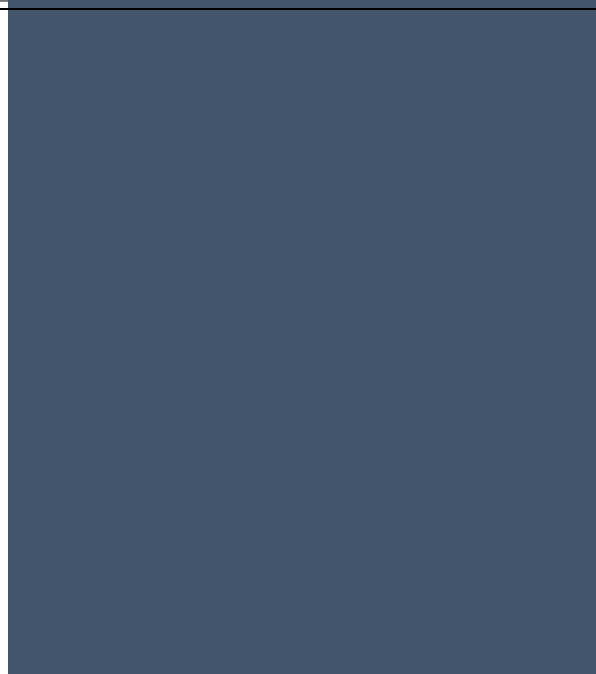




BEng Engineering

Advanced Computational Methods

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Executive Summary:

The helicopter is an indispensable but unique means of transportation. During flight, the tail rotor is exposed to forces and frequencies that affect the structural integrity of the rotor blade. Therefore, the use of FE analysis in the design and testing of the tail rotor can be beneficial in evaluating its performance. This report will discuss and identify the essential forces and loads experienced during helicopter flight. It discusses the fundamentals of a FE analysis and model considerations. A suitable FE study of the tail rotor was developed to replicate the nature of stress loading. The FE methodology evaluates the tail rotor via a linear static and frequency study. The results of the study identified areas of stress concentrations and natural frequencies. The results were clearly advantageous but limited by the software's ability to analyse complex material arrangements.

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1 Introduction

Helicopter flight is a complex arrangement of engineering principles including aerodynamics, mechanical and structural forces. According to (Fletcher & Brown, 2008) the fundamental theories and complex forces involved make analysis a complicated quandary. To understand the basic aerodynamics of flight we must first consider four basic forces: - Thrust, drag, lift and weight (FAA, 2019).

Table 1 - Principle forces of aerodynamic flight (Vandeveld, 2011)

Force	Description
Lift	opposes the downward force of weight, is produced by the dynamic effect of the air acting on the air foil and acts perpendicular to the flightpath through the centre of lift.
Weight	the combined load of the aircraft itself, the crew, the fuel, and the cargo or baggage. Weight pulls the aircraft downward because of the force of gravity. It opposes lift and acts vertically downward through the aircraft's centre of gravity (CG).
Thrust	the force produced by the power plant/ propeller or rotor. It opposes or overcomes the force of drag. As a general rule, it acts parallel to the longitudinal axis.
Drag	a rearward, retarding force caused by disruption of airflow by the wing, rotor, fuselage, and other protruding objects. Drag opposes thrust and acts rearward parallel to the relative wind (FAA, 2019)

According to Newton's Third Law: "for every action there is an equal and opposite reaction". So, as a consequence of the engine creating thrust/lift and overcoming weight/drag, the fuselage is subjected a substantial torque see Figure 1. This torque or antitorque is the result of the engine turning the rotor anticlockwise, forcing the fuselage to turn clockwise. To alleviate this, helicopters are designed with an antitorque/tail rotor which provides an opposite force outside of the central axis of the helicopter. In addition to this, it enables control of direction or (yaw) (Fletcher & Brown, 2008). The yaw or torque is controlled by the pilot using anti-torque pedals. As the main rotor power/torque is increased the tail rotor must produce more thrust to overcome the increased fuselage torque (FAA, 2019).

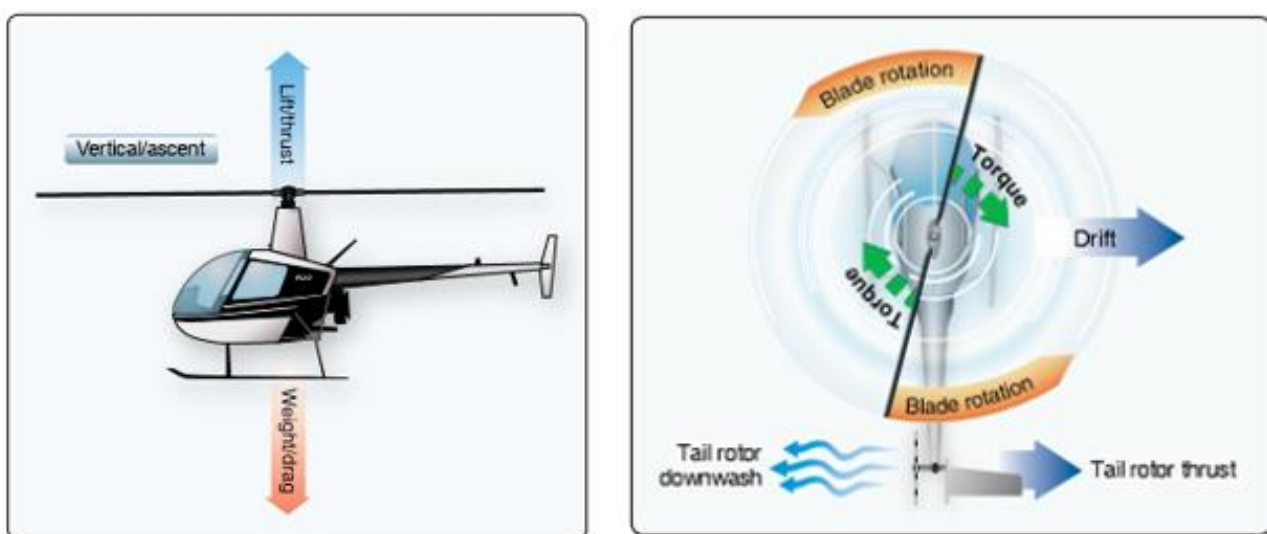


Figure 1 -Diagram of four basic principles and the resultant torque produced (FAA, 2019)

