Design and Analysis of a Carbon Composite Propeller for Podded Propulsion

Ashok Kumar, G. Lal Krishna and V. Anantha Subramanian

Abstract Though the bulk of marine propellers are almost exclusively manufactured in metal alloys, there has been a recent trend to look into composite materials for propellers. Carbon fibre because of its extremely high strength and favourable strength-to-weight ratio is therefore a strong candidate as an alternate material for propellers. This paper investigates the design, analysis and basic strength aspects of a carbon composite propeller for application as a podded propulsion unit. Propellers are roto-dynamic machines and are prone to fatigue, and therefore, this is one of the important considerations in the choice of the material. Therefore, long-term study in terms of not only strength, hydrodynamic performance, but also fatigue properties must be well established if carbon composite propellers are to be used as substitute for the conventional propellers. This study presents the design of a propeller based on favourable stacking orientation of the multiple layers using unidirectional carbon fibre and epoxy resin, technique of manufacture and test results for hydrodynamic performance. For this purpose, the propeller conforms to standard NACA profiles for high efficiency. The study reports the analysis for strength on the basis of modelling the layer sequence and assigning the directional properties for the carbon fibre. To validate the results, a segmented loading frame has been designed and the deflections measured in the radial direction. The results help to verify the deflections obtained and therefore to confirm the analytical approach to obtain the dynamic stresses and the deflections. The study lays the foundation for redesigning the propeller making full advantage of the strength-to-weight ratio of carbon composite to obtain high efficiency and to obtain the hydro-elasticity-based response characteristic.

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Static loading test · FEM

Nomenclature

CFRP	Carbon fibre reinforced plastic
MRF	Moving reference frame
η_0	Open water efficiency
K_T	Thrust coefficient
K_Q	Torque coefficient
n	Propeller rpm
V_A	Speed of advance
d	Propeller diameter
ρ	Density of water
T	Thrust
Q	Torque

1 Introduction

Marine screw propellers are roto-dynamic machines which produce thrust from hydrodynamic action. They are subjected to high loading, pulsating forces as they rotate in the disc area, subjected to vibrations, centrifugal force, bending and axial-based thrust forces. They generally work in a heterogeneous flow environment due to the characteristic wake pattern behind a ship, and therefore, long-term stresses such as due to vibration, fatigue are also typical loading conditions. Therefore, choice of material is important and not only from the immediate thrust consideration. Conventional propeller materials include nickel aluminium bronze, manganese bronze, aluminium alloy and stainless cast steel alloy. Some common drawbacks of the conventional propeller materials are corrosion, cavitation, formation of galvanic cell and maintenance cost. Composite propellers may offer a solution. They are designed and constructed based on combinations of resins and reinforcement fibre. Composite materials are mainly known for the excellent strength properties, lightweight, improved fatigue properties, less corrosion, high thermal resistance and low maintenance cost. Material properties of carbon fibre, aluminium alloy, nickel aluminium bronze and manganese bronze are compared and listed in Table 1.

Carbon fibre reinforced plastic (CFRP) has polymer resin matrix material which binds together the reinforcing fibre. The resin and fibre may be made available separately and the laminate prepared to set at room temperature or cured in higher temperature controlled environment. Carbon fibre is also manufactured in the form of pre-preg material, which can be set and cured in an autoclave. The matrix polymer material is usually epoxy resin, and it binds the fibres together. The stacking sequence

Table 1 Comparison between properties of carbon fiber, aluminium, NAB, manganese bronze

