RESEARCH ARTICLE

DOI: 10.54926/jnamt.2025.248

J Nav Architect Mar Technol 2025;227(1):43-51

Investigating the Torsional Vibration Behaviour of Composite Drive Shafts in Marine Propulsion Shaft Systems

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To cite this article: Halilbeşe AN. Investigating the torsional vibration behaviour of composite drive shafts in marine propulsion shaft systems. *J Nav Architect Mar Technol*.

Received: 30.10.2024 - **Revision Requested:** 18.01.2025 - **Last Revision Received:** 11.03.2025 - **Accepted:** 02.06.2025 - **Publication Date:** 30.06.2025

Abstract

Within ship propulsion shaft systems, shafts function as crucial connecting elements, like springs, where their stiffness values significantly influence the overall vibration behavior of the system. Torsional vibration is particularly perilous in propulsion shaft systems due to the irregular forces exerted by the propeller. This study aims to enhance the integration of composite material in the construction of drive shafts used in the shipbuilding industry and to promote the use of composite materials while investigating torsional vibration behavior. To achieve this objective, a composite drive shaft is modeled using the ANSYS ACP Module, with production details such as ply angle and the number of layers meticulously defined within the ACP Module. The natural frequency of the drive shaft is determined through Modal Analysis, while the torsional angle is obtained using Static Structural Analysis. Optimization techniques are employed with ANSYS Direct Optimization Tool, involving precise adjustments to ply angles, to enhance overall performance. This study focuses on the effects of ply angles, thickness, and material on the torsional vibration behavior of the drive shaft, providing a comprehensive analysis that underscores the potential of composite materials and advanced manufacturing techniques in improving the efficiency and durability of propulsion systems in marine engineering.

Keywords: Composite shaft, torsional vibration, propulsion shaft system, optimization

1. Introduction

In the field of marine engineering, the design and analysis of propulsion shaft system components are crucial for ensuring the efficiency and durability of ships. A key component in this regard is the drive shaft, which is essential for transmitting torque and power between different parts of the propulsion system, exhibits vibrational behavior along various axes during its operation. Torsional vibration, resulting from oscillatory motion along the drive shaft's axis and considered the most dangerous type of vibration, is a significant area of study due to its potential to induce fatigue and failure during the drive shaft's operation. As technological advancements drive the demand for lightweight and high-performance materials, composite materials, particularly with the use of additive manufacturing, have emerged as promising alternatives to traditional metallic alloys in shaft construction. The unique mechanical properties of composites, such as high strength-to-weight ratios and tailored stiffness, provide an opportunity to improve the torsional behavior of shafts. However, optimizing composite shafts poses a challenge, requiring a thorough investigation of design factors such as layup angles, plate thicknesses, and stacking sequences to unlock their full potential.

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The complexity of the design problem of the composite structure is compounded by numerous variables and constraints, potentially limiting the performance of the final structure [1]. Previous research on composite shafts has predominantly focused on the torsional behaviour of cylindrical structures subjected to vertical or horizontal forces, with fixed supports at both ends [2]. Various beam models and analysis methods, such as the Timoshenko theory [3-5] thin-walled beam theory [6], and finite element method [7], have been employed to examine the critical speed, natural frequencies, and stability under axial loads during whirling of the composite shaft [4,6,7]. Chang et al. [7] presented a model based on the first-order Timoshenko beam theory, while Badie et al. [8] utilized finite element analysis (FEA) to investigate the effects of fibre orientation angles and stacking sequences on torsional stiffness, natural frequencies, bending strength fatigue, life, and failure modes of composite tubes. Experimental tests were also conducted on a composite drive shaft to validate the FEA model [9]. Montagnier and Hochard introduced viscoelastic supports to mount composite shafts, and explored factors such as shaft length and support stiffness [10,11]. In contrast to linear system considerations, nonlinear studies investigating the spinning composite shafts based on the Bernoulli-Euler theory emphasized the presence of extensional, flexural, and torsional vibrations, by incorporating geometrical nonlinearity and linear couplings due to material anisotropy [12-15]. Overall, the exploration of composite shafts involves a comprehensive approach to design and analysis, considering various factors to optimize their performance in mechanical systems.

The literature on shaft torsional response mainly interests with the whirling analysis of axially loaded, simple or fixed supported composite shafts. These studies emphasize the axial loading-induced whirling phenomenon. However, as the integration of composite material into the shipbuilding industry gains prominence, there arises a need to revaluate the role of the shaft, considering its application as a joint element.

