University of New South Wales

MMAN4410 Finite Element Analysis

Major Project Report

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Comparative Study of the Optimum Stacking Sequence for a Composite Drive shaft

Executive Summary

The study was performed to assess the quality of proposed stacking sequences for a carbon epoxy drive shaft suggested by three different literature material. The quality of the drive shaft is assessed on its ability to meet critical speeds as a minimum. Subsequent comparisons are based on the maximum shear stresses induced by rotational torque of the motor, failure criterions and the maximum torque transmission capabilities. The behaviour of composites is more difficult to predict than conventional homogenous materials such as steel or aluminum. For this reason, the finite element method was adopted with careful planning on the composite layups prepared in ACP Prep producing preliminary results using modal analysis in ANSYS software. The results showed that all stacking schemes having first modes of natural frequency well above the operating frequency. The ply layup consisting of the most layers and varied angled other than +/-45˚ and 90˚ produced a significantly higher natural frequency enabling for a greater margin of safety and possibly greater torsion transmission performance. The results were validated with establish data from literature material and the percentage error produced was within acceptable means (below 6%). Hence the simplifications, assumptions and boundary conditions applied in the analysis are acceptable and there is no need to adjust or refine the methodology. Subsequent analysis for the major project will focus on the structural analysis component of analysis with post processing in ACP post for predicting failure of composites using appropriate orthotropic relations such as the Tsai-Wu failure criterion.

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1 Introduction

Conventional metallic drive shafts used for power transmission in automobiles have been associated with weight limitations, low critical speeds and poor resistance to vibration and fatigue. Numerous studies have proven that excellently designed composites can offer significant weight reductions and superior fatigue and vibrational damping characteristics producing higher power transmissions. This is particularly useful in large vehicles requiring a drive shaft length greater than 1500mm as a single composite shaft is able to replace a two-piece aluminium or steel shaft. Unlike its two-piece metallic counterpart, a single composite drive shaft has higher fundamental natural frequencies due to its high specific strength and high specific modulus properties. Resonance will occur at higher operational speeds allowing for a greater margin of safety and increased shaft torsional performance.

Fibre orientation plays a critical role in exploiting the material properties of composites. Aligning fibres parallel to the loading direction results in high strength and stiffness but also a trade-off in performance when loads are applied perpendicularly. Thus a composite that is more isotropic is favoured to account for various loading scenarios. A well-documented method of producing a more isotropic composite is to use multiple plies with fibres oriented at different angles within each ply. Hu et al, Ghatage et al and Bhajantri et al have suggested the following stacking sequences for carbon epoxy documented in Table 1.

Table 1 – Stacking sequences for carbon epoxy composite

	Stacking sequence
Case 1	[+45˚/+45˚/0˚/+90˚]
Case 2	[45/-45/45/-45/45/-45/90/90]
Case 3	[-56/-51/74/-82/67/70/13/44/-75]

Composite behaviour is difficult to model analytically, thus a numerical solution is required. The aims of this study is to compare the three proposed optimum stacking sequences using Finite Element Analysis and assess them for their structural and vibrational capabilities.

1.1 Objectives

The objectives of this analysis is to model a real world drive shaft using the stacking sequences suggested by the literature material comparing based on:

1. The maximum shear stresses induced in the shafts
2. First fundamental natural frequencies and mode shapes

Modelling in ANSYS is used to predict the effect of the proposed plie sequences on the above parameters. The results will be validated by comparison with literature material detailed in later sections**.**

2 Modelling Approach

The first stage in the analysis is to create an appropriate mathematical model to simplify the physical problem. In order to obtain accurate results, a number of factors were considered.

2.1 Design Requirements and Specifications of Composite Driveshaft

To ensure relevance to real world applications, the specifications of the composite driveshaft will be considered to be the same as an optimally designed driveshaft outlined in Table 2. [1] The maximum torque transmission capability will be taken to be 3500Nm to reflect critical speeds achieved in real life. To avoid failure by resonance the fundamental natural frequency should be greater than 6500 rpm. The length of the shaft should be at a minimum of 1500mm to account for the scenario of a metallic drive shaft requiring two sections and the outer diameter should be a maximum of 100mm due to space limitations.

