

Advanced Computational Methods

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1 ABSTRACT

In this work, the aerodynamic forces of a tail rotor system of an Apache helicopter will be discussed. The helicopter model has a perpendicular main rotor to tail rotor design with rigid blades. Static forces such as lift, drag and centrifugal force will be applied to the tail rotor system with results of von Mises stress, displacement and strain will be given and discussed. The natural frequency of 10 modes will be explained in detail to see if there is any frequency that a helicopter produces that may oscillate the tail rotor. The results of the FEA are presented and a conclusion of the credibility of the results is given and the improvements that can be made to produce an accurate model.

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3 INTRODUCTION

In this report, a helicopter tail rotor system will be studied using FEA in Solidworks. The forces that will be applied will be researched and calculated by using geometry and assumptions of the environment that the helicopter will be used in. The results will then be compared to real-life results to see if any similarities can be seen. Recommendations for improvements will be given with an evaluation of the analysis method and possible revisions to the process.

4 RESEARCH

4.1 ANTI-TORQUE SYSTEM (TAIL ROTOR)

The anti-torque system in a helicopter is used to counter the rotational force of the main rotors while engine torque is applied (Leishman, 2006). Newton's third law states that “for every action has an equal and opposite reaction” (Live Science, 2019).

When the torque from the main rotor is increased the amount of thrust that the anti-torque system will need to produce will also increase. This will allow the pilot the ability to control the yaw of the fuselage. As seen in Figure 1 the torque exerted on the fuselage will be in the opposite direction to the rotation of the main rotor blades.

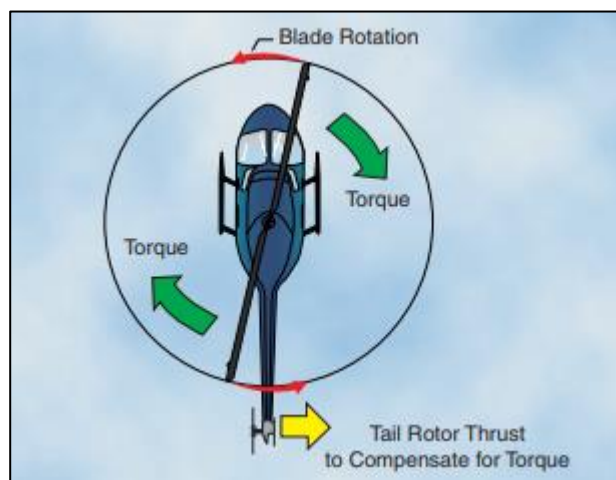


Figure 1 Anti-Torque System Explained

(FAA, 2019)

The thrust produced from the tail rotor will depend on the speed of which the rotors spin and the attack angle of the blades. The tail rotor blades are influenced by many forces such as lift, drag, torque and centrifugal force (Anderson, 2007). These forces must be calculated for the rotor blade due to there being many variables that must be considered.

5 ASSUMPTIONS & EQUATIONS

The test subject to study using FEA will be an Apache helicopter as seen in fig 2.

Due to the torque applied to the tail rotor is a dynamic value and will solely depend on the conditions of the helicopter some assumptions will be made to give a test environment to simulate.

Hovering RPM: based upon the first test flight of the YAH-64 Advanced Attack Helicopter on 30 September 1975 which later become the Apache attack helicopter. The tail rotor had a speed of 1411 rpm (147.76 rad/s) while hovering that day (Boeing, 2019).



The tail rotor tip speed can be calculated $v = r\omega$ *Figure 2 Apache helicopter test subject with tail rotor highlighted*

$r = 0.366m$ and $\omega = 147.76$ Therefore tip speed is 54m/s. Air Density will be calculated at 200m above sea level which is approximately 1.20165 Kg/m^3 (Digital dutch, 2019).

