIS (1706668)

UNIVERSITY OF WALES TRINITY SAINT DAVID
BENG (HONS) MECHANICAL & MANUFACTURING ENGINEERING
KELVIN LAKE

EXECUTIVE SUMMARY

The requirement of this study was to research relevant academic literature and websites in order to establish the appropriate loading forces for the helicopter tail rotor model provided. Once accurate forces had been determined, an FE model was generated and solved in order to provide information on the suitability of the design. The two studies undertaken were a static analysis to ascertain the result of applied centrifugal and thrust forces, and a modal analysis to ensure the FE model's natural frequencies did not interact with the blade passage frequency and cause resonance.

Fundamentally, the result of the static analysis was that the applied forces had developed stress within the model exceeding the material yield strength using the Von Mises Yield Criterion and was unsafe. However, the regions of high stress were localised, pertaining to either stress singularities or stress concentrations. The modal analysis provided evidence based on an assumption that under a constant tail rotor angular velocity, there will not be any interaction or excitement of the natural frequencies to cause resonance. Although, through normal power and speed drifts within helicopter flight, which would directly affect the blade passage frequency, it is likely that amplitudes three and four would be affected and lead to possible design changes.

To conclude, the model design and the analysis were critically appraised, listing concerns with material selection and the dynamic response of the stiffening effect from the centrifugal force on the rotor blades. This effect is not considered within a linear static analysis and was a source of possible error within the study. Recommendation to improve on the design involved elimination of all sharp edges, either by fillet or radius. Once the FE model has been altered, the analysis should be repeated to determine safety.

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1.0 INTRODUCTION

1.1 PROBLEM STATEMENT

The provided helicopter rotor model necessitates thorough research within literature in order to establish accurate in-service loading conditions for the part. Through this research, appropriate FE models will be selected and used to analyse the part to ensure the suitability of the design. The analysis will be critically appraised based on the findings from the FE models to determine a conclusion on the suitability of the design. Any recommendations to improve the analysis or the design of the rotor will be given.

1.2 THE TRADITIONAL SINGLE MAIN ROTOR HELICOPTER OVERVIEW

Helicopters are often classified as rotary-wing or rotorcraft aircraft, because of their use of horizontal rotors, which propel and lift the aircraft during flight. The most commonly recognised helicopter design or rotor configuration is the single main rotor helicopter. The single main rotor helicopter uses a horizontal rotor to provide lift and propulsion, and a separate variable pitch tail rotor to compensate for the torque generated from this main rotor. The tail rotor is often referred to as the antitorque rotor, which is located on the end of a tail boom extension at the rear of the fuselage. The antitorque rotor provides opposing force in accordance with Newton's law of action and reaction, to prevent the fuselage from rotating in the opposite direction to the main rotor blades. The amount of compensation thrust from the antitorque rotor can be varied in relation to the torque produced by the engine in order to maintain directional control, or to make heading changes during hovering. The antitorque rotor is driven by the main rotor at a constant ratio and a significant amount of the engine's total power output is necessary to drive the antitorque rotor. Through literature this figure ranges from between five to thirty percent and is dependent on the size and design of the helicopter (faa.gov, 2019; heli-air.net, 2019; amumagazine.com, 2019).

2.0 FORCES LOADING THE ANTITORQUE ROTOR BLADE

In order to establish the suitability of the antitorque rotor blade model, the fundamental forces loading this component must be understood. The two major forces acting on a tail rotor are:

- Centrifugal force (inertia); generated through blade rotation which tends to pull the blades straight outward from the main rotor hub. The faster the rotation, the greater the centrifugal force.

- Thrust force; the amount of force required to compensate for the main rotor torque. Thrust, or lift when describing the main rotor, is generated by the rotor blade's lower surface striking and deflecting air. In accordance with Newton's law of action and reaction, the air deflected produces an opposing action, therefore, thrust.

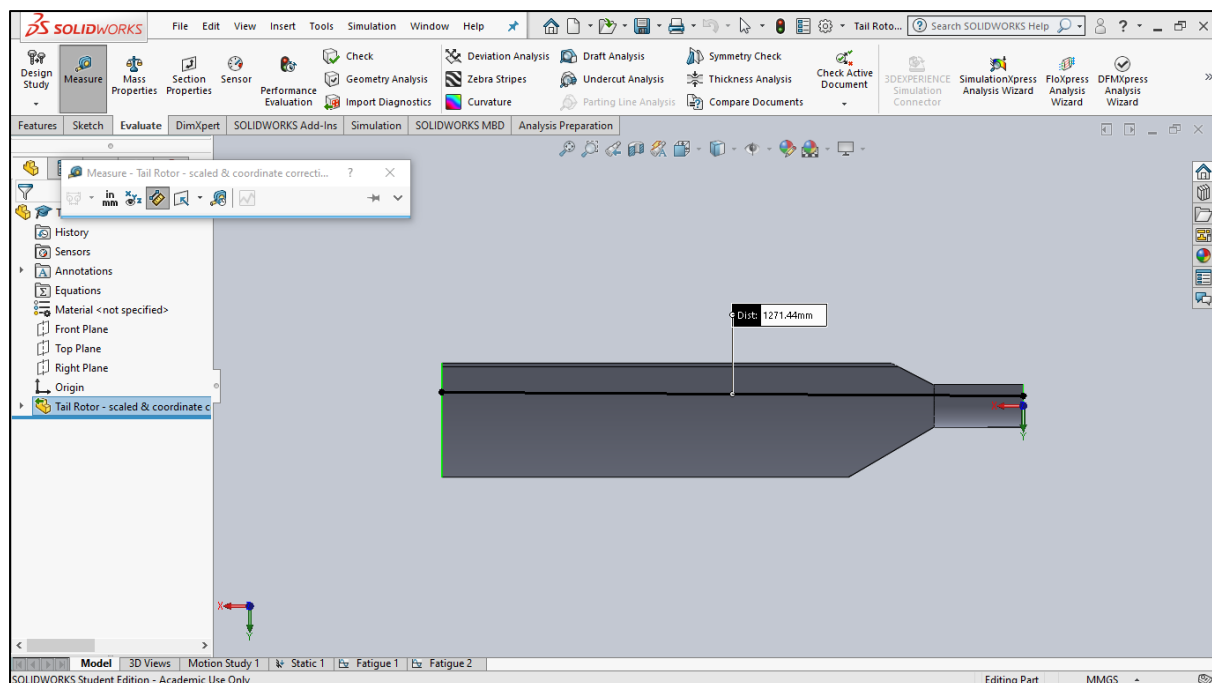
(Chen et al., 2018; Faa.gov, 2019)).