According to (Vandeveld, 2011) in addition to considering the four fundamental forces, a helicopter rotor is subjected centrifugal/centripetal force. Centrifugal/centripetal force are the opposite and opposing forces what control an items distance from the centre of rotation (FAA, 2019). A consequence of centrifugal/centripetal force is the coning effect of rotor blades. This coning effect is detrimental to helicopter flight as it reduces the rotor disk area and reduces lift. (Vandeveld, 2011) describes the “quadratic relation between lift and speed, and drag and speed, the lift/drag increases quadratically with respect to the distance to the center”

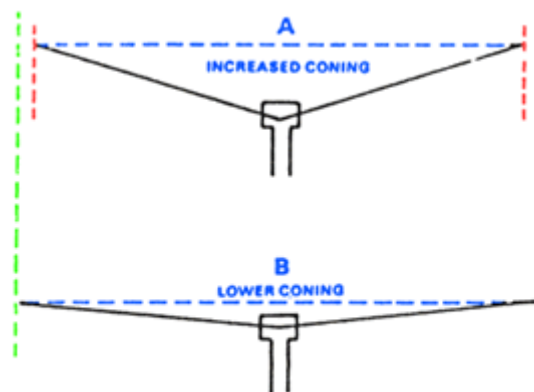


**FIGURE 2-30. LOSS OF DISK AREA
DUE TO CONING.**

*Figure 2 - Reduced rotor disk area due to coning
(Pilotfriend, 2019)*

Vibration and natural frequency analysis are a critical function of helicopter design. The relationship between vibration caused by rotating components and natural frequency can have devastating effects. According to (Robins, 2010) interaction between main and tail rotor vibration have resulted in entire tail sections failing in flight. This was the result of forced and natural frequency interaction, this potential infinite response is referred to as resonance (Heffernan, Precetti`D, & Johnson , 1991) (Halfpenny & Walton, 2009) describe the primary triggers for helicopter vibration as main/tail rotor, engine and air load. The biggest amplitude of vibration is caused by the main/tail rotors or blade passing frequency (BPF), this can be calculated by using $Rpm \times Number\ of\ Blades / 60$. This amplitude is a result of the periodic forces generated by a rotor (Maia, Neves, & Sampaio, 2013).

<http://www.vibrationdata.com/apache.wav>

2 Technical Specifications

The Apache AH-64 first flight was in 1975 and was designed for tough combat situations. This required it be capable of high speed, high manoeuvrability whilst carrying army personal and heavy artillery (Boeing, 2019). The technical specifications of the Apache AH-64 can be seen in Table 2 below.

Table 2 - Apache AH-64 technical specification

Apache AH-64 Attack Helicopter (Boeing, 2019) (Swopes, 2019)	
First Flight	Sept 30 1975
Model number	AH-64
Rotor Diameter	48ft - 14.83M
Rotor RPM	289rpm
Rotor Tip Speed	726.36 ft/s – 211.7m/s
Tail Rotor Diameter	9ft2 - 2.79M
Tail Rotor RPM	1411rpm
Tail Rotor Tip Speed	727.09ft/s – 221.62m/s
Length	49ft5 – 15M
Distance between rotors	29ft5 - 8.943M
Height	15ft3
Ceiling	21000ft
Range	260 miles
Power	Two 1900 HP GE T700 Turbo Engines
Top Speed	192Mph
Weight -Unladen	5165kg
Mission	8006kg
Max Laden	10433kg

3 Assumptions and Substitutions

To accurately simulate the rotor performance in different testing scenarios, an accurate representation of the forces, rotor dimensions and material characteristics are critical. The SolidWorks rotor model doesn't conform to known dimensions investigated within section 2. For consistency between the calculated forces and part dimensions, I've chosen to scale up the rotor by a ratio of 4.1:1. The part is now 1395mm in length. The helicopter rotor is stereotypically a composition of various materials, these can include titanium, steel and carbon fibre (FAA, 2019). (Rasuo, 2011) describe the high-performance of composite rotors is advantageous due to its high strength/stiffness, low density and good fatigue/corrosion resistance. As SolidWorks is a linear solver, carbon fibre doesn't conform to the stress strain linear relationship used in solid works static analysis. Carbon fibre has no plastic deformation properties and at failure the material is susceptible to delamination. Consequently, within SolidWorks simulation there is no option to use carbon fibre, so I've chosen to use Titanium due its isotropic characteristics see Figure 3 for material data .

Name:	Titanium Ti-13V-11Cr-3Al Solution Treated
Model type:	Linear Elastic Isotropic
Default failure criterion:	Max von Mises Stress
Yield strength:	8.3e+08 N/m ²
Tensile strength:	9.9e+08 N/m ²
Elastic modulus:	9.9e+10 N/m ²
Poisson's ratio:	0.3
Mass density:	4820 kg/m ³
Shear modulus:	4.3e+10 N/m ²
Thermal expansion coefficient:	9.67e-06 /Kelvin

Figure 3 – Material data used within simulation

Due to the complex nature of forces involved, I will simplify my analysis and consider the above technical information to calculate values to be used within the simulation. I will calculate the max torque of the main rotor, the opposing force required by the tail rotor and the centrifugal force. These calculations have assumed 100% main rotor power, but tail power typically varies from 5-30% (Fletcher & Brown, 2008) The resultant force on the tail rotor is consistent with results generated by (Figueira, Cruz, & Andrade, 2010) of F1150N tail rotor thrust for a helicopter of 2200kg.

Main Rotor	$P = T\omega$ $\therefore T = P/\omega$
Rpm - 289 = 30.26rad/s	$T = \frac{2833660}{30.26}$ $T = 93644Nm$
HP - 3800 = 2833.66KW	
Tail Rotor	$T = Fr$ $\therefore F = T/r$
Rpm – 1411 = 147.76rad/s	$F = \frac{93644}{8.9}$ $F = \frac{10522}{4}$ $F = 2630.5N$
Rotor to Tail Rotor Radius – 8.9m	

Table 3 - Simulation calculations

(Cantrell, 2019) states that a helicopter can generate over 40 tons or 392266N of centrifugal force on each main rotor. Below are figures calculated for centrifugal force, it uses a combination of data from SolidWorks and Table 2. The material has been substituted from a composite to titanium, the result is a component weighing 28kg and force of 853259N.

1411 rpm = 147.8 rad/s or 23.51hz	$F_c = m\omega^2 r$
Rotor Mass = 28kg	$F_c = 28 \times 147.8^2 \times 1.395$
Tail Rotor Radius = 1.395	$F_c = 853259$

Table 5 - Centrifugal force calculations

According to (Irvine, 2003) the tail rotor has the greatest vibration effect due to being forced through the air sideways. The apache has a special blade arrangement of 125/55 degrees to improve efficiency see Figure 4, the result is BPF for the tail rotor is calculated considering just two blades see Table 4/Figure 5.