The material of the tail rotor: due to the tail rotor of an Apache helicopter being made of a composite of a stainless steel skeleton, fiberglass skin, and titanium tips (howstuffworks, 2019). It would be difficult to simulate in this

environment so the assumption that the whole rotor assembly is made from 316 stainless steel.

Figure 3 shows the properties of 316 that will be used in the simulation.

Property	Value	Units
Elastic Modulus	1.929999974e+11	N/m ²
Poisson's Ratio	0.27	N/A
Shear Modulus		N/m ²
Mass Density	8000.000133	kg/m ³
Tensile Strength	580000000.8	N/m ²
Compressive Strength		N/m ²
Yield Strength	172368932.3	N/m ²
Thermal Expansion Coefficient	1.6e-05	/K
Thermal Conductivity	16.3	W/(m·K)

Figure 3 316 Stainless Steel Properties SolidWorks

(SolidWorks, 2019)

5.1 DRAG EQUATION

$$F_D = C_D \cdot A \cdot \rho \cdot \frac{v^2}{2}$$

F_D – Drag Force	0.15878 N
C_D – Drag Coefficient	0.045
A – Area	0.002014 m ²
ρ – Air density	1.20165 Kg/m ³ @ 200m
v^2 – Tip Velocity	54 m/s

5.2 LIFT EQUATION

$$F_L = C_L \cdot A \cdot \rho \cdot \frac{v^2}{2}$$

F_D – Drag Force	16.1496N
C_L – Lift Coefficient	0.569
A – Area	0.01624 m ²
ρ – Air density	1.20165 Kg/m ³ @ 200m
v^2 – Tip Velocity	54 m/s

5.3 LIFT COEFFICIENT

$$C_L = 2\pi \cdot \text{Angle of Attack}$$

6 FEA

6.1 LINEAR STATIC ANALYSIS

Linear static analysis is an analysis used in FEA where load and displacement have a linear relation. When an increased load is applied the displacement will have a linear response by increasing (FEA for all, 2017). To use linear static analysis there are several limitations that should be factored in before use. The load applied should not exceed the linear elastic range of the material. After the limit of proportionality is reached the linear solver will carry on in a linear fashion however the material relationship between load and displacement is now in non-linear meaning the results are no longer credible. The stiffness of the material is considered constant throughout the analysis and the material used must obey Hooke's Law (Midas, 2019). The main advantage of this type of analysis is the little computational effort needed. This is a very quick way of studying a structure and can give a good estimation of the outcome. If further analysis is needed due to the stress exceeding the yield point the non-linear analysis can be used but is far more computational heavy but will give far more accurate results. With an understanding of these factors, the linear static analysis will be used in the FEA study of the tail rotor due to the load and displacement being under the yield point and the material obeys hooks law.

6.2 VON MISES (STRAIN ENERGY DENSITY)

The von Mises stress is a scalar quantity which is used to calculate if a material will yield or fracture in a given environment. It measures all three principal stresses components in a 3D state and is commonly used for ductile materials such as metals and is widely used in FEA analysis (Kurowski, 2012). The von Mises stress of a material under a given load must not be equal to nor greater than the yield limit of the material in tension (Simscale, 2019). The von Mises stress will be used in the FEA study due to the material being ductile and it can predict the complex loads being applied.

6.3 MESH & ELEMENT SIZE

Mesh is the term described to the division of the model into small pieces called elements that are solved using equations. Defining the size of the mesh is a balance of accuracy of study and computing time (Liu, 2013). The finer the mesh size the more accurate the study will be, however having a finer mesh will consume far more computing power than a coarser mesh (Dassault, 2017). Often high-stress levels occur at corners areas so it is vital the mesh is fine enough to capture the distribution of stress (GSC, 2017). The mesh size of the tail rotor was determined incrementally, a 2mm mesh size was deemed to give accurate enough results with good solve time. The mesh gave 613,684 nodes and 387,761 elements with a mesh time of 51 seconds (Solidworks, 2019).