Material properties	Carbon fibre (unidirectional)	Aluminium alloy	Nickel aluminium bronze	Manganese bronze
Young's modulus (GPa)	120–220	68–72	122–130	110–120
Tensile strength (MPa)	800–1500	270–330	550–660	410–490
Density (g/cm^3)	1.35–1.85	2.65	7.55	8.22
Thermal conductivity (W/m K)	20	117	42	80
Low coefficient of thermal expansion $\times 10^{-6}$ (Inch/inch degree Fahrenheit)	−1 to 8	7–13	9	12
Poisson's ratio	0.27	0.33	0.32	0.34

of the fibre significantly influences the structural properties of the composite. Carbon composite has high initial strength-to-weight ratio. Two important aspects that need investigation are the effect of absorption of moisture in marine condition and fatigue behaviour. Hence, a safe design approach is to have higher factor of safety for the CFRP material under cyclic loading conditions. Some other associated characteristics are less compression strength, complex manufacturing techniques, low fracture toughness and moisture absorption. Considering all the above-known characteristics and the unknown areas of long-term behaviour, it is important to make a first-hand beginning in the design, fabrication analysis of carbon composite propeller for marine application. This paper reports a systematic study which includes hydrodynamic performance analysis as well as strength and deflection under thrust loading.

2 Literature Survey

Izabella Krucinska [1] studied the bending method to evaluate the strength and failure strain of carbon fibre based on the mathematical framework of flexural theory. Gilchrist et al. [2] studied the static behaviour, fractographic observations, fatigue behaviour and finite element predictions of composite I-beams subjected to mechanical loads and also the failure under fatigue as well as impact on CFRP. Sun and Jun [3] brought out the effect of fibre misalignment and nonlinear behaviour of the matrix on fibre micro-buckling and the compressive strength of unidirectional fibre composite. Young [4] studied the hydro-elastic behaviour of flexible composite propeller in wake flow. Young [5] also studied the flexible propellers with fully coupled BEM and FEM for subcavitating and cavitating flows and compared with experiments. Lin et al. [6] studied the effect of stacking sequence on a composite blade. The blade was analysed with different stacking sequences of composite lay-up. Blasques et al. [7] addressed the design and optimization of a flexible composite marine propeller by tailoring the laminate to control blade shape and consequently the developed thrust. Hara et al. [8] worked on the performance evaluation of composite marine propeller for a fishing boat by fluid–structure interaction analysis. Paik [9] made a comparative study of different composite propellers both numerically and experimentally. Das and Kapuria [10] studied the use of bend–twist coupling of a composite marine propeller for enhanced hydrodynamic properties. Because of the steadily widening application of carbon fibre composites, it is vital to initiate studies starting from application for small composite propellers and building up. Carbon composite propellers are also of strategic importance as non-metallic materials with high strength.

3 Design and Construction

The propeller geometry must suit direct connection to a submerged three-phase electrical motor prime mover characterized by a large hub to diameter ratio of 0.44, delivering 5 kW of input power. The CFRP propeller has been adapted from the standard Wageningen-B series data with sectional geometry from the same series. The design data gives the pitch, diameter, number of blades and the available thrust power. The blade sections chosen from the series give the most favourable blade sections, and primarily, these are intended for metal alloy propellers. The objective is to evaluate the hydrodynamic and strength characteristic of the carbon fibre propeller and modify the same in future to take advantage of the high strength of carbon fibre, also considering the long-term behaviour such as fatigue, moisture absorption effect etc. Table 2 provides the geometric properties of the propeller.

Negative form provides a monolithic propeller with hub and three blades. The propeller casting process involves hand lay-up process where the epoxy resin is bonded

Table 2 Geometric properties of carbon fibre propeller

Diameter (D) mm	450
Hub diameter (d) mm	198
Pitch ratio (P/D)	1
Hub–diameter ratio (d/D)	0.44
Expanded area ratio (A_E/A_o)	0.35
Number of blades (Z)	3
Rotation	Left handed
RPM	748

with the carbon fibre layers in predetermined orientation. The reinforcement and matrix materials are to be laid within the split negative form. Due to the complexity in the split mould, the manufacturing of the propeller was carried out using hand lay-up process.