2.1 MODEL SCALING, PARAMETERS AND ASSUMPTIONS

Through an evaluation of the rotor model geometry within SolidWorks, it became evident that the dimensions of the model did not align with any of the information available throughout literature regarding a tail rotor for an Apache Helicopter. This eventuality presented a risk in obtaining unworkable analytical data. As all other parameters such as rpm, engine power output, material and the like, are all available from multiple sources. To provide a solution to this eventuality, the model was scaled to a factor of 3.9 uniformly about the centroid, which gave a very near appropriation of an AH-64 Apache Helicopter antitorque rotor blade (Army-technology.com, 2019; Swopes, 2016).

Figure 1. Illustrates the tail rotor model dimension evaluation after scaling.

Figure 1: SolidWorks Screenshot - Tail Rotor Model Dimension Evaluation Post Scaling.



2.2 MATERIAL SELECTION

Material selection for the antitorque rotor was a concern, as modern helicopter rotors are manufactured from composite materials. Generally, composite materials are anisotropic, meaning the properties of the material are directionally dependent. When considering a linear static analysis within SolidWorks, a linear elastic isotropic material must be selected. As a linear elastic material is assumed to behave linearly regardless of stress and holds in all directions to Hooke's law. As a result of this constraint on material selection and in an attempt to generate some useful analytical data; Titanim (Ti-6Al-4V Solution treated and aged) was selected because of its high strength to low density ratio and fatigue strength (Rsc.org, 2019; SolidWorks.com, 2019c),

2.3 AH-64 APACHE HELICOPTER REQUIRED PARAMETERS

Table 1 was populated listing all the parameters required to calculate the loading conditions on the tail rotor. Many of the parameters were recovered from websites and literature, and those sources have been listed within the table. However, some parameters could not be found and had to be determined from the FE model geometry provided.

Table 1: Apache Helicopter AH-64 Parameters

APACHE AH-64 HELICOPTER SPECIFICATION		
Detail	Parameter	Reference/Assumption
Main Rotor Speed (RPM)	289	(Army-technology.com, 2019; Swopes, 2016).
Main Rotor Speed Power (KW)	2530	(Army-technology.com, 2019; Swopes, 2016).
Main Rotor Diameter (m)	14.63	(Army-technology.com, 2019; Swopes, 2016).
Main Rotor No. of blades	4	(Army-technology.com, 2019; Swopes, 2016).
Antitorque Rotor Speed (RPM)	1411	(Army-technology.com, 2019; Swopes, 2016).
Antitorque Rotor Speed Power (KW)	5-30% of total power output	(Faa.gov, 2019; heli-air.net, 2019; Han & Barakos, 2016).
Antitorque Rotor Diameter (m)	2.539	(Army-technology.com, 2019; Swopes, 2016).
Antitorque Rotor No. of blades	4	(Army-technology.com, 2019; Swopes, 2016).
Antitorque Rotor Blade Mass (Kg)	22.6314	SOLIDWORKS 2019, FE Model Geometry
Helicopter Loaded Weight (Kg).	5553	(Army-technology.com, 2019; Swopes, 2016).
Rotor Centre Distance (m).	9.03	SOLIDWORKS 2019, FE Model Geometry

2.4 CENTRIFUGAL FORCE CALCULATION

When a body of mass rotates about an axis (such as a helicopter rotor), an outward radial force is exerted upon the axis arm or cord, directly from the axis that restrains it from moving in a straight (tangential) line (Engineersedge.com, 2019).

Equation 1: Centrifugal Force Calculation.

Therefore; to calculate the centrifugal force loading the antitorque rotor blade with:

$$Mass = 22.6314 \text{ Kg}$$

$$Radius = 1.27 \text{ m}$$

$$Angular \text{ velocity} = 1411 \text{ rpm}$$

Where:

$$F = m\omega^2 r$$

$$F = 22.63 \times (1411 \times \pi / 30)^2 \times 1.27$$

$$F = \underline{627479.5 \text{ N}}$$

2.5 THRUST FORCE CALCULATION

The torque generated from the main rotor rotation must be compensated for by creating opposing forces from the antitorque rotor. In order to establish the compensation force required and to define an approximated force acting on the antitorque rotor; the torque being generated at the main rotor must be calculated. Considering the relationship which exists between power and torque, and knowing:

- AH-64 Apache helicopters are equipped with two engines, each providing 1,265 kW of power. Throughout literature, helicopters are stated to operate at a constant 100% engine power output, and that the tail rotor consumes a substantial amount of this total power. Typical figures given range from 5% to 30% depending on the size and design of the aircraft. Assuming that there are no other losses to engine power, and the thrust needed from the tail rotor would be greatest when the majority of the engine power is delivered to the main rotor. The power to the main rotor can be calculated by:

$$(1265 \text{ KW} \times 2) - 5\%$$

- Apache helicopter main rotors rotate at 289 rpm

(Army-technology.com, 2019; Swopes, 2016)

Equation 2: Main Rotor Torque Calculation.