6.4 CENTRIFUGAL FORCE

Centrifugal force is the force that applies to an object viewed in a rotating frame of reference that is directed away from the axis (Weidner & Sells, 1973). As the rotor blade will be rotating around an axis centrifugal force will be applied. Knowing the rotation angular velocity of the blade, Solidworks is able to calculate the stress, displacement, and strain from the centrifugal forces.

The centrifugal force is applied to the center of the rotor on the cylindrical face at an angular velocity of 147.8 rad/s as seen in Figure 4 Applied Centrifugal Force.

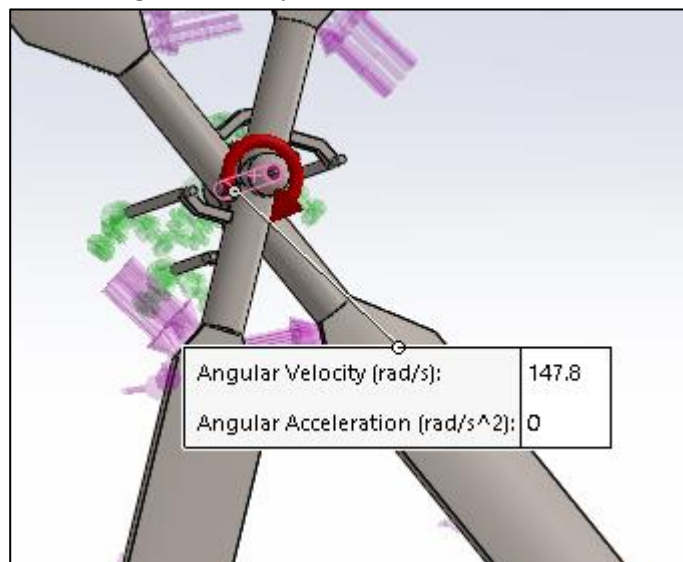


Figure 4 Applied Centrifugal Force

6.5 DRAG

Drag is the amount of force applied in the opposite direction of motion due to the motion of any object moving with respect to a surrounding fluid in this case air resistance (Anderson, 2007). Drag will be applied to the model due to the tail rotor motion through the air. The drag will be calculated using the

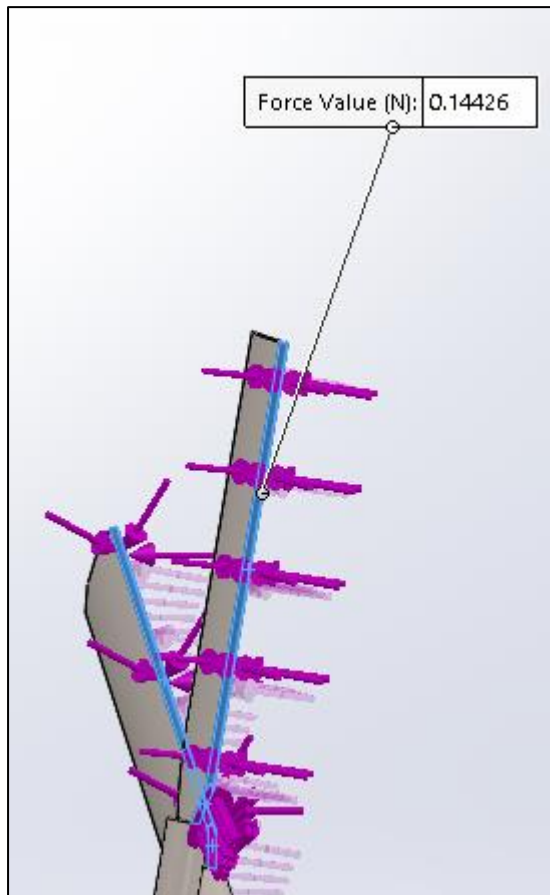


Figure 5 Applied Drag Force

formula seen in section 5.1. The drag coefficient will be assumed based upon NASA's report of the shape effects on drag which assumes that an airfoil of similar shape to the rotor blade has a coefficient value of 0.45 (NASA, 2014).