Table 2 – Design Requirements and Specifications of Composite Driveshaft

Parameter	**Notation**	**Unit**	**Value**
Ultimate Torque	T_{max}	Nm	3500
Maximum rotational speed of shaft	N_{max}	Rpm	6500
Length of shaft	L	mm	1500
Outer diameter	d	mm	100

2.2 Material Selection

Carbon epoxy composite was selected as the composite material of interest for the reasons listed below.

1. High tensile strength and modulus of rigidity in comparison to other composites
2. Low coefficient of thermal expansion meaning thermal stability
3. High fatigue strength ideal for torque transmission
4. Wear and corrosion resistant
5. Vibrational damping characteristics
6. Widespread use in automobile applications, supporting the relevance of this study

The material properties are summarised in Table 3 below.

Table 3 – Material Properties for Epoxy Carbon UD Prepreg

Parameter	**Notation**	**Value**	**Unit**
Young's Modulus	E_1	GPa	121
	E_2	Gpa	8.6
	E_3	Gpa	8.6
Shear Modulus	G_{12}	GPa	4.7
	G_{23}	GPa	3.1
	G_{13}	GPa	4.7
Poisson's Ratio	ν_{12}	-	0.27
	ν_{23}	-	0.4
	ν_{13}	-	0.27

Density	ρ	Kg/m^3	1600

2.2 Assumptions and Simplifications

As shown in Figure 1, a drive shaft is composed of many components. However only the cylindrical tube component will be considered and all subsequent attachments will be disregarded. This is a reasonable assumption as the cylindrical shaft component takes up majority of the drive shaft's length and weight which are determining factors for a modal analysis.

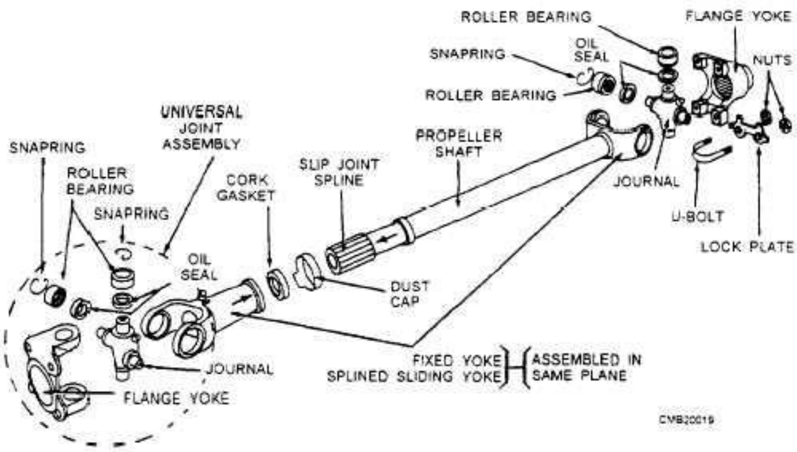


Figure 1- Exploded view of drive shaft assembly [2]

Furthermore, the driveshaft will be assumed to have a uniform hollow cross-section. A hollow cross-section is selected over a solid cross-section as the stress variation is smaller across a small thickness as opposed to being zero at the centre and maximum at the circumference. Also hollow circular shafts have greater strength capabilities per a kilogram. The effect of assuming a uniform body free of stress concentrators or groves is unrealistic but applicable in this study as the variable of the analysis is fibre orientation angles.

Other assumptions used to simplify the analysis include: the shaft rotates at constant speed, is perfectly balanced and undamped and that the composite laminate material is considered predominately homogenous for simulations on a laminate level.

3 Analysis Procedure

Composite modelling in ANSYS requires careful consideration as the material does not behave isotopically. Pre-processing in ANSYS ACP Prep is required to define the materials, layups, draping influence to generate a solid model from the defined layup before the data is imported onto subsequent analyses. Post-processing can then be used to develop failure criteria for the composite. A project scheme undertaken for the torsional analysis of the composite drive shaft is depicted below in Figure 2. A similar methodology will be taken for the modal analysis to account for the carbon epoxy composite material.