The design follows the optimum stacking sequence given by Lin et al. [11]. The propeller is designed with six layers of 300gsm carbon fibre stacked with the orientation sequence (0/-45/90/45/90/0) implying the angle in degrees in each layer. The matrix material is epoxy resin (LY556) mixed with the hardener HY951 in a ratio of 10:1. The manufacturing process has two options, viz. using pre-preg reinforcement carbon fibre with baking in an autoclave or hand lay-up. The manufacturing method adopted hand lay-up in view of the complexity of the multiple split mould required for the manufacture of a monolithic propeller with integral blades and hub. The lamination is a high-skill process. The matrix material permits room curing for 24 h. See Fig. 1 for the finished propeller.

First tests quantify the hydrodynamic characteristics as defined by the open water tests. The test set-up is shown in Fig. 2. The main propulsion motor was used as the prime mover in the open water test set-up, and the thrust and torque characteristics were obtained as a function of the forward speed, and these are plotted in Fig. 3. In the test set-up, the input power was measured using electrical input quantities and the output thrust was measured using a cantilever vertical beam and load cell at the upper end based on the principle of moments. The central shaft and plummer block shown in the figure act as the pivoting point in the cantilever arrangement for measuring the thrust.

An HBM 1t U1A-type load cell was used to measure the thrust produced by the pod propulsion unit. The load cell is enclosed with full-bridge connected strain gauges with temperature error compensation. The load cell is connected to HBM PMX which is a PC-based electronic measurement system to measure the thrust generated. The PMX is configured for the experiments using Catman software, which manages the settings and calibration data of the measuring instruments.

Fig. 1 Carbon fibre propeller manufactured using hand lay-up process

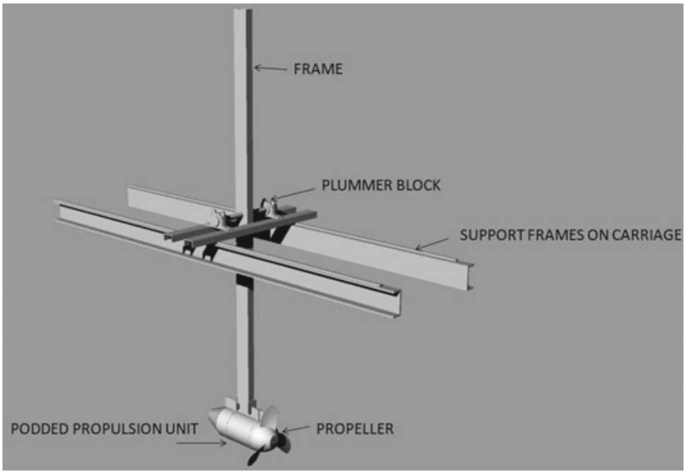

Fig. 2 Test set-up to identify open water performance of carbon and Al propeller for a podded propulsion system

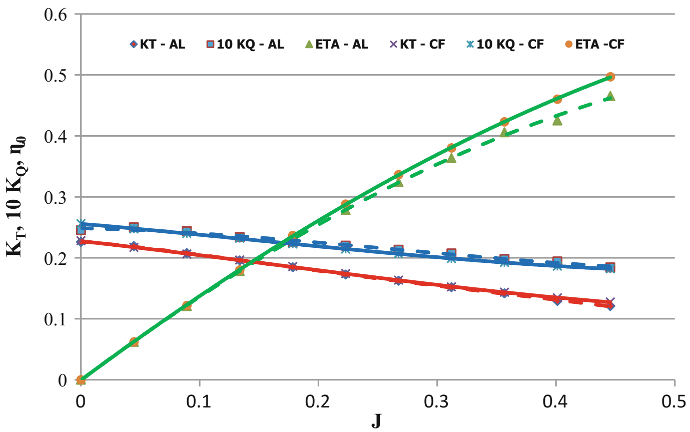

Fig. 3 Open water characteristics of carbon fibre and aluminium propeller at 748 RPM

3.1 Towing Tank Experiments

The test procedure includes setting the towing carriage to a predetermined steady speed from zero which is also bollard condition to the cover maximum possible speed of the carriage for constant revolution of propeller; in this case, it is 748 RPM. This is the highest-rated rpm of the motor.