Helicopter Frequency	My Calculations	Research Calculation (Irvine, 2003)
Main Rotor (BPF) RPMx4/60	289x4/60 = 19.26hz	Integer harmonics 21 Hz. 43, 62, 84, 105 Hz
Tail Rotor (BPF) RPMx2/60	1411x2/60 = 47hz	Integer harmonics 51 Hz, 102, 153, and 204 Hz.

Table 4 - Vibration frequency calculations

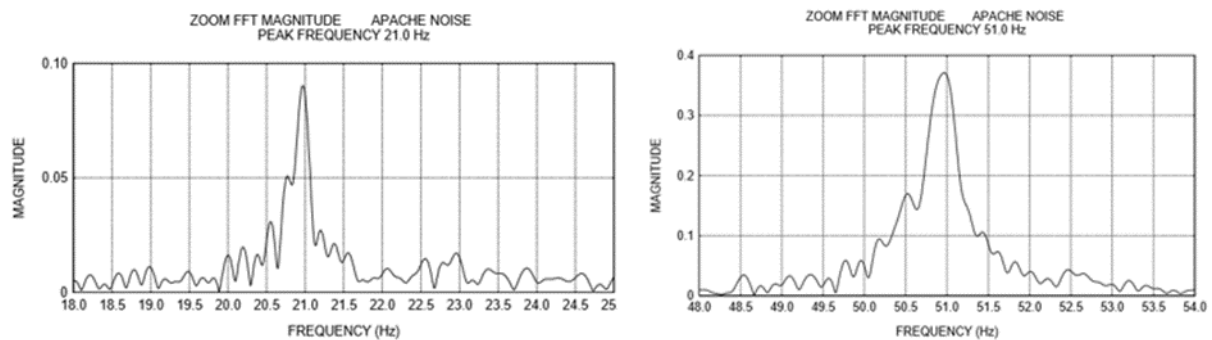


Figure 5 – Graphical representation of main/tail rotor frequencies (Irvine, 2003)



Figure 4 - Apache tail rotor arrangement

4 Analysis Methodology

FEA analysis when implemented with the appropriate knowledge can be a very powerful design/analysis tool. For this report it has been decided to analyse the rotor in two different scenarios, linear static and natural frequency. FEA analysis must consider numerous variables to provide an accurate analysis, these include mesh size, element type and stress measurement.

4.1 Mesh Refinement

According to (Comsol, 2019) an FEA study's accuracy is directly proportional to the finite element mesh. The mesh is defined to split the model into elements which are calculated individually. It is commonly considered that a small mesh is more accurate, but small mesh sizes require complex calculations. A standard practise within analysis is to start with a coarse mesh and begin the process of mesh refinement. Each result is plotted on a graph where the solution will converge in-line with mesh refinement (Comsol, 2019).

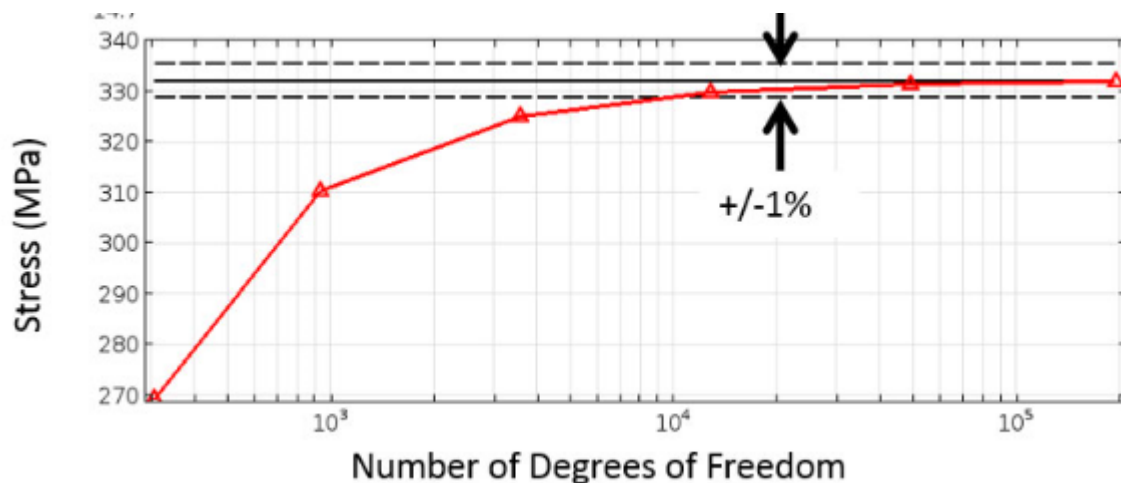


Figure 6 - Example plot for solution convergence (Comsol, 2019)

Figure 6 displays a typical convergence plot. Where the line levels out, there is +/- 1% error between stress results. Further to this, (Lake, 2019) describes the need for further mesh refinement at localised areas of increased stress. So, element concentration at areas of high stress is clearly advantageous. There several methods for localised mesh refinement within SolidWorks. This can be done manually using mesh control or via the software using adaptive meshing or the stress hot spot function.

4.2 Element Selection

According to (Dassult Sytems - Solidworks, 2019) the selection of node or element stress, can allow for a different interpretation of stress within a component. Nodal and element analysis use different arithmetical techniques, typically nodal is referred to as averaged and element a non-averaged stress. (Cati, 2019) describe the true representation of stress using element as opposed to the average/diluted nodal stress.

4.3 Von mises – Principal Stress

There are numerous stress, strain and displacement values that can be calculated within Solid works analysis. Typically, Von mises is used within Solid works as it combines the principal forces in the X/Y/Z axis to assess failure. If the stress falls outside the ellipse created by distortion energy theory used in von mises, it is deemed a yield failure Figure 7 . Von mises is non direction whereas principal stresses are measured about the co-ordinate axis. The first principal stress could be of advantage within this study for its ability to define max tensile stress of the rotor when subjected to the antitorque thrust.

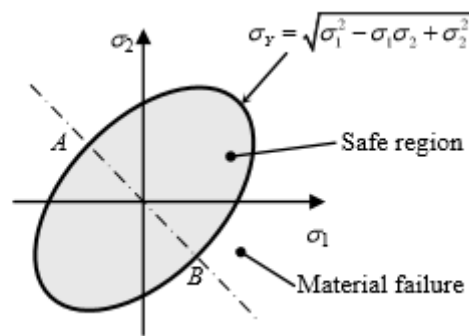


Figure 7 - Failure envelope of the distortion energy theory

5 Tail Rotor FE Analysis

In this section, FE models have been created for static and natural frequency studies. The forces acting on the tail rotor are simulated using CAE software.