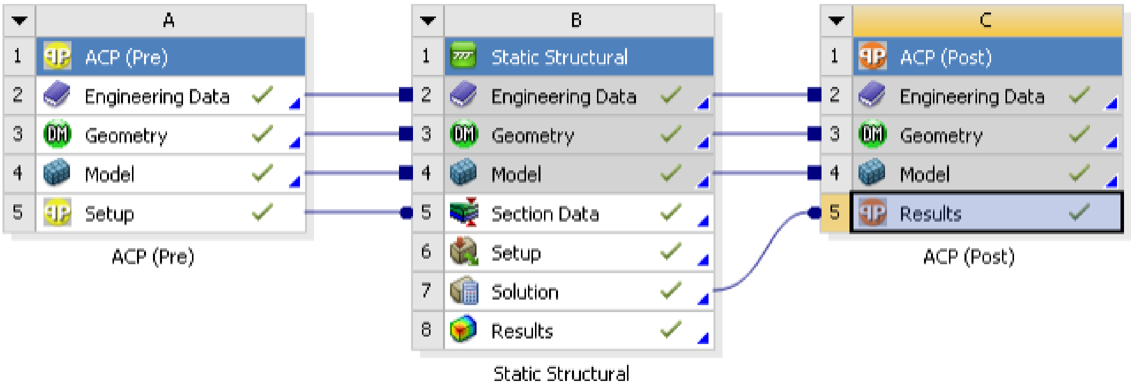


Figure 2 – single analysis sequence scheme for carbon epoxy composite modelling

3.1 Composite Modelling

The composite drive shaft is considered to be a thin-walled orthotropic tube. Thus nine variables are required to be defined for the analysis; Young's modulus, shear modulus and Poisson's ratio in each coordinate direction. Epoxy Carbon UD (230GPa) Prepreg and Resin Epoxy data were imported into ANSYS ACP (Pre). The geometry of the driveshaft structure was drawn by defining a hollow circular cross section of outer diameter 0.1m and 0.09m inner diameter, extruding it to a length of 1.5m to produce the solid depicted in figure 3.