The drag force of 0.14436 N will be applied to the leading edge of the rotor blade due to that being the edge that will be the edge that is most affected. An assumption will be made that there will be only air resistance and no wind resistance acting upon the rotor this meaning that the drag coefficient will remain a constant throughout. Furthermore, velocity and air density will remain constant

6.6 LIFT

Lift is a component of the force that is applied when an object passes through a fluid and acts perpendicular to the fluid flow (NASA, 2008). Lift is usually calculated experimentally in a wind tunnel or using computational fluid dynamics. However, it can be calculated mathematically using the lift equation 5.2 but the coefficient of lift must be calculated. NASA states that thin airfoils at a small attack angle the lift coefficient can be calculated using equation 5.3 (NASA, 2018). The angle of attack

is measured to be 5.19 degrees, therefore, the coefficient of lift will be 0.569. The lift force applied will be 16.1496N. The lift force will be applied to the underside of the blade as seen in Figure 6. The assumption will be that the velocity and air density will remain

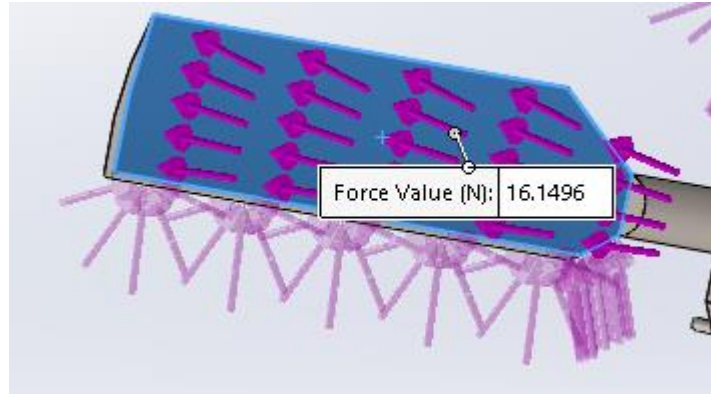


Figure 6 Applied Lift Force

constant values and neglect the lift force from the rotor arm due to the lift coefficient equation is based on thin airfoils.

6.7 FREQUENCY

Natural frequency is the rate that a system oscillates without any driving force or damping. Each degree of freedom of an object will have its own natural frequency (Zhao, et al., 2018). It is important to understand the natural frequency of a system to ensure that the operational task does not cause the system to oscillate and fail (Blevins, 1998). The rotor blade will be studied in 10 modes of frequency. 1-6 modes will be the six degrees of freedom, 6-10 will be first-order torsion, first-order bending, second-order torsion, and second-order bending respectively. By increasing the modes of frequency it gives a greater range of oscillation frequencies that may occur so changes in geometry and material can be made to ensure that no system will be affected by the frequency (Khaksar, et al., 2016).

6.8 FIXED GEOMETRY & CONNECTION

To analysis, such forces and parts of the rotor blade must have fixed geometry so give a better representation of results. The rotor blade will be fixed on the rear of the rotor system as seen in Figure 7. The rotor struts which control the angle of attack were also fixed. A bearing connection was added for the frequency study to give a better real-life frequency of the model.

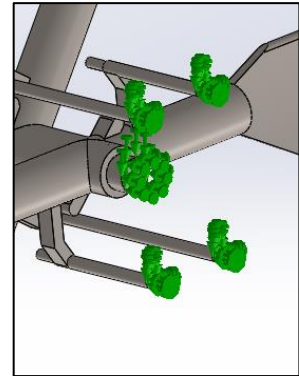


Figure 7 Fixed Geometry of Rotor Blades

7 RESULTS & ANALYSIS

The static analysis of the three forces previously mentioned was calculated with three defining results.