The torque being generated at the main rotor can be calculated through the expression:

$$P = T \omega$$

Where;

P = power (W)

T = torque or moment (Nm)

ω = angular velocity (rad/s)

$\pi = 3.14...$

n_{rps} = rotations per second (rps, 1/s)

n_{rpm} = rotations per minute (rpm, 1/min)

Therefore:

$$P = T \pi n_{rpm} / 30$$

Where;

$$T = 30P / (\pi n_{rpm})$$

$$= 30 \times 2403500 / (\pi 289)$$

$$= \underline{79417.79 \text{ Nm}}$$

From Equation 2 an approximation of the torque being generated at the main rotor has been determined. To calculate the antitorque thrust required to counter the main rotor torque, the torque divided by the distance from the hub centre of the tail rotor to the main rotor shaft must be calculated. (Han & Barakos, 2016). Unfortunately, extensive research of literature and websites has proven unsuccessful in determining the required dimension. However, through scaling the Apache helicopter model provide by a factor of 3.9, a dimension of 9.03 m was determined. Justification of the model's dimension was provided by dividing the main rotor and antitorque rotor by two, and adding the results together to ensure the geometry was feasible based on the literature revue, as illustrated in Equation 3:

Equation 3: Antitorque Calculation.

Main rotor length = 14.63 m

Antitorque rotor length = 2.539 m

Therefore:

$$(14.63 / 2) + (2.539 / 2) = \underline{8.58 \text{ m}}$$

Therefore; utilising the Apache helicopter model geometry, the antitorque required from the tail rotor is given by:

$$79417.79 / 9.03 = \underline{8794.88 \text{ N}}$$

Therefore; the thrust loading on each antitorque blade is given by:

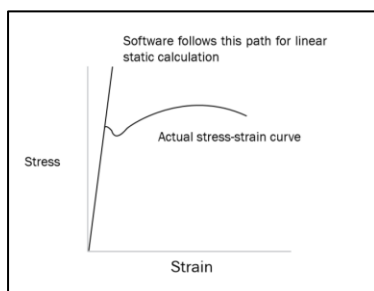
$$8794.88 / 4 = \underline{2198.72 \text{ N}}$$

3.0 FE MODEL ANALYSIS

3.1 STATIC ANALYSIS

A Static analysis assumes material properties are linear; loads or boundary conditions do not change with time; deflections are small and no dynamic effects are in the system. The FE solver plots a straight line from origin to deformed state on a stress-strain graph and assume the Elastic Modulus is constant as illustrated in Figure 5. However, in real applications, when a material crosses the yield point it follows a nonlinear curve. Therefore, an analyst must conclude on whether a component is safe or has failed from a comparison to a known yield or ultimate stress value (Altair Engineering, 2015).

Figure 2: FE Solver Stress-Strain Curve Assumption.



(Altair Engineering, 2015).

The basic finite element equation to be solved for structures experiencing static loads can be expressed as in Equation 4.

Equation 4: Static Load Basic Element Equation.

$$K u = P$$

Where:

K = stiffness matrix of the structure

u = displacement vector

P = vector of loads applied to the structure.

The above equation is the equilibrium of external and internal forces.

(Altair Engineering, 2015).

3.1.1 MESH REFINEMENT

A process of mesh refinement is required for Finite Element Analysis in order to determine an optimum level of mesh density, which will provide the required level of accuracy for the application, and deliver the results in an appropriate amount of time. In its simplest form, mesh refinement involves resolving a model with progressively finer elements in order to attain mesh convergence. Errors associated with poor mesh refinement, are missed regions of high stress from a mesh being too coarse, or wasted time on computational resources from a mesh being too fine. To begin the refinement process on the tail rotor FE model, a preliminary mesh was established based on a measurement taken from the FE model to allow three elements through its thickness (Comsol.com, 2019).

Figure 3: SolidWorks Screenshot - FE Model Dimension Evaluation

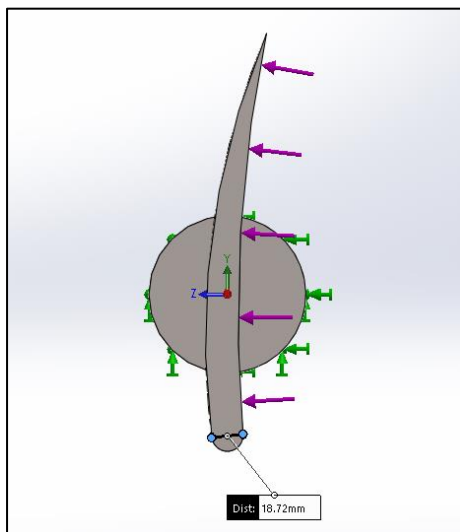


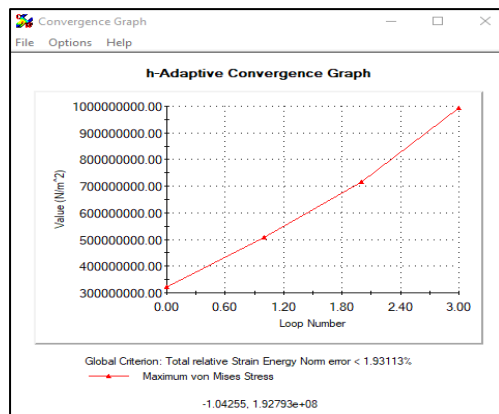
Table 1 Illustrates the differences in obtainable results based only on mesh quality for Von Mises stress. The Von Mises Yield Criterion is the default application within SolidWorks and was selected for this analysis because of its suitability to determine whether an isotropic and ductile metal will yield when subjected to a loading condition. Table 1 demonstrates that a standard mesh with a size of 6.3 mm presented a maximum stress development on the FE model of $1.06\text{e}+09 \text{ N/m}^2$. However, the h-adaptive method of mesh convergence presented a maximum stress development on the same FE model as $1.63\text{e}+09 \text{ N/m}^2$. The 6.3 mm standard mesh was quicker in obtaining results, but had missed vital regions of high stress. The additional time needed to obtain this level of accuracy was deemed acceptable for this study and the benefit of automating the mesh convergence was realised. Conversely, for different applications where a high level of accuracy is not required, the h-adaptive method may be too time consuming because of the time taken for each loop to repeat and reevaluate until convergence is reached (Dvorak, 2004).