Within the propulsion shaft system, all constituent elements, including the crankshaft, intermediate shaft, propeller shaft, and any auxiliary shafts, are tasked with the transmission of torque. Torsional vibration manifests as a result of the engine torque, coupled with the inherent instability in propeller power output and power transmission dynamics [16-19]. In the context of passive vibration isolation, the system is systematically pre-tuned for torsional vibration by judiciously adjusting key parameters. These parameters encompass the torsional stiffness of the shafts, contingent upon their respective diameters, and the mass moment of inertia, potentially achieved through the incorporation of a flywheel [20,21]. Furthermore, alterations in torsional stiffness may be effectuated by the introduction of additional elements into the system, such as flexible shaft couplings [22,23].

The torsional vibration characteristics of a composite drive shaft have undergone thorough examination through systematic variation of pertinent parameters, including plate angle and material, within one side fixed supported configurations, as extensively documented in the literature. In the context of a shaft system; the composite shaft connects the components of the propulsion system (e.g. propeller, main engine) and has freedom of rotation. This study is motivated by elucidate the effects of various composite shaft parameters on the torsional vibration behaviour of the shaft system. To achieve this aim, the composite shaft is modeled with ANSYS Workbench ACP Module. The first naturel frequencies of the propulsion shaft system obtained with the help of ANSYS Workbench Modal Analysis, besides, the maximum torsional angle due to external moment is obtained with ANSYS Workbench Static Structural Analysis. The influence of the material, thickness and ply angle on naturel frequency and torsional angle is shared. In addition, employing the Direct Optimization tool within the ANSYS Workbench program, new permutations were made to attain the minimum torsion angle while varying ply angles. This approach aimed to systematically investigate the influence of these parameters on torsional vibration, and the findings of these analyses are subsequently elucidated.

2. Methodology and Numerical Model

This study investigates the torsional vibration of drive shaft which is a component of propulsion shaft system using single degree of freedom and ANSYS Software which is based on finite element method. Figure 1 provides an illustrative example of the appearance and structural configuration of a drive shaft.

Table 1 presents the detailed specifications of the drive shaft modeled using numerical method and ANSYS, and composite shaft details derived from the literature [24].

The torsional natural frequency of a shaft, with one end fixed and the other end free, can be approximated using the following expression [25];

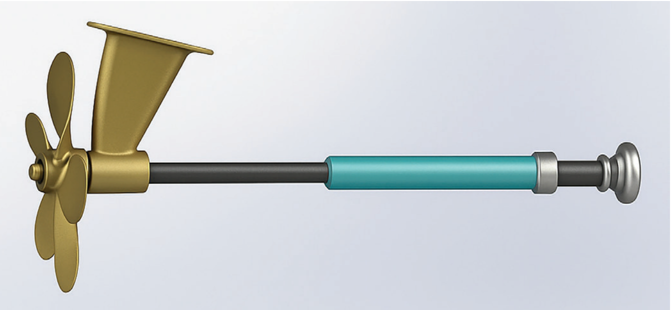

Figure 1. Drive shaft manufactured with steel.

Table 1. Mechanical details of the drive shaft [24]	
Length of the shaft	1200 mm
Inner diameter	75 mm
The transmitted torque	80 Nm
Fabric angle	0, ±30, ±45, ±60, 90
Fabric 1 (E-glass/Epoxy) thickness	3 mm
Fabric 2 (Carbon/epoxy) thickness	0.75 mm

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K_T}{I}} \tag{1}$$

while K_T is torsional stiffness of the composite shaft [26], I is polar mass moment of inertia per unit length, and the torsional stiffness of the composite hallow shaft can be given as;

$$K_t = \frac{G_{eq}J}{L} \tag{2}$$

Here, J is polar moment of inertia of the hollow shaft which has 7 layer given with Equation 3 [27], and G_{eq} is shear modulus of the composite shaft and aproximatly calculated by considering the shear modulus of the meterials which are given with Table 2.

$$J = \frac{\pi}{32}\sum_{i=1}^{7}\left(d_{0,i}{}^{4} - d_{i,i}{}^{4}\right) \tag{3}$$

$$G_{eq} = \frac{G_1 t_1 + G_2 t_2}{t_1 + t_2} \tag{4}$$

d_0 is outer diameter (m), d_i inner diameter (m) in Equation 3. The mechanical properties of the drive shaft is given in Table 1. The natural frequency obtained using Equation 1 is compared with the ANSYS Modal analysis results to first verify the accuracy of the ANSYS model.