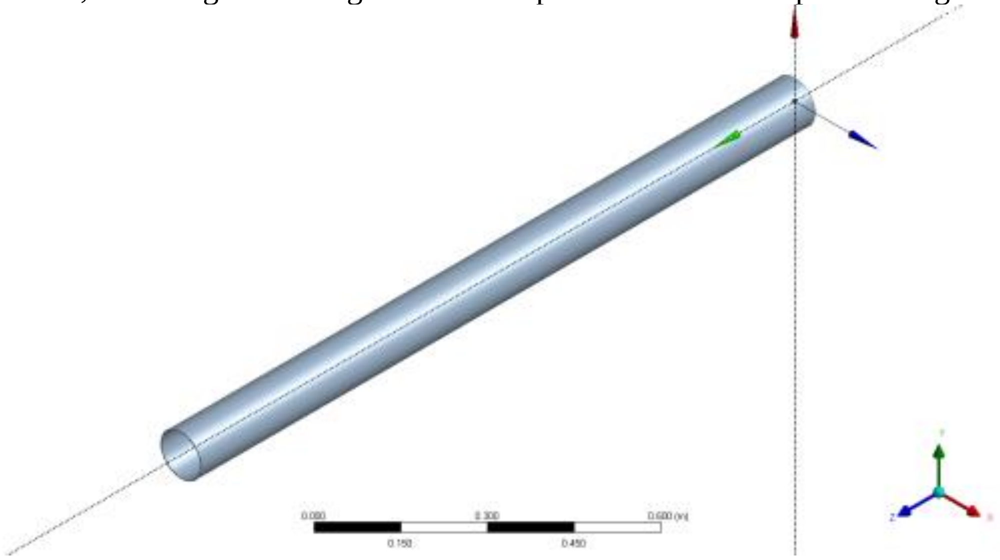
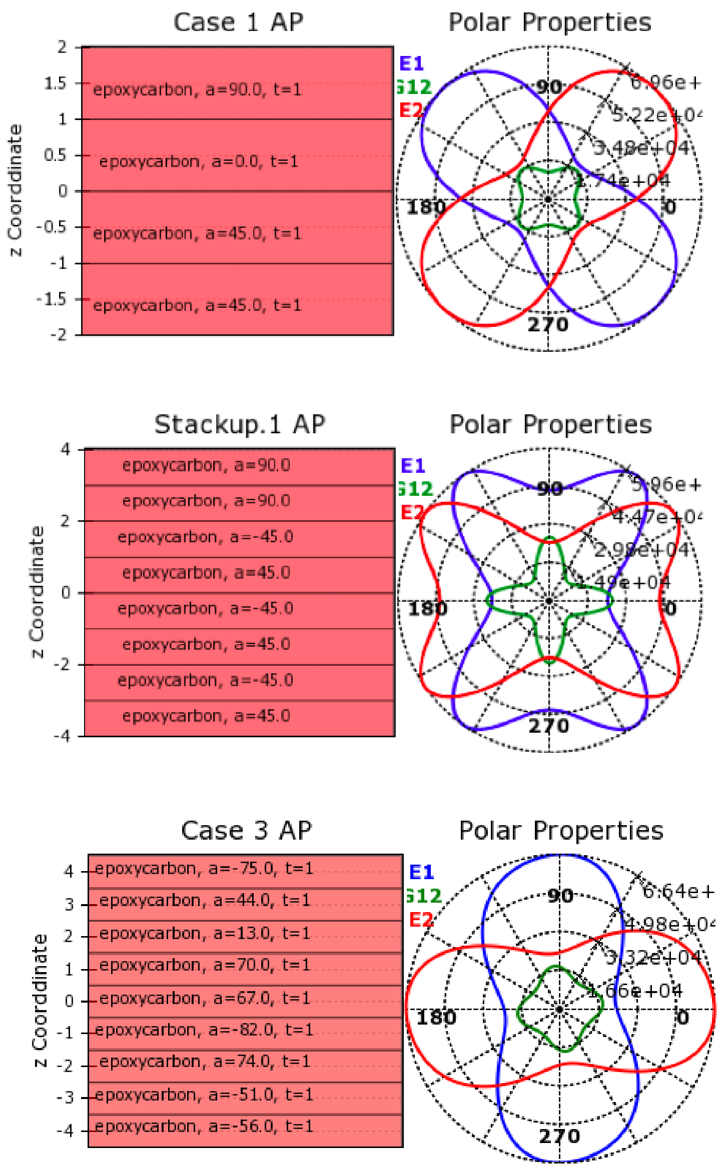