Table 2: Mesh Convergence Results

Helicopter Tail Rotor Static Analysis - Mesh Refinement						
Mesh Type / Method	Mesh Size (mm)	No. of Nodes	No. of Elements	Degrees of Freedom	Time to Solve (s)	Max Stress - Von Mises N/m^2
Standard mesh	SolidWorks Default 17.22756528	17862	10125	53217	00:00:32	$6.96\text{E}+08$
Standard mesh	6.3	201066	127988	600999	00:04:12	$1.06\text{E}+09$
Standard mesh	3	1585957	1089994	4748253	01:46:12	$1.27\text{E}+09$
Mesh Control	6.3 / 3	281902	183677	843252	00:05:33	$1.22\text{E}+09$
Curvature based mesh	6.3	385848	253504	1155090	00:07:40	$9.65\text{E}+08$
h-adaptive method	6.3	313639	206275	938751	00:06:11	$1.63\text{E}+09$

On evaluation of the h-adaptive convergence graph it became evident the trend shown did not illustrate a typical mesh that had reached convergence. However, after three loops the Error Norm tolerance with a target accuracy of 98% was satisfied and the two remaining loops from the five selected were missed.

Figure 4: SolidWorks Screenshot - h-Adaptive Convergence Graph.



3.1.2 STATIC ANALYSIS - THRUST AND CENTRIFUGAL FORCE

A static analysis was used to simulate the thrust and centrifugal loading on the antitorque rotor blade. Fixed geometry was applied to the circular end face to imitate the in-service structural arrangement. The antitorque thrust force calculated was applied to the underside of the rotor as a normal load of 2198.72 N. The centrifugal force was applied as a remote point load to simulate the centrifugal loading on the rotor blade. Whilst establishing the centre of mass and direction of force for the remote point load. It became apparent that the model had not been correctly aligned to the SolidWorks default coordinate system. This was quickly corrected by arranging a new coordinate system to align the model to.

Figure 5: SolidWorks Screenshot - Remote Point Load Coordinate Alignment

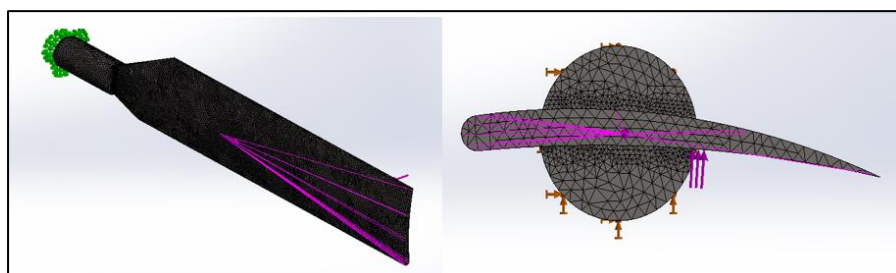


Table 3: Static Analysis - Parameters

Helicopter Tail Rotot Static Analysis - Parameters		
Analysis type:	Static	Thrust & Centrifugal Force Loading
Study Properties	Solver type	FFEPlus
Volumetric Properties	Mass	22.6314 Kg
	Volume	0.000511006 m ³
	Density: 4428.78 Kg/m ³	4428.78 Kg/m ³
	Weight	221.787 N
Mesh Type/Details	Mesh type	Solid Mesh
	Mesher Used:	Standard mesh
	Jacobian points	4 Points
	Element Size	6.3 mm
	Tolerance	0.315 mm
	Mesh Quality Plot	High
	Total Nodes	217901
	Total Elements	139392
	Maximum Aspect Ratio	11.789
	% of elements with Aspect Ratio < 3	98.5
	% of elements with Aspect Ratio > 10	0.00156
	% of distorted elements(Jacobian)	0
	Time to complete mesh(hh:mm:ss):	00:00:11
	h-adaptive Method	Target accuracy
		Accuracy bias
		Max No. of loops
		Mesh coarsening
Material Properties	Name	Ti-6Al-4V Solution treated and aged (SS)
	Model type	Linear Elastic Isotropic
	Yield Strength	8.27371e+08 N/m ²
	Tensile Strength	1.05e+09 N/m ²
	Elastic modulus	1.048e+11 N/m ²
	Poisson's ratio	0.31
	Mass density	4428.78 kg/m ³
	Shear modulus	4.10238e+10 N/m ²
	Thermal expansion coefficient	9e-06 /Kelvin

Table 4: Static Analysis - Loads and Fixtures.