For the ANSYS modal analysis, the SOLID185 element type was selected to construct the FEA model of the transmission. The model consists of 2904 nodes and 2880 elements after meshing. The boundary conditions specify that one end is a fixed support, while the other end is subjected to a transmitted torque. This is a seven-layer hybrid composite beam, and the first layer is of E-glass/Epoxy and upper layers are of Carbon/epoxy. ANSYS ACP model is used to create composite layers with varying orientation angles, as detailed in Figure 2. The green section represents the configuration without any composite material, whereas the red section demonstrates the layer-by-layer arrangement of composite materials. In this context, a represents the angle, and *t* represents the thickness of the plate. This representation is commonly used in composite manufacturing.

The [0/0/0/0/0/0/0] layup configuration was chosen to compare the numerical model and ANSYS. According to Equation 1, the natural frequency is 319.42 Hz, while the natural frequency obtained from the modal analysis is 339.82 Hz, as shown in Figure 3. Figures 3 and 4 present the mode shapes corresponding to these frequencies. The numerical analysis and ANSYS modal analysis have been observed to exhibit similar mode shapes at comparable natural frequency values.

The ANSYS model has been validated as accurate since it demonstrates similar natural frequency values and the same mode shape as the numerical analysis. Therefore, the study has proceeded using the ANSYS model. Various cases were examined to assess the impact of material type, ply angle and thickness on the natural frequency and torsional angle of the drive shaft. The materials utilized, along with their respective properties, are detailed in Table 2, and the thickness detail are shared with Table 1. To evaluate the effect of ply angle on the natural frequency and torsional angle, sequences with orientations of [0/0/0/0/0/0/0], [0/30/-30/30/-30/30/-30], [0/45/-45/45/-45/45/-45], [0/60/-60/60/-60/60/-60], [0/90/90/90/90/90/90] were employed.

3. Results and Discussion

To initially determine the effects of thickness and ply angle on natural frequency, an analysis was conducted with the inner tube diameter fixed at 75 mm. To measure the first naturel frequency of the drive shaft with different ply angle

Table 2. Mechanical properties of materials [24,28,29]

	T300-934 Carbon/epoxy	**T300-7901 Carbon/epoxy**	**T300-12K Carbon/epoxy**	**ER1200-FW E-glass/Epoxy**
Density, (kg/m^3)	1500	1478	1760	1850
Young's Modulus (E_{11}), GPa	148	125	144.11	39.3
Young's Modulus (E_{22}), GPa	9.65	11.3	10.23	4.8
Shear Modulus ($G_{12,}$ G_{13}), GPa	4.55	5.43	6.12	4.0
Shear Modulus (G_{23}), GPa	4.55	3.98	6.12	4.0
Poisson ratio ($\nu_{12,}$ ν_{13})	0.30	0.30	0.246	0.25
Poisson ratio (ν_{23})	0.30	0.42	0.246	0.25

and ply number ANSYS Workbench Modal Analysis is used. The ply angle was varied at 0°, ±30°, ±45°, ±60°, and 90°, which are the most commonly used ply angles in manufacturing. The drive shaft thickness was increased in increments of 2 layers (0.75 mm), with the first layer being E-glass/Epoxy fixed, and the additional layers spanning from 6 layers to 14 layers (7.5 to 13.5 mm). The analysis results, depicted in Figure 5, indicate that the first natural frequency increased significantly with changes in ply angles. The indicators 0, 30, 45, 60, 90 in Figures symbolize 0°, ±30°, ±45°, ±60°, and 90°. Conversely, Figure 6 demonstrates that thickness has a relatively minor effect on natural frequency compared to ply angle. Additionally, Figure 6 shows that the increase in natural frequency becomes more pronounced as the ply angle increases. These findings suggest that ply angle is the most influential factor affecting natural frequency, rather than thickness.

Figure 7 shows that the torsional angle is the minimum at ±45 degrees for each ply number and the maximum at 90 degrees. The torsion angle values for complementary angles, such as 0 and 90 degrees or 30 and 60 degrees, are similar, though not identical. This pattern is not observed for natural frequency; however, it is evident that complementary angles result in comparable torsion angles.

Figure 8 indicates first naturel frequency for different material at ply angle ±30. Since similar results are seen at different ply angles, the result is shared only for ±30 degrees to avoid confusion in the figure. Even at different ply number of the shaft, the highest natural frequency is seen for T300-12K while the lowest natural frequency value is seen for T300-934.