The speed of advance is non-dimensionalized as the usual advance coefficient J. The test results are plotted as non-dimensional thrust and torque values against J.

$$K_{\mathrm{T}} = \frac{T}{\rho n^2 d^4} \tag{1}$$

$$K_{\mathrm{Q}} = \frac{Q}{\rho n^2 d^5} \tag{2}$$

$$\eta_0 = \frac{K_{\mathrm{T}} J}{K_{\mathrm{Q}} 2\pi} \tag{3}$$

4 Numerical Modelling for Obtaining Pressure Distribution on the Propeller Blades

The numerical modelling gives the distribution of pressure and in turn provides the input for structural analysis of the propeller blade section under the bollard pull condition (maximum thrust condition).

The geometry of the solid propeller is obtained using the 3D CAD modelling software Rhinoceros 5. The co-ordinates of the blade are imported, and the solid model is generated using loft technique; see Fig. 4. The data has been converted into .step file for further CFD studies.

A RANSE-based solver STAR-CCM+ was used. In this approach, an inertial frame of reference is attached to the outer domain and a moving reference frame fixed to the sub-domain. The rate of revolution is specified to the moving or rotating reference frame, and the flow is modelled as a steady problem with respect to the moving reference frame. Hence, at grid points in the sub-domain a rotational component according to the relative propeller rotations is added to the velocity. Figure 5 shows the domain developed in STAR-CCM+.

The propeller is modelled in a sub-domain as part of the outer domain with separate mesh generation for the sub-domain and outer domain and interfacing to connect the outer domain and sub-domain meshes, which are common for both regions. The grid uses a combination of structured and unstructured grids.

Hexahedral meshing is used for the volume mesh, and hexahedral cells trimmed to form polyhedral cells are used near the complex geometrical shape of the propeller

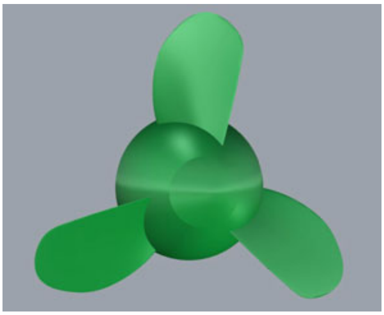

Fig. 4 3D-CAD model of the propeller

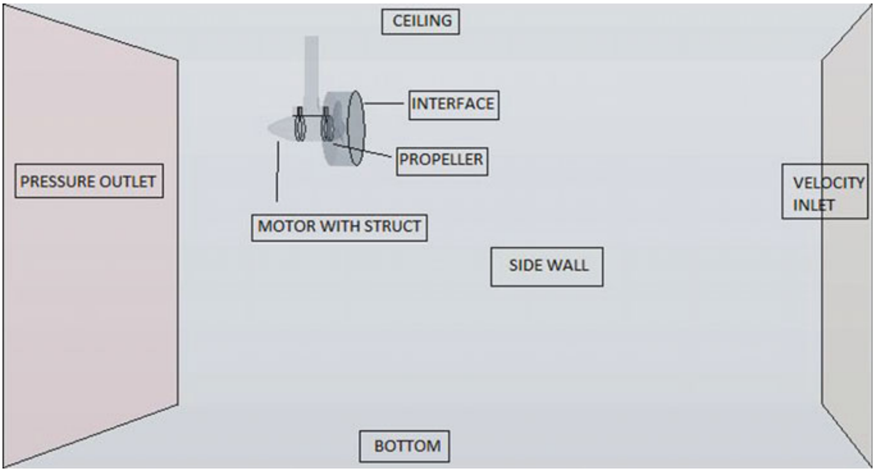

Fig. 5 CFD domain created in STAR-CCM+

Fig. 6 A view of generated mesh for CFD studies

body. To ensure proper calculation of forces and gradients on the propeller surface, it is necessary to have the mesh elements orthogonal to the propeller surface. Prism layer meshing is used in conjunction with the core volume mesh (Fig. 6). Mesh template growth rate is specified for a medium rate transition of mesh from inner fine mesh to the outer coarse mesh. The thrust distribution at bollard pull condition is given in Fig. 7. The total thrust from the computation is 1735 N, whereas from experiment the value is 1448 N. The thrust distribution is used as input for the structural analysis to obtain the deflections of the blade (Tables 3 and 4).