Figure 3 – 3D Model of Composite Drive Shaft in ANSYS

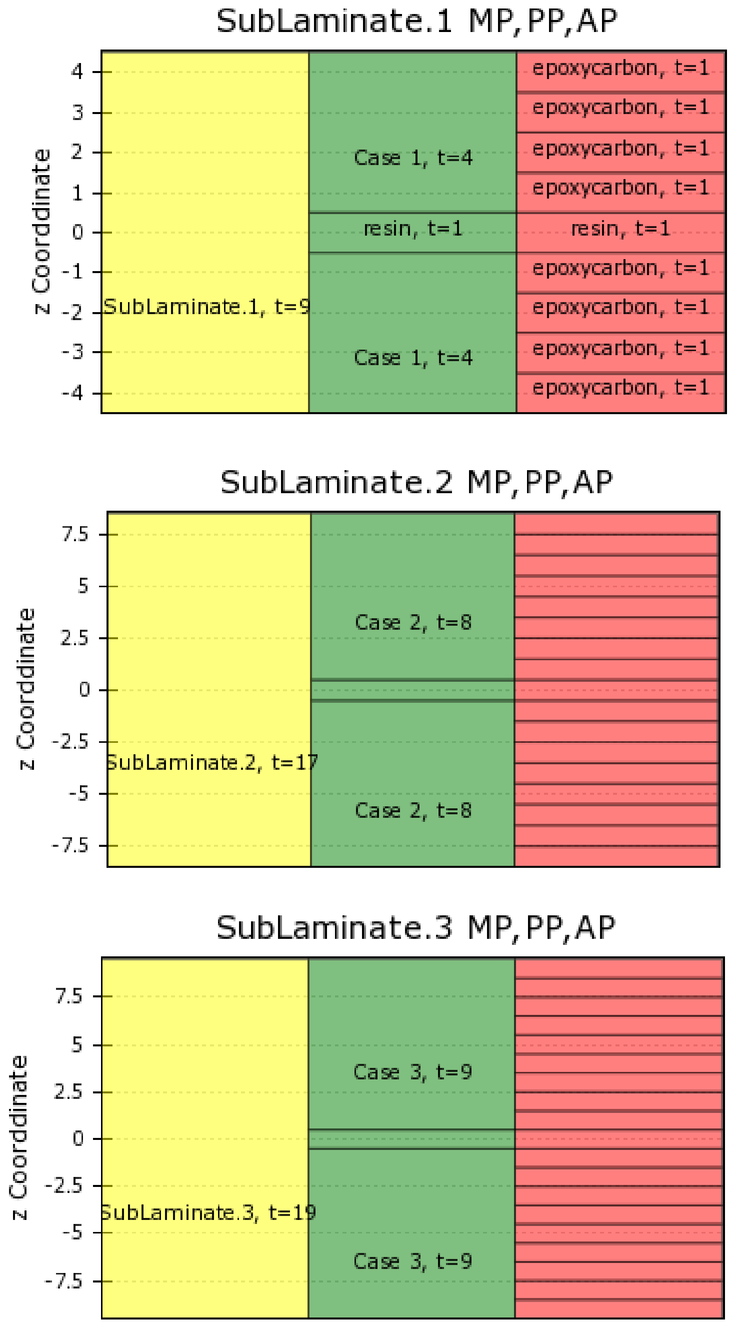
To set up the composite data, fabrics were created from the initial material selections. Both Epoxy Carbon UD and Resin Epoxy were set to a thickness of 1mm to enable valid comparison between laminate stacks based on fibre orientation angle. Each stacking sequence defined earlier in Table 1, was inputted into the software to produce the laminate schemes depicted in Figure 4. Also note the polar variation of Young's modulus in direction 1 and 2 and shear modulus in direction 12 between each case.

Figure 4 – Laminate ply schemes and associated angles, thickness and polar properties for case 1,2 and 3



Sub laminates were created by sandwiching a resin layer between two laminates for each of the cases. A single layer of resin oriented 90˚ to the laminates was used. The sub laminate schemes and associated layers and thickness can be seen below.

Figure 5 – Sub laminate schemes and associated thickness for cases 1,2 and 3



The plies are then applied to the model by creating ply groups and defining the ply angle and layers to apply to the selected elements. A single layer of sub laminates is selected to enable valid comparison between cases. Table 4 summarises key data for the composite stacking schemes of interest.

Table 4 – Determining variables between cases

	Stacking sequence	Thickness of sub laminate (mm)
Case 1	[+45˚/+45˚/0˚/+90˚]	9
Case 2	[45/-45/45/-45/45/-45/90/90]	17
Case 3	[-56/-51/74/-82/67/70/13/44/-75]	19