Figure 9 illustrates the variation in natural frequency for different ply angles while maintaining a constant number of 10 plies. The natural frequency shows a slight increase from 0 degrees to 30 degrees. However, a sharp increase is observed from ±30 degrees to ±45 degrees, with the most significant rise occurring at ±60 degrees. Beyond ±60 degrees, up to 90 degrees, the natural frequency decreases slightly. These observations suggest that ply angles have a pronounced impact on natural frequency, with the most substantial effect occurring around ±60 degrees.

Figure 10 demonstrates that T300-12K has the highest density among the materials used, and the lowest torsion angle is observed in this high-density material. For each material, the lowest torsion angle occurs at ±45 degrees. Additionally, similar torsion angle values are observed at complementary angles (0,90, ±30, ±60), indicating a consistent pattern across different materials.

4. Optimization

This study investigates the effects of material, thickness, and ply angle on natural frequency and torsional angle. During the optimization phase, the objective is to minimize the torsion angle by modifying the arrangement angles in the

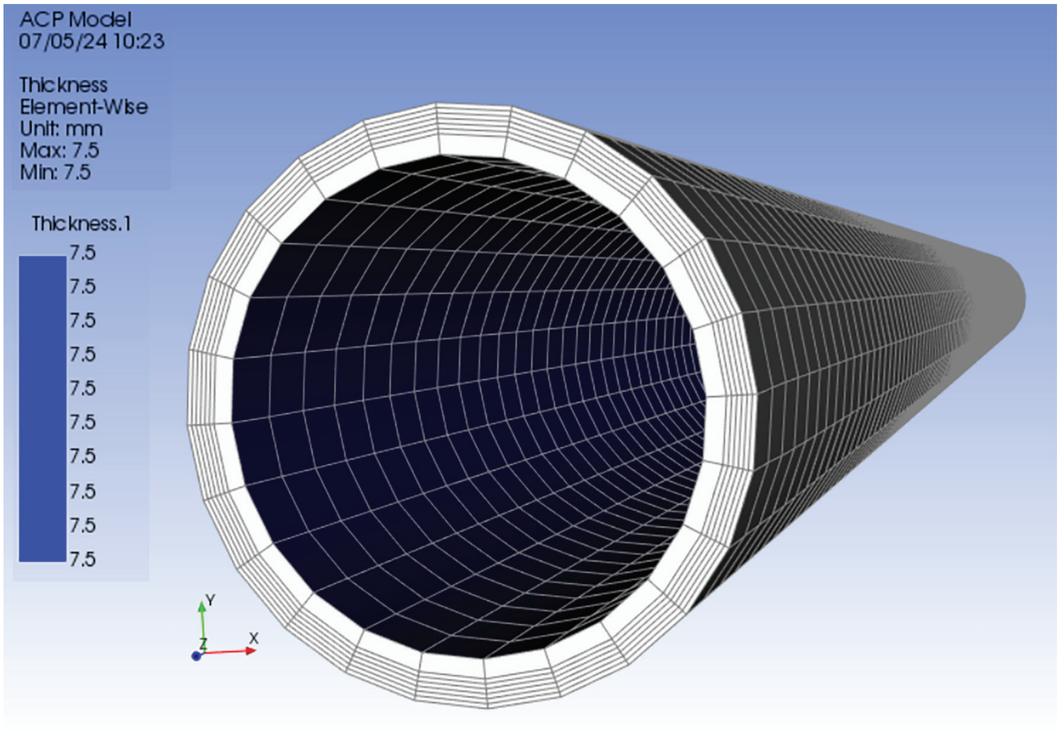

Figure 2. Details of the drive shaft with ANSYS ACP Module

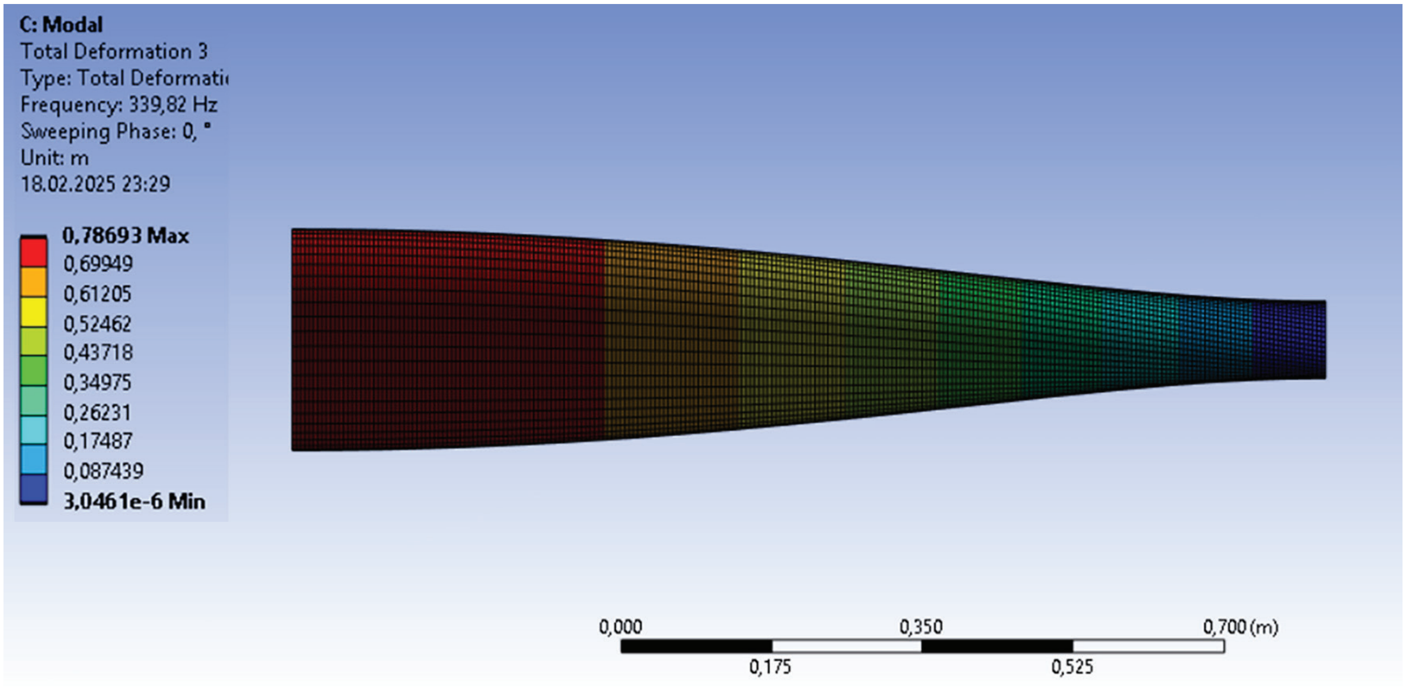

Figure 3. The mode shape of the composite shaft obtained with ANSYS Modal Analysis.

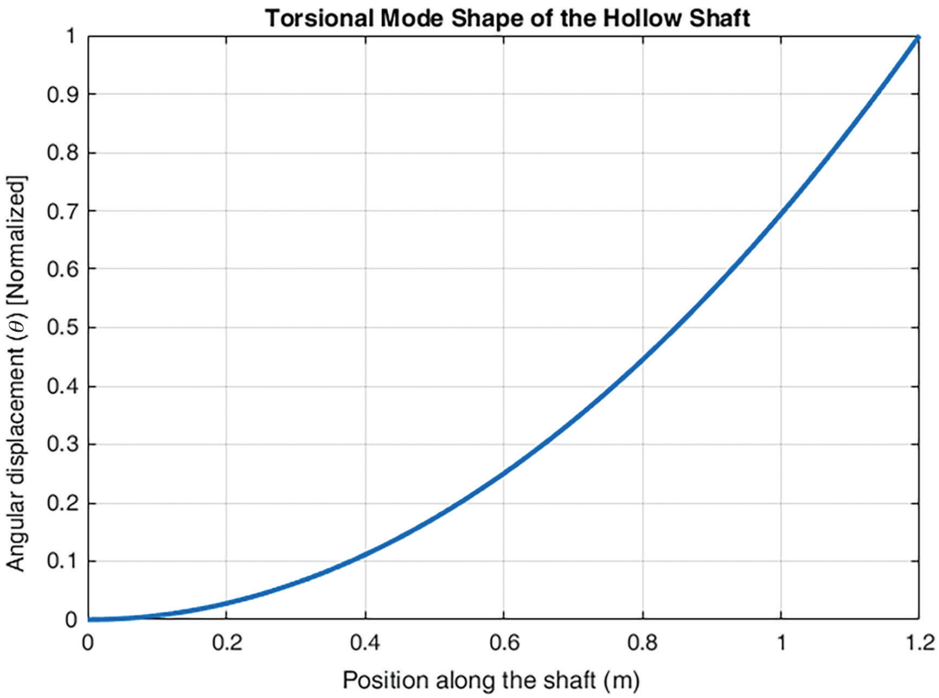

Figure 4. The mode shape of the composite shaft for 319.42 Hz.