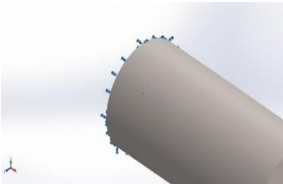
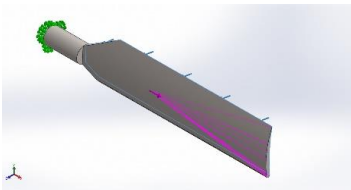
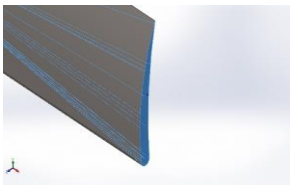
Helicopter Tail Rotot Static Analysis - Loads & Fixtures																		
Loads and Fixtures	Fixture details	Fixed 1.		1 face														
				Fixed Geometry														
		Fixed 1. Image																
		Resultant Forces		<table><tr><th>Components</th><th>X</th><th>Y</th><th>Z</th><th>Resultant</th></tr><tr><td>Reaction force(N)</td><td>-627480</td><td>-121.432</td><td>-2188.26</td><td>627484</td></tr><tr><td>Reaction Moment(N.m)</td><td>0</td><td>0</td><td>0</td><td>0</td></tr></table>	Components	X	Y	Z	Resultant	Reaction force(N)	-627480	-121.432	-2188.26	627484	Reaction Moment(N.m)	0	0	0
	Components	X	Y	Z	Resultant													
	Reaction force(N)	-627480	-121.432	-2188.26	627484													
	Reaction Moment(N.m)	0	0	0	0													
	Load Details	Force-1. Details	Force-1.	Entitie		1 face(s)												
				Type		Apply normal force												
				Value		2198.72 N												
		Force-1. Image																
			Remote Load (Direct transfer)-1. Details	Remote Load 1.	Entities		1 face(s)											
					Type		Load (Direct transfer)											
Coordinate System		Global cartesian coordinates																
Force Values		627480 N																
Moment Values		0 N.m																
Reference coordinates		576.666 4.16 -0.16 mm																
Components transferred		Force																
Force-1. Image																		

Figure 6: SolidWorks Screenshot - Static Analysis Results

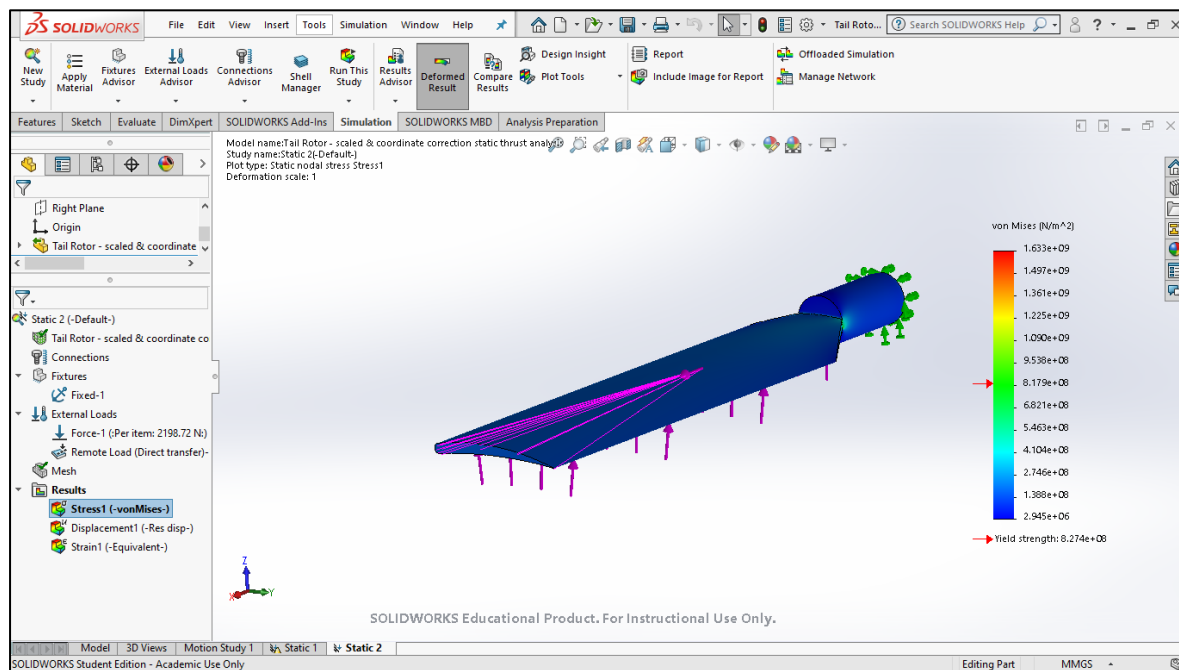


Table 5: Static Analysis - Results.

Helicopter Tail Rotot Static Analysis - Study Results		
Stress	Type	VON: von Mises Stress
	Min	2.945e+06 N/m^2 Node: 37178
	Max	1.633e+09 N/m^2 Node: 31697
Displacement	Type	URES: Resultant Displacement
	Min	0.000e+00 mm Node: 786
	Max	4.771e+00 mm Node: 11
Strain	Type	ESTRN: Equivalent Strain
	Min	0.0000455 Element: 110441
	Max	0.01064 Element: 136117

Fundamentally, the results of the simulation have shown that the FE model has exceeded the material yield strength using the Von Mises Yield Criterion and is unsafe. However, these regions of high stress are localised, pertaining to either stress singularities or stress concentrations. Normally, to differentiate between the two, the mesh would be refined globally or locally at the regions where stress hotspots are detected. SolidWorks has an automated solution to this called the Hotspot Diagnostics Tool, where, if the stresses at the elements of stress hot spots do not increase with mesh refinement and converge towards a finite value, then they are indicative of stress concentrations, or

areas of legitimate high stresses (SolidWorks, 2019b). Therefore, after the hotspot diagnostic tool was utilised it can determine that the tail rotor FE model has stress concentrations pertaining to sharp edges and poor design.

Figure 7: SolidWorks Screenshot – Hotspot Diagnostic Tool.