3.2 Boundary and Loading Conditions

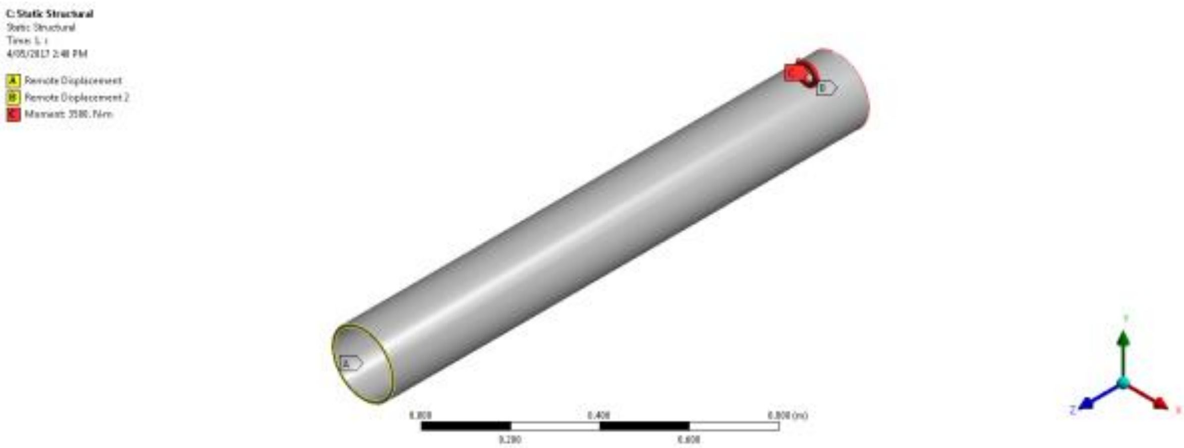
Referring back to Figure 1, the ends of the cylindrical portion of the drive shaft consists of a slip joint spline which fastens to the fixed yokes via threads. The drive shaft rotates in the same direction as the engine motor and is free to displace in directions parallel to the cross sectional face. Resultantly, the appropriate boundary conditions to apply to the shaft is fixed displacement in the direction perpendicular to the cross section (x direction) and fixed rotation in directions differing from the direction of rotation of the motor (y and z direction). The boundary conditions were applied to the outer and inner edges at both ends.

Also the engine motor is located at the rear of the drivetrain assembly. Thus an applied torque of 3500Nm, representing the case of maximum critical speeds achieved, is applied to one end. The boundary conditions inputted into ANSYS for the torsional analysis is summarised in Table 5 and depicted graphically in Figure 6.

Table 5 – Boundary and Loading Conditions for Torsional Analysis

Label	Description	Value
A	Remote displacement	$x = 0m, \theta_y = 0^\circ, \theta_z = 0^\circ$
B	Remote displacement	$x = 0m, \theta_y = 0^\circ, \theta_z = 0^\circ$
B	Moment	3500Nm

Figure 6 – Boundary and loading conditions of composite driveshaft for torsion analysis

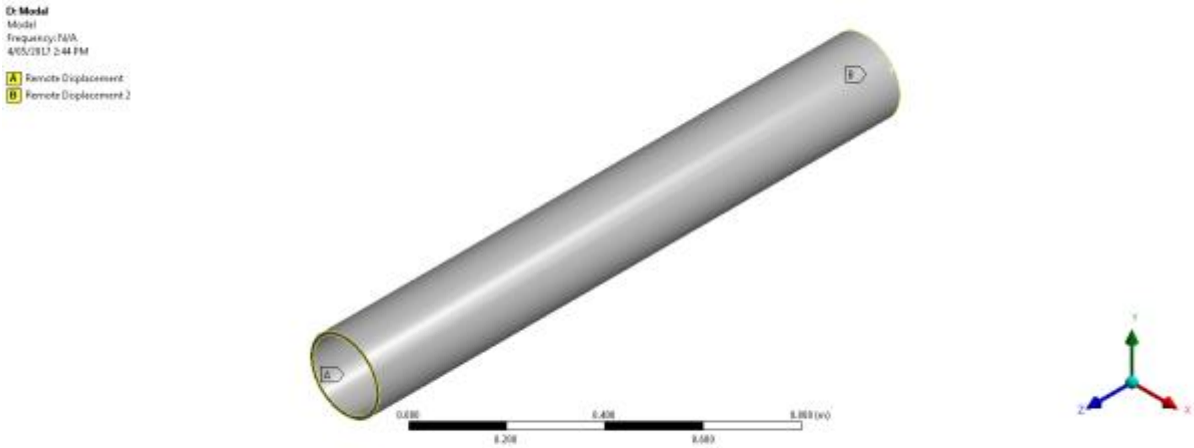


A free vibration analysis is to be performed to determine the natural frequencies and mode shapes of the structure. There is no requirement to input an applied load as the natural frequencies are dependent only on the diameter of the shaft, thickness of the hollow shaft, specific stiffness and length. Thus the modal analysis requires only the boundary conditions described above with negation of the applied torque. Table 6 and figure 7 represents these conditions.