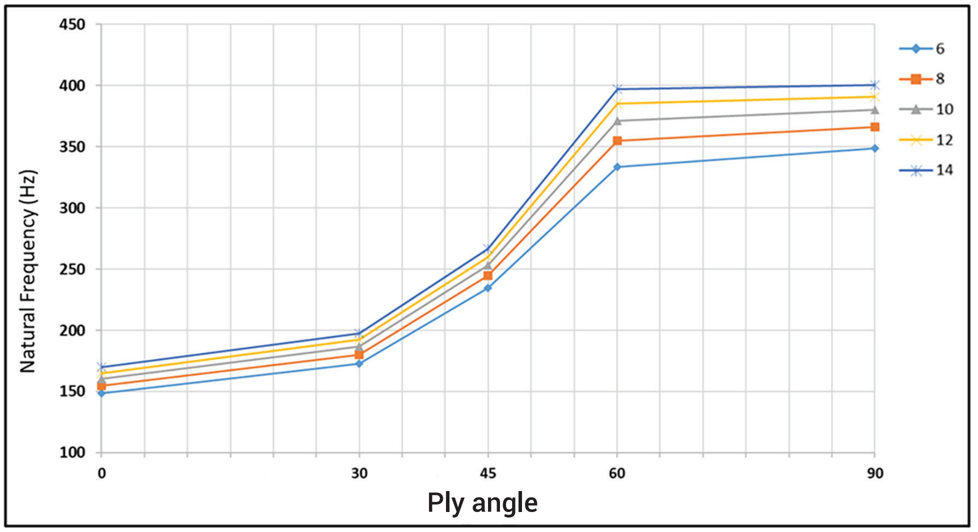

Figure 5. The layers of the composite drive shaft.

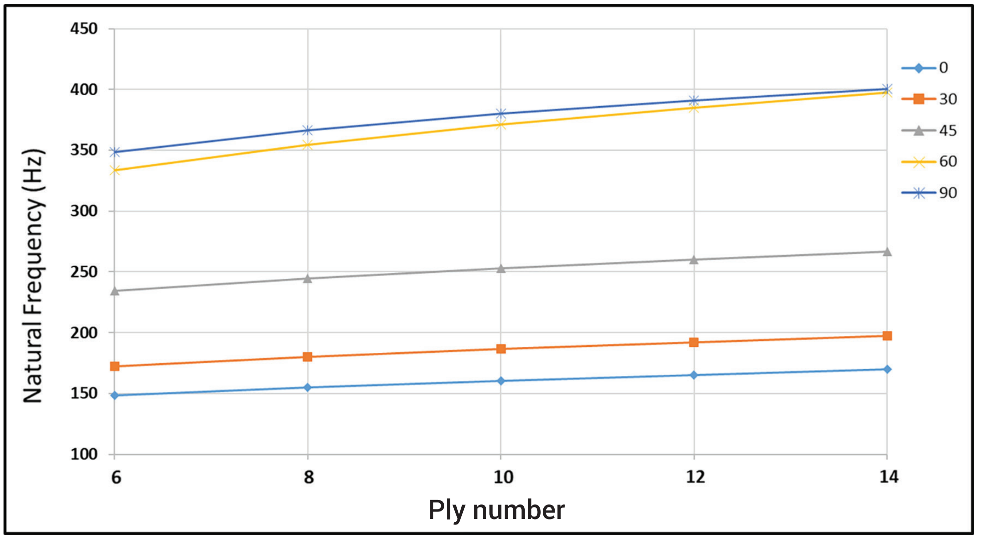

Figure 6. The layers of the composite drive shaft.