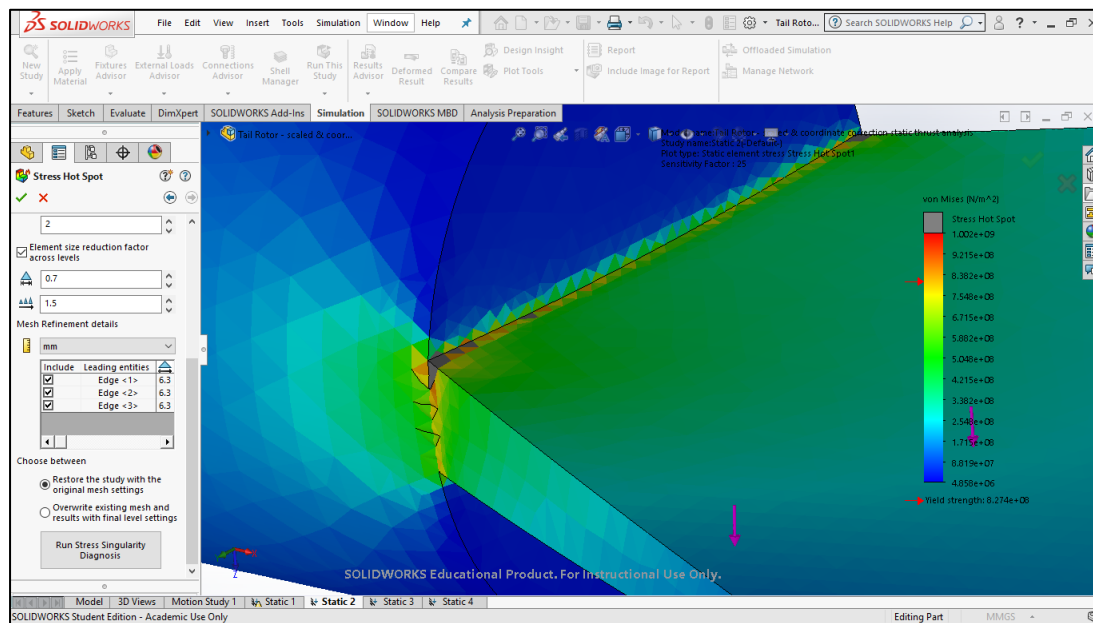


Figure 8: SolidWorks Screenshot – Hotspot Diagnostic Tool Result.

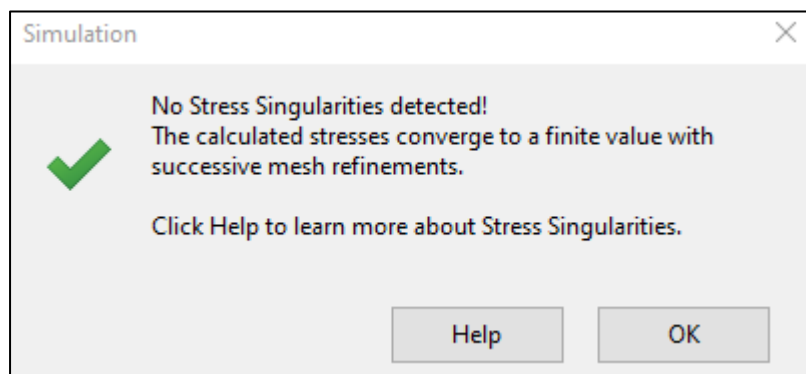


Figure 9: SolidWorks Screenshot – Design Insite Plot Illustrating Highest Loaded Areas.

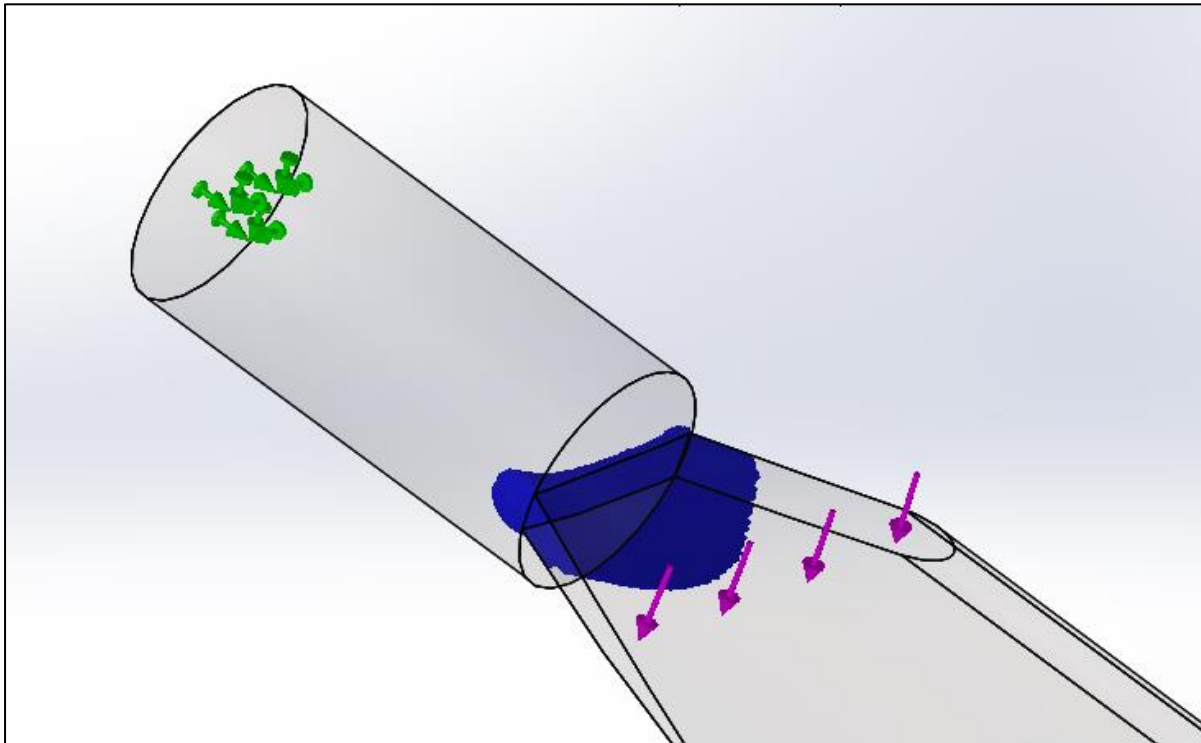
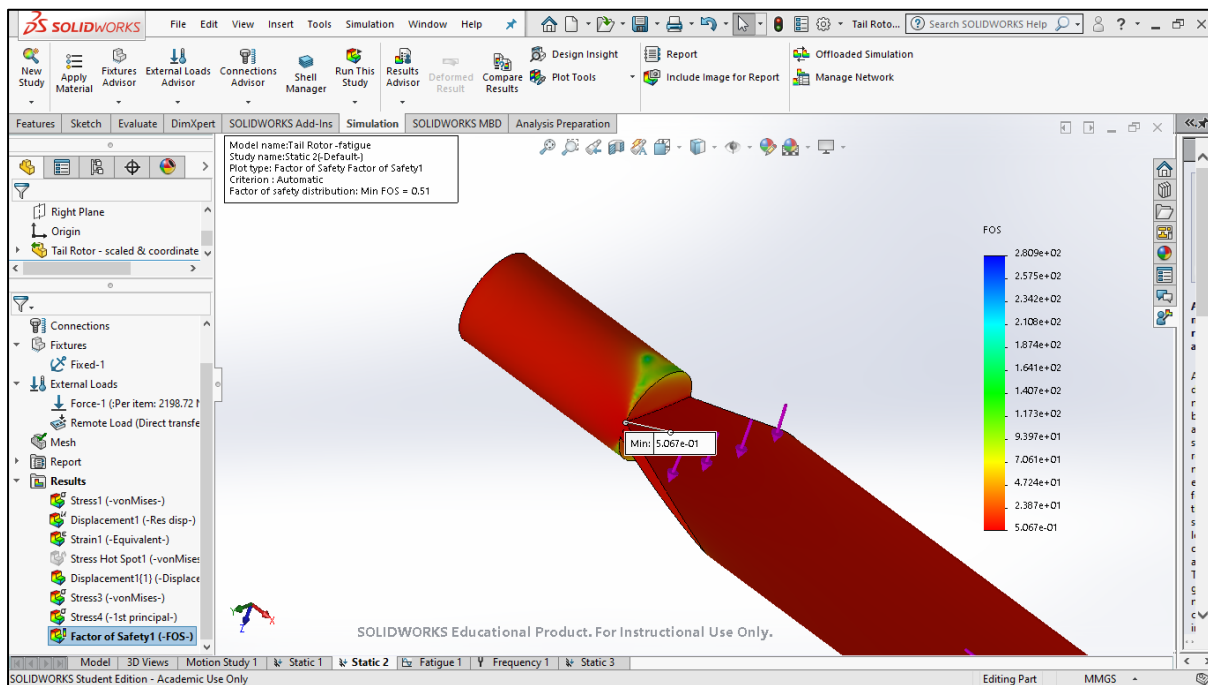