5.1 Static Analysis

The static study combines centrifugal and anti-torque forces acting on the tail rotor. The study was developed using the forces calculated in section 3. The FE model has defined fixed boundary conditions at the end of the rotor, this is to simulate the rotor attachment. The fixed geometry function provides an infinitely stiff, 6-degrees of freedom on the diameter face. The anti-torque force was distributed underneath of the rotor to simulate the force required to counteract the torque created by the main rotor. The vertical force vectors are shown in Figure 8. Instead of using the centrifugal force tool, a remote load was used in its place. This was applied from the rotors centre of mass, in direction of the z axis. To allow for the correct force direction the rotor was re-orientated to align with the z coordinate axis - Figure 8.

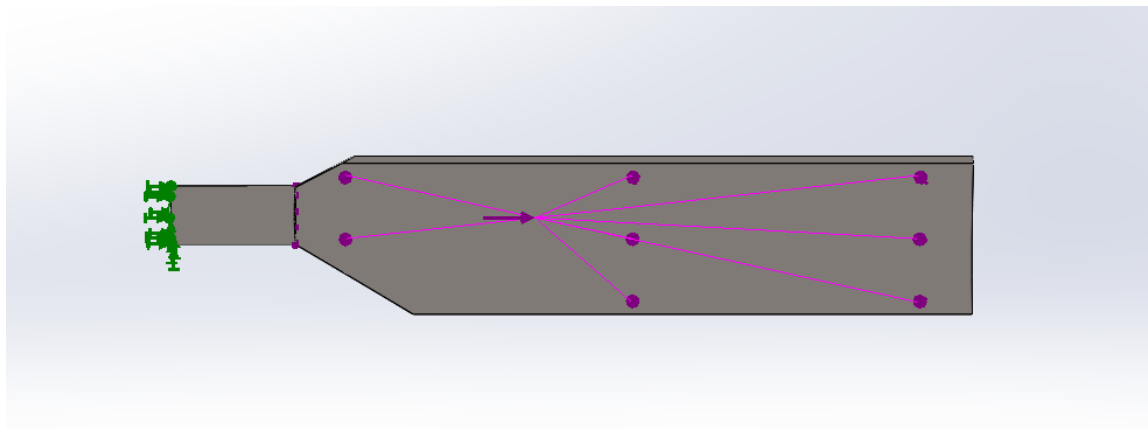


Figure 8 – Rotor static analysis

For an initial compromise between time and accuracy, a coarse 30mm mesh was implemented. The mesh size was refined as shown in Figure 9. As the mesh was refined, the stress plot was expected to converge, as in Figure 6.

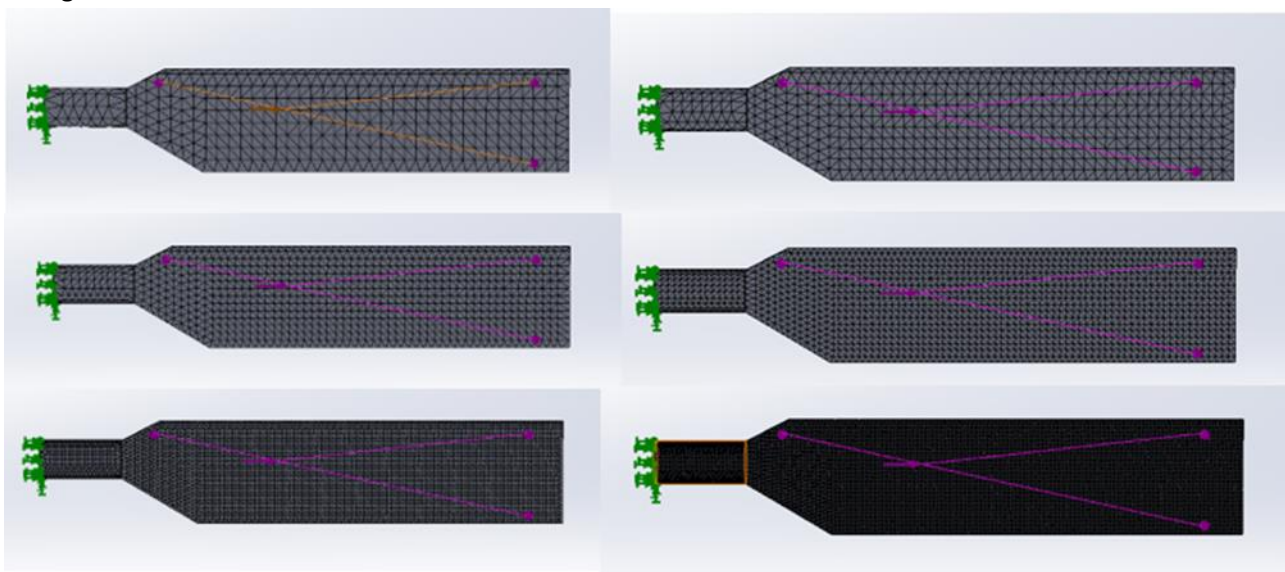


Figure 9 - Mesh refinement - 30/25/20/15/10/5mm

It soon became evident the results were continuing to diverge, Figure 10, iterations 1-6. The divergence of stress can potentially indicate a stress singularity. According to (Dassult Systems - Solidworks, 2019) a singularity is a point where stress values continue infinitely regardless of mesh allocation. This is typical of stress values at sharp/point corners and contact features. Once a potential stress singularity is identified, mesh sizes must be locally refined to identify the effect of the singularity. If it is a true stress singularity, (Kurowski, 2014) states “smaller the element, the higher the stress”. Figure 10, iterations 7-8, are manually altered mesh size combinations, localised to the sharp edges of high stress values, see Table 3.