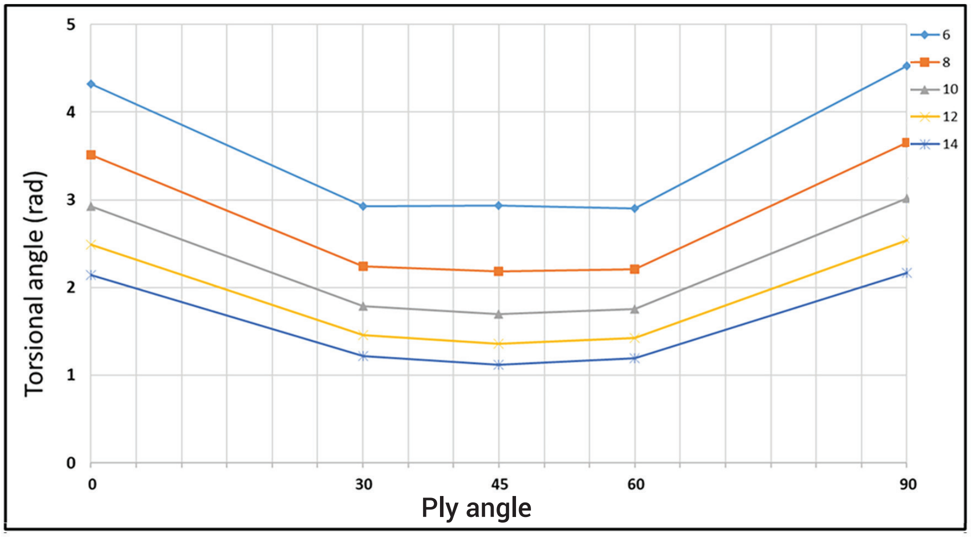

Figure 7. The layers of the composite drive shaft.

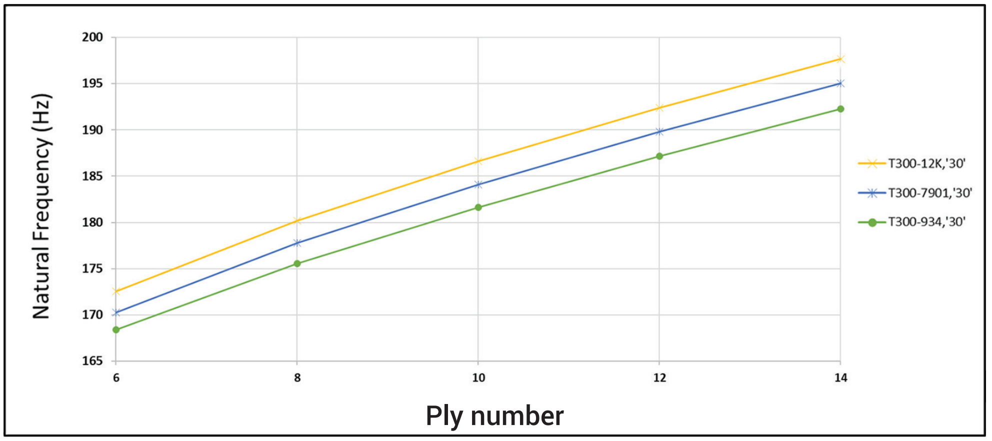

Figure 8. Natural frequencies with different material at ply angle ±30.

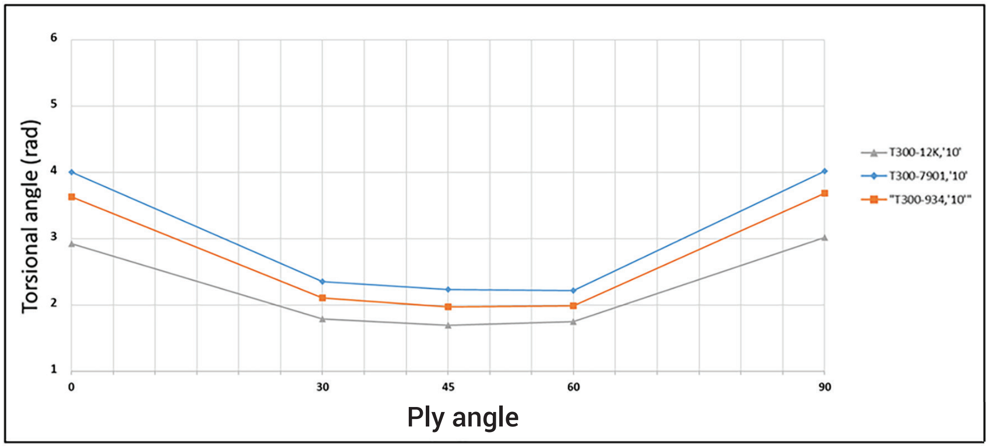

Figure 9. Natural frequencies with different material at different ply angle.