Von Mises Stress, displacement, and strain.

7.1 VON MISES STRESS

As spoken about previously it is imperative that the von Mises stress must not exceed the plastic range of the material or yield limit. The results of the study were that the highest stress concentration of the study did not exceed the limit seen in Figure 8. This gives an indication that the linear static analysis and von Mises stress will give a true representation of results. The stress seen at the corner of the blade was 116 MN/m^2 and as previously stated the yield limit of the material is 172.36 MN/m^2 . However, a factor of safety must be considered. NASA deems an ultimate factor of safety of 1.5 for aerospace and spacecraft (NASA, 2014). On the basis of that safety factor, the stress seen in Figure 8 exceeds the ultimate safety factor, therefore, it is not acceptable.

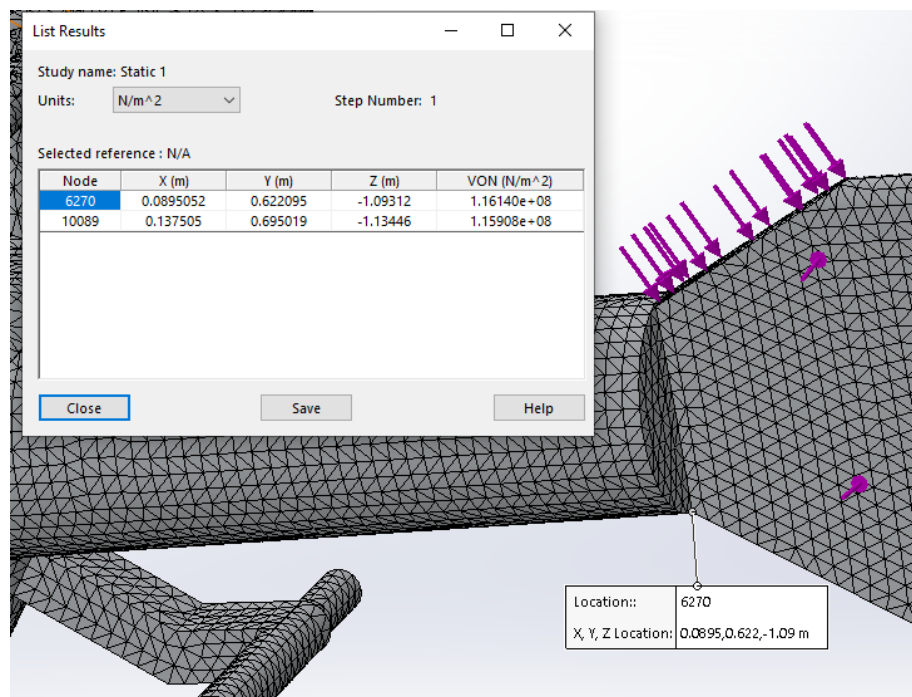


Figure 8 Stress Concentration

7.2 DISPLACEMENT

The results of the displacement of the tail rotor under load were relatively low. Over the span of the blade, there was a maximum displacement of 0.814mm at the tip of the blade. The location of the maximum displacement was expected due to it being the longest distance from the central axis thus having, will have the most force applied. Based upon the von Mises stress given it can be said that the displacement seen in the results will be within the elastic range in the material and thus return to its natural form once forces are removed. This is a clear indication that the material obeys Hooke's law and has a direct relationship to the stiffness of the material. The amount of acceptable displacement is hard to define without further FEA analysis and CFD to incorporate other factors.