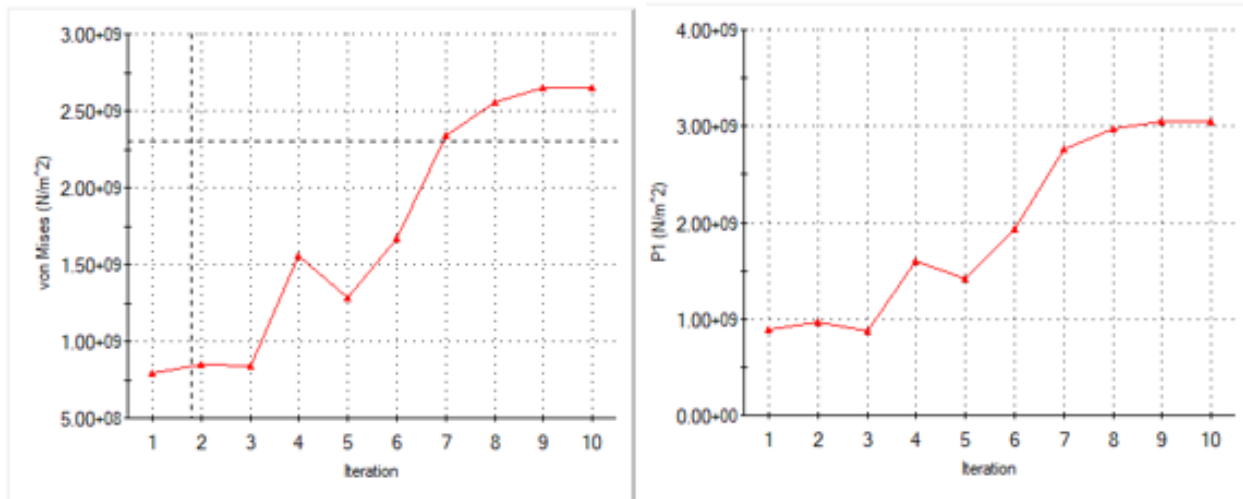


Figure 10 -Plot of static analysis results

SolidWorks has several tools to aid mesh refinement when standard procedures do not produce expected results. Iterations 9-10 are values generated using the SolidWorks H-adaptive function, according to (Lake, 2019) H-adaptive is an automated mesh tool that checks and adjusts mesh size automatically. It aims to achieve a disparity of less than 2% in stress/strain energy. Iterations 8-10, demonstrate stress convergence; this is a result of H-adaptive mesh values refining to 0.0024mm at the localised sharp boundaries, Figure 11.

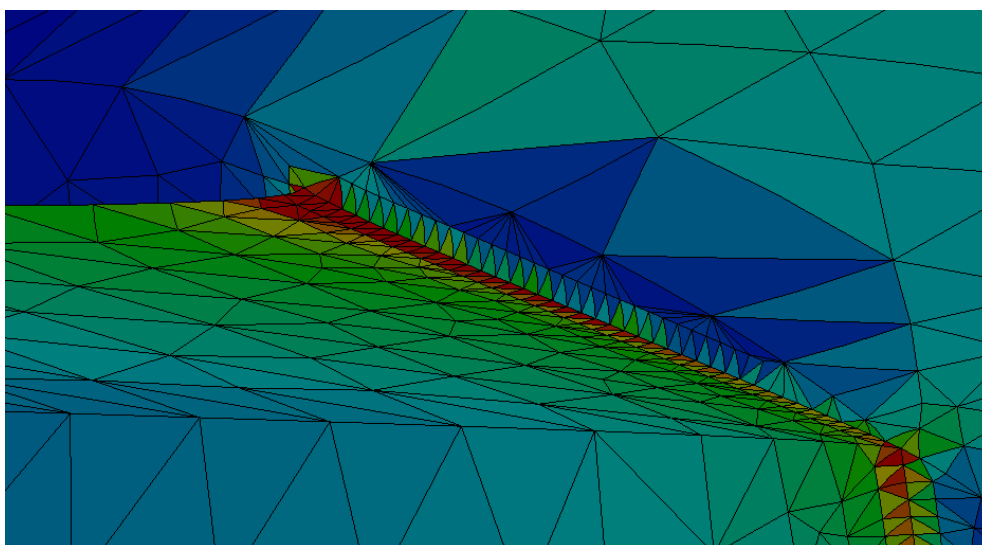


Figure 11 - H-adaptive localised mesh refinement

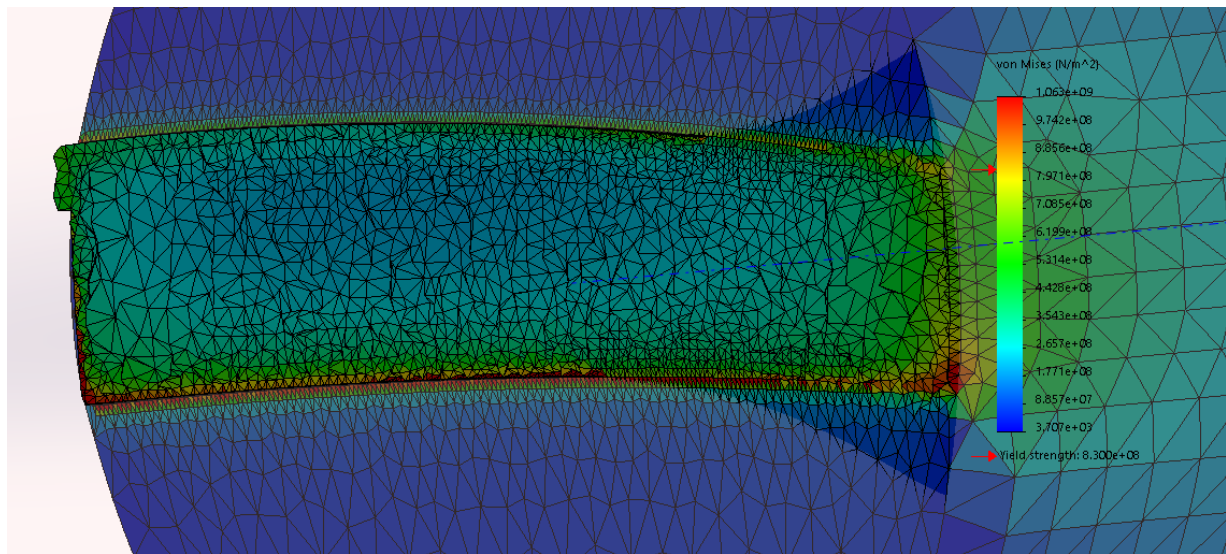


Figure 12 - Section view through area of stress concentration

Figure 11/Figure 12 establish red stress elements at boundary locations, these significantly exceed the material yield. These red elements suggest either stress concentrations or potential stress singularities due to the location. SolidWorks has a stress hot spot function which isolates stress singularities from the part boundaries, enabling a better understanding of max stress values. Figure 13, is the result of the stress hot spot function, the number of red elements has fallen dramatically in comparison to Figure 11