Figure 10: SolidWorks Screenshot – Factor of Safety Plot.



3.2 MODAL ANALYSIS - NATURAL FREQUENCY

Every structure vibrates at certain frequencies, this phenomenon is called natural frequency. If an external factor such as rotational speed coincides with any of these natural frequencies, the structure will become excited and be subjected to vibration. This phenomenon where the excitation frequency coincides with a system's natural frequency is referred to as resonance. Resonance can cause a structure to undergo large displacements and stresses, and should be avoided. Hence, natural frequency or modal analysis is frequently undertaken during the design stage to determine these values and mode shapes. Mode shapes indicate how a system would be deflected while vibrating at any of the natural frequencies. If the external excitation or influencing factors cannot be altered, the structure or part is often redesigned to shift the natural frequency away from the excitation frequency. In general, modal analysis is considered a linear analysis hence non-linearities such as non-linear materials and contacts are not allowed. When considering vibration frequencies in regard to helicopter rotor blades, blade passage frequency must be considered and calculated (Thomas, 1996; Engineeringtoolbox.com, 2019; SolidWorks, 2019a).

Equation 5: Blade Pass Frequency Calculation.

Blade Pass Frequency can be expressed as:

$$BPF = n t / 60$$

Where;

$BPF = \text{Blade Pass Frequency (Hz)}$

$n = \text{rotation velocity (rpm)}$

$t = \text{number of blades}$

Therefore:

$$BPF = 1411 \times 4 / 60$$

$$\underline{94.06 \text{ Hz}}$$

Table 6: Modal Analysis - Parameters

Helicopter Tail Rotot Natural Frequency Analysis - Parameters		
Analysis type:	Frequency	Natural Frequency
Study Properties	Solver type	FFEPlus
	Number of frequencies	6
Volumetric Properties	Mass	22.6314 Kg
	Volume	0.000511006 m ³
	Density: 4428.78 Kg/m ³	4428.78 Kg/m ³
	Weight	221.787 N
	Mesh type	Solid Mesh
	Mesher Used:	Standard mesh
	Jacobian points	4 Points
	Element Size	6.3 mm
	Tolerance	0.315 mm
	Mesh Quality Plot	High
	Total Nodes	201066
	Total Elements	127988
	Maximum Aspect Ratio	11.789
	% of elements with Aspect Ratio < 3	98.5
Mesh Type/Details	% of elements with Aspect Ratio > 10	0.00156
	% of distorted elements(Jacobian)	0
	Time to complete mesh(hh:mm:ss):	00:00:11
Material Properties	Name	Ti-6Al-4V Solution treated and aged (SS)
	Model type	Linear Elastic Isotropic
	Yield Strength	8.27371e+08 N/m ²
	Tensile Strength	1.05e+09 N/m ²
	Elastic modulus	1.048e+11 N/m ²
	Poisson's ratio	0.31
	Mass density	4428.78 kg/m ³
	Shear modulus	4.10238e+10 N/m ²
	Thermal expansion coefficient	9e-06 /Kelvin

Table 7: Modal Analysis - Fixtures.