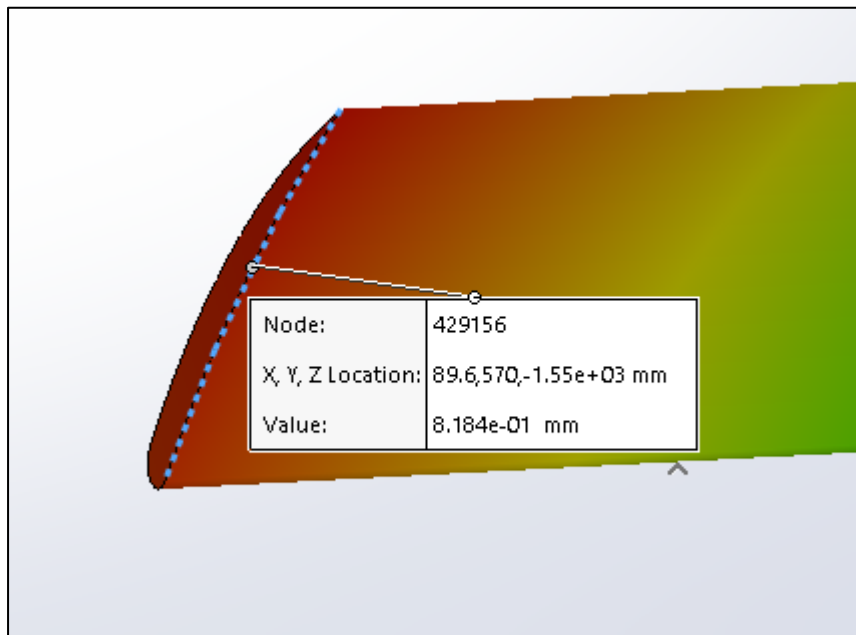


Figure 9 Maximum Displacement

7.3 STRAIN

The maximum strain that the rotor blade is 4.255×10^{-4} and is located at the edge of the blade and rotor arm seen in Figure 10. As seen in 7.1 the maximum stress and maximum strain occur at the same location. This is as expected due to the material stiffness being fixed value throughout (Roylance, 2001). Also, direct stress and strain have a directly proportional relationship inside the elastic limit.