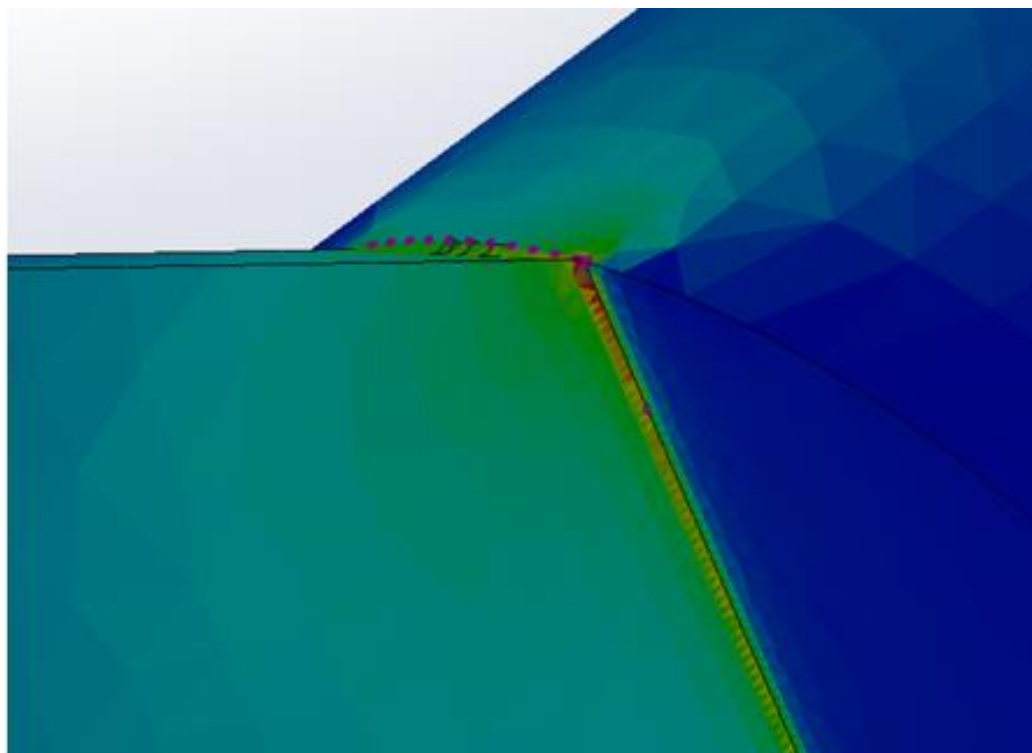


Figure 13 - Stress hot spot result

5.1.1 Analysis Results

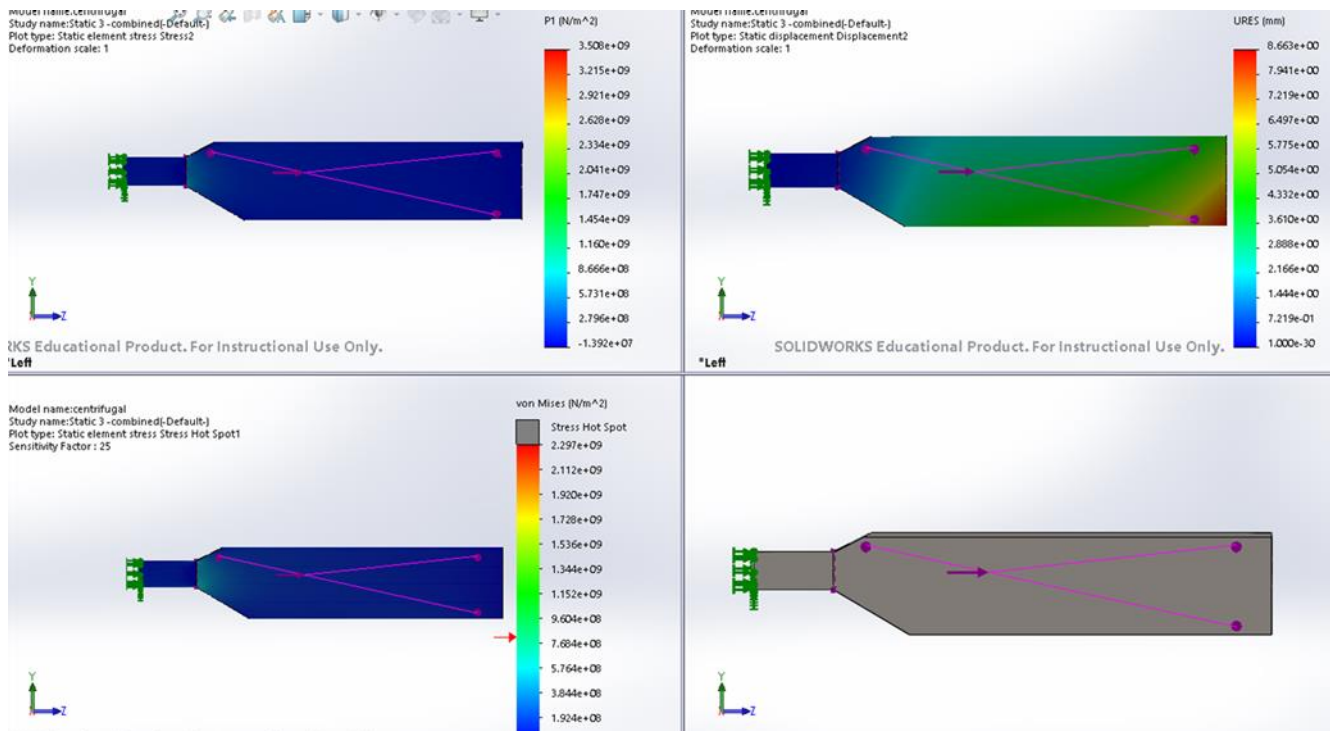


Figure 15 – Analysis results for Principal/Von-mises/Stress hot spot

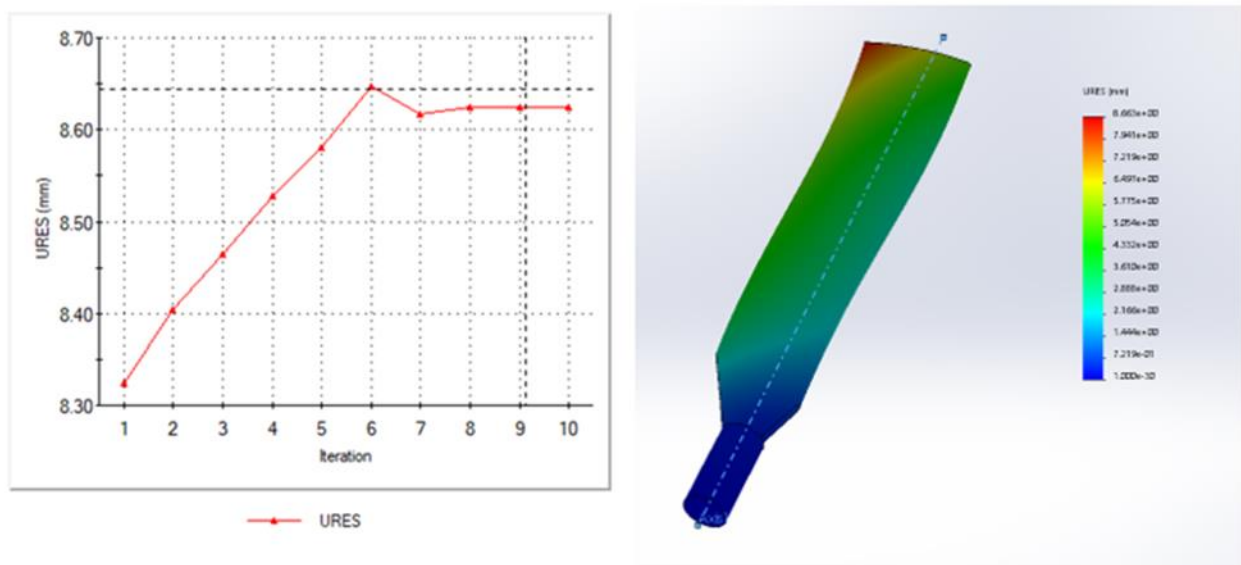


Figure 14 -Static analysis displacement plot

Figure 14 is a display of results for principal stress (3.04×10^9), Von mises (2.65×10^9) and the stress hot spot function (2.29×10^9). Whilst all are above the yield stress of Titanium 8.3×10^8 , the different simulation functions have eliminated singularities and identified areas of highest stress. Figure 15 depicts the displacement resulting from the loading combinations used within the study. Total displacement is 8.62mm and increases along the rotor length as expected. The measurement of displacement is in URES which an averaged displacement in the three principal axis and as a result can only be an indicator of the rotor displacement.

Mesh Plot	30 1	25 2	20 3	15 4	10 5	5 6	10>2 7	10>1 8	H-Adapt 9	H-Adapt 10
Time	00.09	00.13	00.19	00.42	01.35	08.48	02.21	02.31	02.31	02.32
Nodes	4,787	7163	12940	78516	67283	433669	83959	100879	100919	151219
Elements	2310	3581	6993	26328	40057	284777	51008	61619	61650	75360
DOF's	14190	21279	38547	78516	200781	1297077	250809	301569	301689	352630