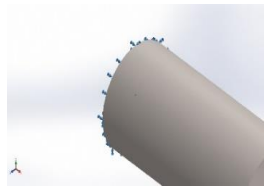
Natural Frequency Analysis - Fixtures			
Fixtures	Fixture details	Name: Fixed 1.	1 face
			Fixed Geometry
		Fixed 1. Image	

Figure 11: Modal Analysis Results

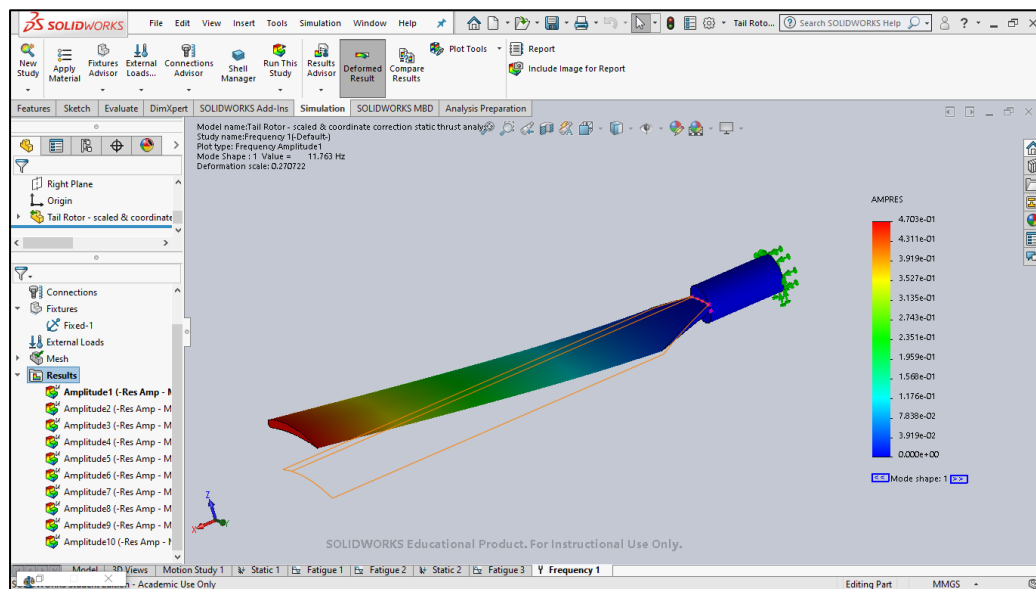


Table 8: Modal Analysis – Results.

Helicopter Tail Natural Frequency Analysis - Study Results			
Name	Type	Min	Max
Amplitude1	AMPRES: Resultant Amplitude Plot for Mode Shape: 1(Value = 11.7893 Hz)	0.00E+00	4.71E-01
		Node: 519	Node: 2336
Amplitude2	AMPRES: Resultant Amplitude Plot for Mode Shape: 2(Value = 56.3946 Hz)	0.00E+00	4.26E-01
		Node: 519	Node: 2336
Amplitude3	AMPRES: Resultant Amplitude Plot for Mode Shape: 3(Value = 77.0659 Hz)	0.00E+00	4.99E-01
		Node: 519	Node: 4
Amplitude4	AMPRES: Resultant Amplitude Plot for Mode Shape: 4(Value = 108.416 Hz)	0.00E+00	8.68E-01
		Node: 519	Node: 2336
Amplitude5	AMPRES: Resultant Amplitude Plot for Mode Shape: 5(Value = 215.307 Hz)	0.00E+00	4.85E-01
		Node: 519	Node: 2539
Amplitude6	AMPRES: Resultant Amplitude Plot for Mode Shape: 6(Value = 327.418 Hz)	0.00E+00	9.26E-01
		Node: 519	Node: 2336

Assuming the tail rotor runs at a constant 1411 rpm, there will not be any interaction or excitement to resonate on any of the six frequencies shown in Table 8 for each degree of freedom. However, through normal power and speed drifts within helicopter flight, which would directly affect the blade passage frequency, it is likely that amplitudes three and four are affected.

4.0 CONCLUSION AND RECOMMENDATIONS

Preliminary evaluation of the provided FE model's geometry highlighted the first obstacle which needed to be overcome during this assignment. The model's geometry and dimensions were unlike any referenceable source found throughout the literature review. After much deliberation, the direction taken involved upscaling the model within the study to a real-world size. Which enabled all readily available data on rotor diameters, velocities and engine power to be directly applied to the upscaled model. Through these parameters, equations were calculated to provide forces which were applied to the FE model to imitate in-service conditions. For this reasoning, many of the calculations are based on dimensional approximations and assumptions. However, all information has been logically reasoned and calculated from referenced sources with the aim to provide reasonable results and useful analytical data.

The static analysis on the FE model involved applying both loads simultaneously for efficiency and to achieve a more realistic loading condition. However, the centrifugal force generated from the helicopter blade rotation, would in real-world applications add to the stiffness of the rotor blade. Unfortunately, this dynamic response would not be calculated within a linear static analysis and is a source of possible error within the study. Another concern regarding the analysis was the FE model material selection, as previously discussed, rotor blades are generally manufactured from composite materials and designed as a hollowed aerofoil. The solidbody titanium FE model had a very high mass, which resulted in an extremely high centrifugal force being applied to the rotor during analysis.

The FE model analysis did however, provide some valuable information in regard to stress concentrations within the design. Regardless of material or loading, these fundamental flaws in the design need to be addressed. Therefore, a recommendation to improve on the design would be to add fillets to eliminate all sharp internal corners and add a radius to all external edges, especially where stress gradients are evident. The curved edges will distribute stress over a greater area and increase the load bearing capacity of the model. Once the FE model has been altered, the analysis should be repeated to determine safety.

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