The RANSE-based solver STAR-CCM+ was used to compute the open water characteristics of podded propeller. From the above analysis, the thrust along the

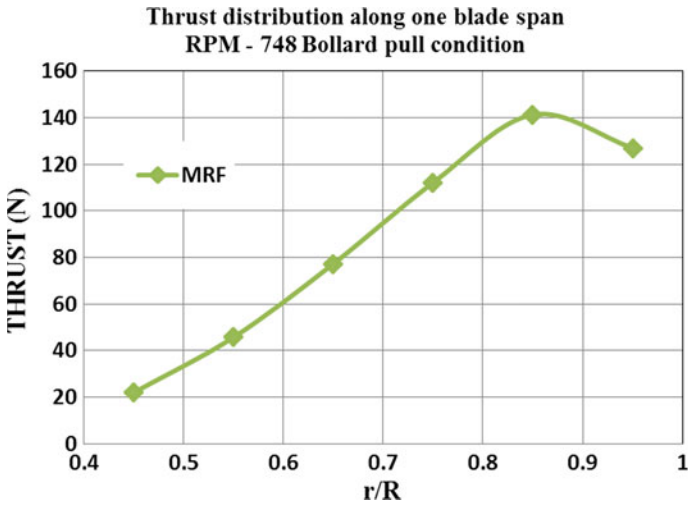

Fig. 7 Thrust distribution along the blade section in MRF method

Table 3 Solver parameters used in MRF method

Parameter	Settings
Solver	3D, steady
Turbulence model	K-Epsilon turbulence
Flow type	Segregated flow
Wall treatment	Two-layer all wall y+ treatment
Equation of state	Constant density
Fluid	Water

Table 4 Boundary condition incorporated for MRF method

Inlet	Velocity inlet
Outlet	Pressure outlet
Propeller blades	No slip
Side walls	Slip
Interfacial domain	Interface

blade sections from 0.4R to 1.0R is estimated for bollard condition and validated with the experimental results.

5 Static Loading Test

The load test was designed for basic understanding of the deflection behaviour of the material manufactured by the specific manual lay-up method. Loads as obtained from the CFD studies were applied at six sections ranging from 0.4R to 0.9R. Figures 8 and 9 shows the blade sections and segmental loading process. The deflections were measured using precision height gauge with 0.01 mm least count. Maximum tip deflection at full load was obtained as 5.2 mm. FEM-based analysis was carried out as described in Sect. 5.1. Table 5 shows the stiffness matrix incorparated for the analysis. The results were compared and are given in Table 6.

Table 5 Stiffness matrix of composite propeller for FEM analysis

$$\begin{vmatrix} 68.28 & 13.28 & 0.00 & -1.25 & -1.08 & 2.32 \\ 13.28 & 68.28 & 0.00 & -1.08 & 3.40 & 2.32 \\ 0.00 & 0.00 & 16.75 & 2.32 & 2.32 & -1.08 \\ -1.25 & -1.08 & 2.32 & 13.55 & 0.88 & -0.46 \\ -1.08 & 3.40 & 2.32 & 0.88 & 4.27 & -0.46 \\ 2.32 & 2.32 & -1.08 & -0.46 & -0.46 & 1.29 \end{vmatrix} \times 10^{9}$$