Von Mises N/m2	7.83E+08	8.49E+08	8.39E+08	1.54E+09	1.28E+09	1.67E+09	2.34E+09	2.55E+09	2.64E+09	2.65E+09
Principal N/m2	8.75E+08	9.66E+08	8.75E+08	1.55E+09	1.41E+09	1.93E+09	2.74E+09	2.97E+09	3.03E+09	3.04E+09
Displ mm	8.32	8.4	8.46	8.53	8.58	8.65	8.62	8.63	8.63	8.62

Table 6 - Static analysis results.

5.2 Natural Frequency

FE modal analysis's ability to determine natural mode shape and frequency for arbitrary shapes is vital when evaluating components suitability within a system. The FE systems use the equations associated with eigensystems; the eigenvalues/vectors are used to depict the frequency/mode shapes. Typically the lowest frequencies dictate the harmonics of higher frequency modes, as a result the first 6 are the most common (Heffernan, Precetti`D, & Johnson , 1991).

This frequency study of the tail rotor will evaluate natural frequency and modal frequency using the forces calculated in section 3. The FE model has defined fixed boundary conditions at the end of the rotor, this is to simulate the rotor attachment. The model was meshed using the experience gained during the static test. Figure 16/**Error! Reference source not found.** below displays the natural frequency modes 1-4 and

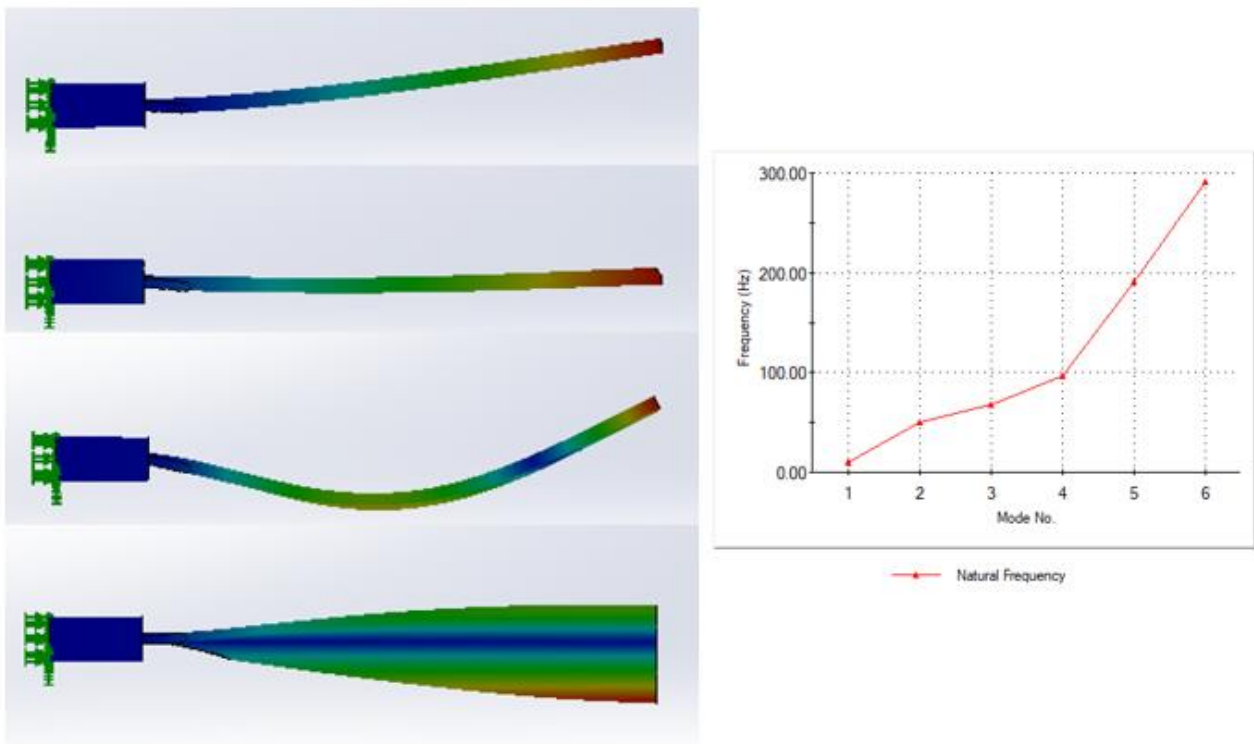


Figure 16 - Natural frequency results

frequency plot 1-6.