Table 6 – Boundary Conditions for Modal Analysis

Label	Description	Value
A	Remote displacement	$x = 0m, \theta_y = 0^{\circ}, \theta_z = 0^{\circ}$
B	Remote displacement	$x = 0m, \theta_y = 0^{\circ}, \theta_z = 0^{\circ}$

Figure 7 – Boundary conditions of composite driveshaft for modal analysis



3.3 Meshing

For analysis purpose SHELL 281 Element is selected. It is an 8-node quadrilateral element with six degrees of freedom at each node. The element is suitable for analyzing thin to moderately-thick shell structures. Its quadrilateral shape functions are better able to model the stress variation across the element making it an appropriate choice appropriate for this linear and large rotation analysis. Meshing in ANSYS produced the highly structured mesh.

3.4 Modal Analysis

A modal analysis is performed to determine the 1st mode of natural frequency. It is required that first fundamental natural frequencies obtained for each ply sequence will be analysed based on sub critical design criteria, that is the rotational speed must be lower than first natural frequency to avoid resonance.

A vibrational analysis requires only a macroscale approach, so each laminate can be analysed as a homogenous shell. Thus the following equations for natural frequency of a composite shaft based on Timeoshenko's beam theory is applicable to the analysis and will be used as preliminary form of validation for the model.

$$f_{nt} = K_s \left(\frac{30\pi p^2}{L^2} \right) \sqrt{\frac{E_1 r^2}{2p}} \qquad (1)$$

$$\frac{1}{K_s^2} = 1 + \left(\frac{\pi^2 p^2 r^2}{2L^2}\right)\left(1 + Fs\frac{E_x}{G_{xy}}\right) \quad (2)$$

where
$f_{nt} = natural\ frequency\ (Hz)$
$p = first\ natural\ frequency\ (Hz)$
$K_s = shear\ coefficient\ of\ natural\ frequency\ (< 1)$
$f_s = 2\ for\ hollow\ circular\ cross - sections$

Natural frequencies are converted into critical speeds (rpm) via equation 3.

$$N_{critical} = 60 f_{nt} \quad (3)$$

3.4.2 Preliminary results and validation

Preliminary values of the first natural frequencies for all three stacking sequences are shown in Table 7. Case 3, having the largest sub laminate thickness and having fibre orientation angles other than +/-45˚ and 90˚ produced the largest first natural frequency. Case 1 and 2 both consisting of variations of +/-45˚ and 90˚ angles produced natural frequencies relatively of the same magnitude. All cases have values that are well above the operational maximum critical speed of 3500rpm, supporting the use of composite materials over metals for drive shaft torque transmission. The data shows a clear indication between fibre angle and the natural frequencies of the system. The data obtained in ANSYS shows good accordance with literature values, producing errors of less than 10%. The assumptions and loading conditions used are valid.

Table 7 - 1st Natural frequencies for varying fibre orientation angle stacking sequences

	Natural frequency (Hz)	**$N_{1st\ mode}$ (rpm)**	**$N_{1st\ mode,theoretical}$ (rpm)**	**% Error**
Case 1	340.03	20402	20753	1.69
Case 2	314.97	18898	19987	5.45
Case 3	1632.62	97957	101520	3.51

4 Conclusion

From the results there is a clear indication that orienting the carbon fibres angles within each layer will have a determining effect on the natural frequencies of the carbon epoxy composite shaft. The ply sequence of case 3 has the most number of layers and varied angles other than +/-45˚ and 90˚, in turn producing a significantly higher first mode of natural frequency; 1532.62 Hz in comparison to cases 1 and 2. However all cases have first mode of natural frequencies much higher than the maximum operating speeds, so resonance is avoided and the safety margin is increased. The data also showed good correlation with literature values, obtaining an acceptable error of below 6%. Resultantly, the simplifications, boundary conditions have been validated. With the initial pre-processing of the composite material and preliminary analysis completed, the subsequent analysis for the major project will focus on the structural analysis component. This requires more complex planning and post processing in ACP post for predicting failure using Tsai-Wu failure criterion.

5 References

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