Fig. 8 Blade sections with supporting structures

Fig. 9 A view of segment loading for static load test

5.1 Finite Element Analysis of Propeller Under Static Loading

Static analysis of the propeller blade under thrust loading is carried out using a commercial finite element-based software ANSYS. The geometry of the propeller is imported to ANSYS APDL V15 in .iges format and is meshed. Tetrahedral mesh is used to capture the geometry. SOLID 185 elements are used for the finite element analysis of the propeller. The stacking sequence of the carbon fibre propeller is considered as designed, viz. 0/-45/90/45/90/0. In order to incorporate the effects of skewness and thickness variation in the finite element model, solid modelling is used. Composite lamina is orthotropic in nature. Material property of the laminate is modelled by the assembled 6×6 global stiffness matrix considering the various fibre angles. The elements of the matrix are given in Table 5.

The mesh file which is generated in ANSYS has been exported to STAR CCM+, and the fluid boundary element pressures are mapped to the exterior surface of the ANSYS mesh. A load file is generated which applies the pressures developed on the propeller based on the nodal points. The boundary condition is used to simulate the actual conditions of the propeller. Translational degrees of freedoms at the shaft

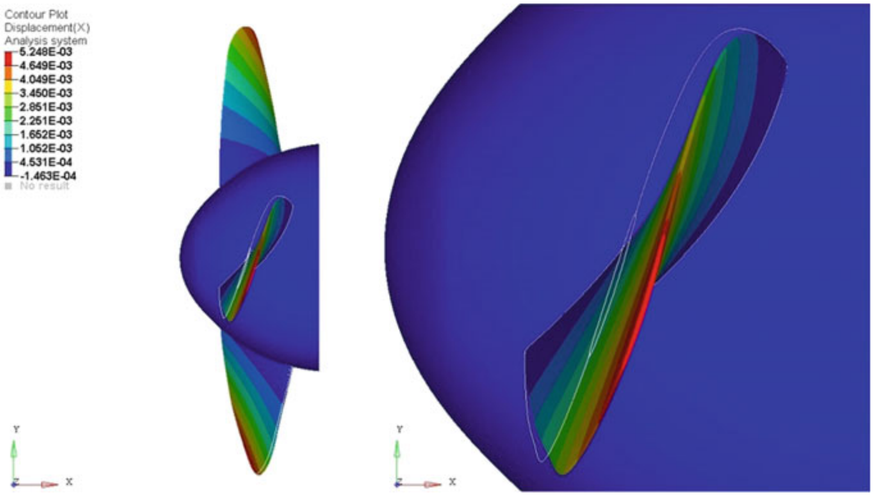

Fig. 10 Propeller deflection using FEM-based software

Table 6 Comparison of static deflection on a CFRP propeller in experiment and FEM analysis

Serial no.	Propeller radius	Load (kg)	Deflection based on experiments (mm)	Deflection using FEM-based software (mm)	Percentage of error
1	0–3R	0	0	0	0
2	0.4R–0.5R	2.06	0	0	0
3	0.5R–0.6R	4.28	0.5	0.69	0.38
4	0.6R–0.7R	7.24	1.18	1.48	0.254
5	0.7R–0.8R	10.51	2.14	2.49	0.164
6	0.8R–0.9R	13.25	3.44	3.54	0.0291
7	0.9R–1R	11.9	5.02	5.24	0.0438

and hub connection are arrested. From the solution of FEM analysis, the maximum deflection was found to be 5.248 mm and it is close match with the value obtained from experimental static loading test. Table 6 shows the comparison between experiments and FEM values. Figure 10 shows deflection of blade tip.

6 Conclusion

Carbon composite propeller has been designed, fabricated and tested for both hydrodynamic and structural properties. The carbon fibre propeller for podded propulsion has been successfully fabricated with characterization of its properties. The study establishes the feasibility and practicality of manufacturing carbon composite propeller. High strength, lightweight, non-corrosion in marine environment are the important attributes. The deflection characteristics have been quantified and found to be within reasonable limits. The results encourage trial application for further understanding carbon composite propellers with long-term implications.

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