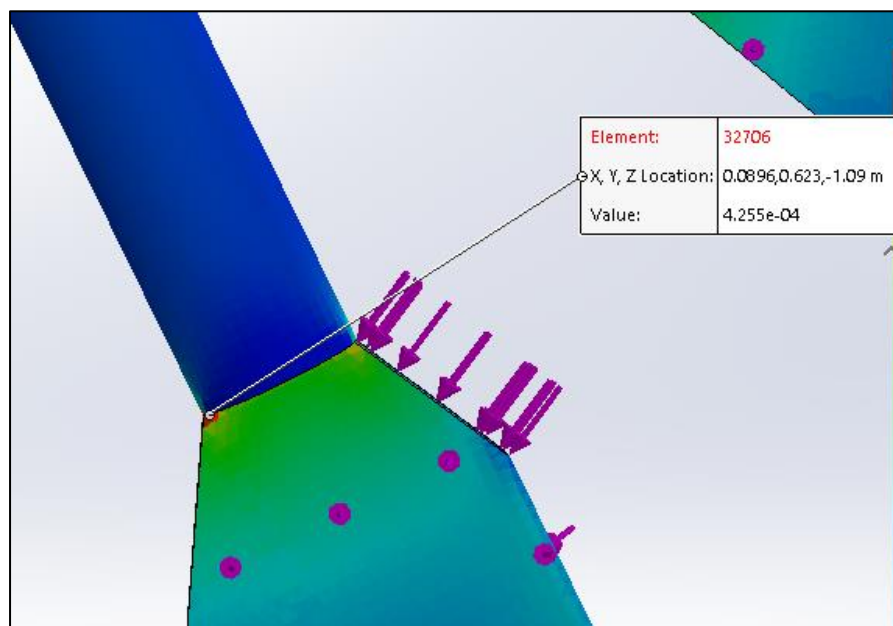


Figure 10 Maximum Strain

7.4 FREQUENCY

As seen in table 1 of each mode of natural frequency has been calculated and the hertz of which it gets excited and starts to oscillate is defined. Frequency analysis is an essential FEA of a helicopter, due to there being many systems that cause frequency and have a wide range of frequencies. The FAA expresses that the main rotor is commonly low frequency, the engine and tail rotor tends to be high frequency (FAA, 2019). To better understand the results of this it needs to be compared to vibration analysis of a helicopter to see if any frequency will cause oscillation. In an experiment by (Stupar, et al., 2012) a vibrational analysis was carried out in flight to see if defects could be identified in flight. In table 2 the result of the experiment is shown, it can be seen that there is a wide range of low range frequencies some of which are very close to the frequencies in Table 1. This could lead to possible oscillation if not correctly damped or failure. As the tail rotor as one of the main system which produces vibrational frequency then these frequency results should be carefully analysed and precautions should be put in place to reduce the effect. To stop or reduce the likelihood of such oscillation occurring a damping system should be put in place this will stop the frequency from the tail rotor system affecting other systems and vice versa.

Table 1 Modes of Frequency

Frequency Number	Rad/sec	Hertz	Seconds
1	274.41	43.674	0.022897
2	285.33	45.411	0.022021
3	288.91	45.981	0.021748
4	289.05	46.003	0.021738
5	531.4	84.575	0.011824
6	1027.6	163.54	0.0061147
7	1049.1	166.97	0.0059891
8	1105.2	175.9	0.0056851
9	1564.9	249.07	0.0040149
10	1779.2	283.17	0.0035314

Table 2 Vibration Analysis Experiment

Profile of flight	V [km/h]	f [Hz]	Ch 1 [g RMS]	Ch2 [g RMS]	Ch 3 [g RMS]
Hover (H=10 m)	0	19.35	<0.0015	<0.0015	<0.0015
		38.70	0.0032	0.0059	0.0061
		58.05	<0.0015	<0.0015	<0.0015
		60.45	0.0074	0.0098	0.0106
		77.40	<0.0010	<0.0010	<0.0010
Vmax	240	19.35	0.0087	0.0050	0.0044
		38.70	0.0112	0.0186	0.0211
		58.05	0.0104	0.0213	0.0241
		60.45	0.0062	0.0091	0.0100
		77.40	0.0058	0.0243	0.0302

(Stupar, et al., 2012)

8 CONCLUSION

To conclude there are some fundamental issues with the FEA of the rotor blade which could deem this analysis uncreditable. The structure and material of the rotor blade, a rotor blade is an assembly of many different components comprising many different materials, with each component giving a characteristic needed. An alloy frame for strength, a composite skin for weight reduction, titanium tips for impact resistance is some of the components that a blade would be made with. The model which the FEA used was a solid body comprising of one material and the assumption made that it was comprised of 316 stainless steel was not adequate enough to give a true representation of results.

Forces applied to the rotor in the FEA was not a true representation of the forces applied to a real rotor blade. The main force that the rotor blade produces is thrust which keeps the fuselage from rotating is impossible to simulate without the use of CFD or knowing the main rotor output power or torque.

The use of linear analysis, element size and order could also have a questionable effect on the results of the analysis. Firstly linear analysis is vital for quick computational analysis for such a model. However, the von Mises stress results seen in section 7.1 are close to the elastic modulus limit when a safety factor is considered. This should be a concern as explained in section 6.1 and non-linear analysis should be carried to ensure that there is no concern of failure. Secondly, element size should be further reduced to give a better representation of the stress concentrations and the location. This could allow for geometry changes in the design such as removing straight edges on high-stress points and replace with fillets and radii. Thirdly, the element order should be revised from linear solid elements to parabolic solid elements. This will give far more accurate results due to the curved boundaries which in turn give a better mathematical approximation, however, with the change in order far more computational resources are needed (Solidworks, 2019).

The frequency analysis could be deemed useful if the correct assembly of the model is used. It has given a good indication of the natural frequencies that will excite and oscillate the tail rotor and precautions put in place help reduce such occurrences.

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