Mode No.	Frequency (Rad/sec)	Frequency (Hertz)	Frequency (Rad/sec)	Frequency (Hertz)
1	65.467	10.419	240.59	38.29
2	313.46	49.888	378.39	60.222
3	428.35	68.174	622.89	99.136
4	605.05	96.296	701.16	111.59
5	1197.3	190.56	1506.4	239.74
6	1877.2	298.81	1899.5	302.31

Table 7 - Natural and modal frequency results

Centrifugal/tensile stresses are of interest in this study as they instigate stiffening of rotational components. The resultant increased stiffness alters the fundamental/natural frequency, this can be clearly demonstrated when tuning a guitar string (Kurowski, 2014). As coning is of detrimental effect to helicopter flight, an understanding of centrifugal force would be greatly beneficial.

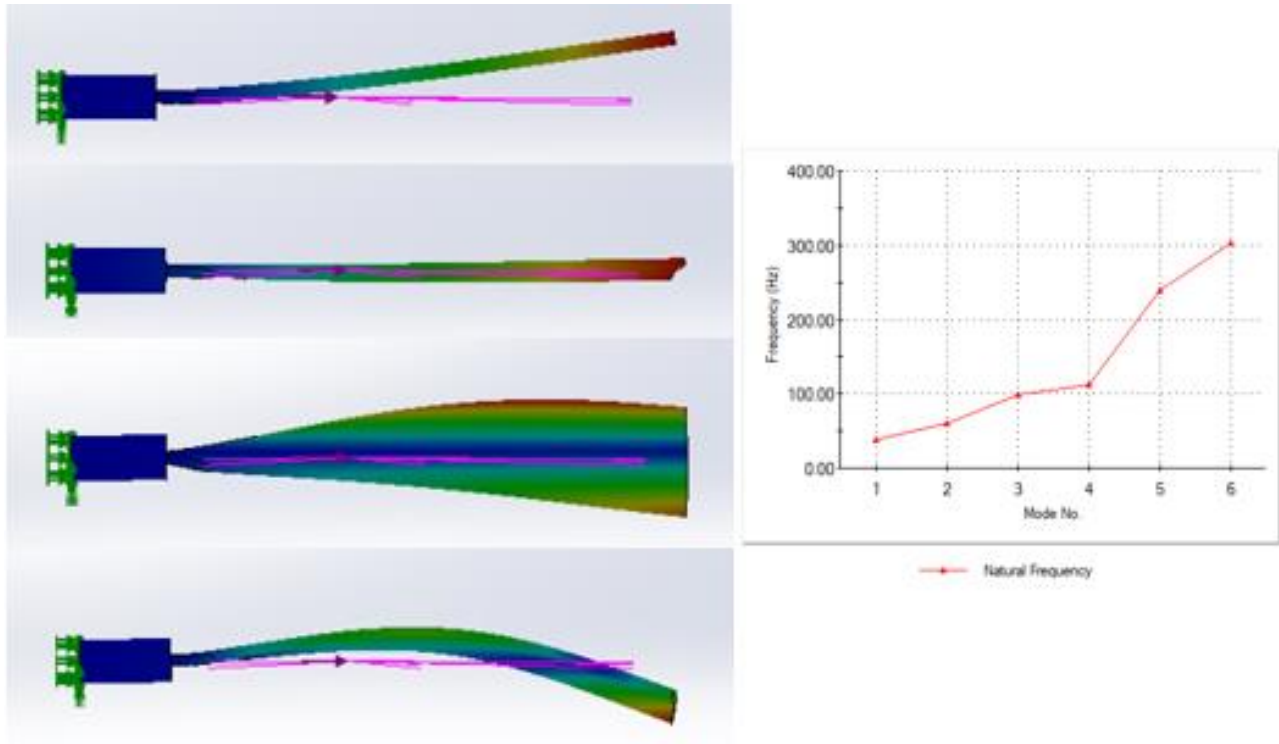


Figure 17 -Frequency results with additional centrifugal force

A comparison of results with the addition of centrifugal force, show mode shapes for 1-2 have remained the same, 3-4 have switched position. The shapes are essentially very similar, the more significant is the change frequency. Mode 1 has increased by over 300%, clear evidence of the stiffening effect of rotational/centrifugal forces. The increased stiffness is the combination of the materials elastic stiffness and the stress stiffness.

The figures produced my analysis are shown in Table 7. These need to be considered in relation to the results in Table 4. There is considerable difference between the frequencies of rotational helicopter components and the tail rotor blade fundamental frequency. Therefore, there is no discernible resonance between component frequencies.

6 Conclusion

To conclude, FEA has real advantages for the design/evaluation of components. The abilities of software like SolidWorks, can change the typical 'design, prototype and test' process. As a result, prototyping can be for validation and not part of the design process.

The techniques used within this report are relatively straightforward forms of analysis. FEA software is a powerful tool which requires a profound knowledge of the subject to be fully utilised. Analysis can be complex, time consuming and the results are subject to interpretation. It is generally the role of design engineers to design and implement FEA to harness its true potential. With extremely challenging scenarios often requiring expert analysts/consultants.

This study has provided me with an introduction into the field of FEA. The results of my analysis are limited by my software ability and my fundamental knowledge to interpret the results. Whilst I have produced a study which has real benefits in understanding the tail rotor performance under loading. The results are limited by my material choice and my basic calculations of the forces involved. Whilst I understand my limitations with this software, I feel this study has given me real insight into the process of FEA.

This study has enabled me to develop an analysis methodology and gain an understanding of how CAD geometry can effect FEA results. I now understand the importance of element selection and mesh refinement in generating interpretable results. Stress concentrations/singularities were identified which far exceeded the yield strength of my material selection. But with the experience gained from this study I now understand the effect of infinitely sharp edges/corners and their effect on stress values.

The natural frequency of components is paramount to helicopter design. The interaction of natural frequency, modal frequency and the frequency noise produced by rotational components is of the upmost importance. This study has produced frequency results which coincide with results discovered through my research. The fundamental frequency shows no interaction with the rotational frequency of either the main/tail rotor. Although further understanding of its interaction with integer harmonics would be beneficial.

7 Recommendations

As a result of the knowledge gained from this study there are several recommendations, I now have for producing more accurate FEA simulations/results.

This study has highlighted the complex nature of rotor composition, a linear solver like SolidWorks is limited in truly evaluating this loading situation. For more accuracy, a nonlinear solver would enable the study of the rotor with its true material structure. In addition, there is a simple design change which would increase the accuracy of results produced in the study. The infinitely sharp corners/edges generated in CAD modelling do not recreate the real edges produced in manufacturing processes. So, as a result I would suggest implementing a fillet/chamfer that accurately reproduced the same corner/edge as the chosen manufacturing process. This should reduce or eliminate the chance of generating stress singularities.

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