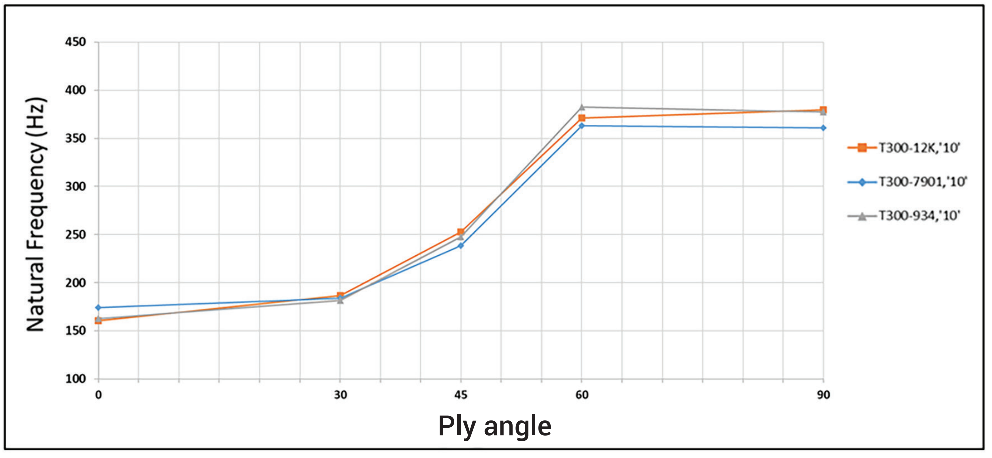

Figure 10. Torsional angle with different material at different ply angle.

[0/0/0/0/0/0/0] configuration for a composite shaft consisting of a first layer of E-glass/Epoxy and 6 layers of T300-12K. The goal is to achieve a torsion angle below 4.32 radians under the same applied moment for the specified configuration. Optimizations were conducted using the Direct Optimization module of the ANSYS Workbench program. Initially, the input and output parameters were identified using the ANSYS ACP module, which facilitated composite modeling with ply angle, and the Static Structural module, which provided torsion angle values. The allowable values for each input parameter were determined, and an experimental matrix was created based on these values. Analysis was then performed for each combination in the matrix. A total of 728 different combinations were analyzed. As shown in Table 3, more optimal combinations were identified.

Table 3. Optimization results.

Combination	Layer angle	Torsional angle (rad)
1.	[0/0/0/0/0/0/0]	4.32
2.	[0/-30/45/-30/30/-30/0]	2.62
3.	[0/-30/30/-30/30/-30/-0]	2.65
4.	[0/-30/30/-30/45/-30/-0]	2.66

5. Conclusion

This study provides a comprehensive analysis of the effects of material composition, thickness, and ply angle on the natural frequency and torsional angle of composite drive shafts in marine propulsion systems. The findings underscore the critical influence of ply angle on the natural frequency, with variations in ply angles yielding significant changes in performance. Specifically, the analysis revealed that the first natural frequency increased substantially with changes in ply angles, while thickness exhibited a relatively minor effect. This highlights the importance of optimizing ply angles to enhance the dynamic behaviour of composite shafts.

The investigation demonstrated that the most significant increase in natural frequency occurred around ± 60 degrees, suggesting that this ply angle configuration is particularly effective in shaft performance. Conversely, torsional angle analysis indicated that the lowest torsion angles were observed at ± 45 degrees for all materials tested, with high-density materials such as T300-12K showing the most favorable results.

Optimization efforts focused on minimizing torsion angles by modifying the arrangement angles in the composite shaft's configuration. Utilizing the Direct Optimization module of ANSYS Workbench, a systematic approach was employed to identify the optimal ply angle combinations. The study successfully identified several configurations that significantly reduced the torsion angle, with the best-performing combination achieving a torsion angle of 2.62 radians, compared to the initial 4.32 radians.

In conclusion, this research highlights the potential of composite materials and advanced manufacturing techniques in enhancing the performance of drive shafts in marine engineering. The findings provide valuable insights into the optimal design parameters, paving the way for the development of more efficient and durable propulsion systems. Future work should continue to explore the interplay between different design variables to further optimize composite shaft performance in various operational contexts.

Footnote

Financial Disclosure: Dr. Akile Nese Halilbese's research is supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) through the TÜBİTAK 2219 International Postdoctoral Research Fellowship Program.

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