Design, Fabrication and Analysis of Composite Marine Propeller

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Abstract: In this paper, a composite marine propeller is designed and modeled from three composite materials. The model is evaluated for its open water characteristics and cavitation performance numerically using hydro-elastic model. To validate the results, composite propeller is fabricated using open mould technique and is tested in cavitation tunnel available at NSTL vizag. From the results it is concluded that, the hydro-elastic model used for analysis of composite propeller is in close agreement with experimental results. The stacking sequence which contributed to the optimum performance is selected from the choice of stacking sequences. The results of the same are presented in this paper.

1. Introduction

The marine propeller is regarded as critical component with regard to the performance of the ships and torpedoes. In general screw propellers are used for these purposes. Mostly, propellers made of Nickel-aluminium-bronze(NAB) are found to be used in most of the marine applications. But with the demand of high power propellers composite marine propellers have come into picture. Traditionally marine propellers are made of manganese-nickel-aluminum-bronze (MAB) or nickel-aluminum-bronze (NAB) for superior corrosion resistance, high-yield strength, reliability, and affordability. More over metallic propellers are subjected to corrosion, cavitation damage; fatigue induced cracking and has relatively poor acoustic damping properties that can lead to noise due to structural vibration. Moreover, composites can offer the potential benefits of reduced corrosion and cavitation damage, improved fatigue performance, lower noise, improved material damping properties, and reduced lifetime maintenance cost. In addition the load-bearing fibers can be aligned and stacked to reduce fluttering and to improve the hydrodynamic efficiency by automatically adjusting the shape of the blade [young 2001]. Lin (1991a, 1991b) analyzes by the finite element method a moderately skewed partial composite blade from a 0.21m diameter seven-blade propeller, and compares the results with an all-alloy blade of the same geometry. The stress computations are performed using three-dimensional solid finite elements, and strength checks are made based on the finite element results. The computed tip deflection of the composite blade is an order of magnitude larger than that of the isotropic alloy blade. The maximum in-plane bending and shearing stresses for the composite blade are approximately 50 percent greater than the all-alloy blade. Lin and Lin (1997) examine the effects of stacking sequences on the performance of a composite propeller using a coupled fluid-structure interaction method. A geometrically non-linear finite element procedure for the structural analysis is coupled with non-cavitating lifting surface theory for the fluid analysis. The finite element analysis uses a degenerate shell element with five degrees of freedom per node. The effects of stacking sequence on the thrust, torque, efficiency and deflections are examined for a 1.40m diameter three-blade carbon fibre and epoxy propeller. Model scale analysis remains the standard means of evaluating the performance of the prototype because of the cost and the configuration considerations. In this work, the prototype is scaled down using the dynamic hydro-elastic scaling laws for the flexible rotors. Then the model is analyzed using the fluid and structural analysis. The fluid analysis is carried out using the general purpose CFD software Fluent 6.3.26 and structural analysis is carried out using ANSYS11. With the increased use of fiber-reinforced composites in structural components, studies involving the behavior of such structures and their members are receiving considerable attention. In this work, hybrid composite marine propeller is fabricated and is tested for its open water and cavitation performance.

2. Materials and their properties

The composite propeller is modelled with the three materials. For the purpose of calculating the composite propeller characteristics, the propeller is modelled with the three materials. The total number of layers is assumed to be 25.
To explore the effect of bend-twist coupling on the performance of composite propeller, the following 18 stacking sequences are assumed. (45°/−45°/22.5°/−22.5°/90°/45°/θ_R/0°/67.5°/−67.5°/90°/45°/−45°/−30°/30°/−22.5°/−15°. Although the ultimate objective of the problem is to enhance the operating range of the composite propeller, the process of calculating the cavitation inception with stacking has not yet been automated. However the cavitation inception of a propeller at a specific condition is dependent on the pitch angle of the propeller operating at the advance coefficient. In fact, the analytically optimal efficiency for a propeller for each value of \( J \) corresponds to an optimal pitch angle at that value of \( J \). The plots of fig. 1 presented by [43], showed the calculated set of optimal efficiencies and optimal pitch angles. The same figure shows the limitations of a rigid propeller design; because a rigid propeller maintains a constant pitch angle, independent of the advance coefficient, it can achieve maximum efficiency for only one specific value of the advance coefficient. The advance coefficient itself is the function of advance velocity \( V_a \), the rotational speed \( n \) rps and the diameter of the propeller. For rigid propellers, the propeller is designed to work optimally for a specific design advance coefficient, and there is a small range of inflow velocities where the propeller is optimal. However, the large deviations from the design conditions result in sub-optimal efficiency and cavitation performance. This loss in efficiency and cavitation performance can be overcome by a propeller that could change the pitch angles according to the changes in flow conditions. Because self-twisting propellers deform in response to changes in inflow conditions, they are not constrained to a single pitch angle and can approach the set of optimal pitch angles. Thus the objective of the present problem is formulated as a minimization of the total distance between the optimal theoretical pitch angles and the pitch angles predicted for a self-twisting propeller.

**Table 1: Composite materials and their properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Density (gm/cc)</th>
<th>( E_1 ) (Gpa)</th>
<th>( E_2 )</th>
<th>( E_3 )</th>
<th>( v_{12} )</th>
<th>( v_{23} )</th>
<th>( v_{13} )</th>
<th>( G_{12} ) (Gpa)</th>
<th>( G_{23} )</th>
<th>( G_{13} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>R Glass roving UD / Epoxy</td>
<td>0.3</td>
<td>2</td>
<td>48.3</td>
<td>12.4</td>
<td>12.4</td>
<td>0.16</td>
<td>0.28</td>
<td>0.28</td>
<td>6.6</td>
<td>4.14</td>
<td>4.14</td>
</tr>
<tr>
<td>S Glass fabric / Epoxy</td>
<td>0.32</td>
<td>1.8</td>
<td>22.92</td>
<td>12.4</td>
<td>12.4</td>
<td>0.12</td>
<td>0.2</td>
<td>0.2</td>
<td>4.7</td>
<td>4.2</td>
<td>4.2</td>
</tr>
<tr>
<td>Carbon UD / Epoxy</td>
<td>0.3</td>
<td>1.6</td>
<td>25</td>
<td>10</td>
<td>10</td>
<td>0.16</td>
<td>0.2</td>
<td>0.16</td>
<td>5.2</td>
<td>3.8</td>
<td>6</td>
</tr>
</tbody>
</table>

Fig 1: Efficiency and pitch angle for a rigid propeller as function of advance coefficient \( J \) [43].
This can further be simplified since it is sufficient to only maximize the twist in a candidate propeller design, as any increase in twist will increase the slope of the \( \phi - J \) curve (Fig 1), hence approaching the set of pitch angles that maximizes the efficiency and the cavitation for a range of inflow velocities. However, increasing twist reduces the bending stiffness of the propeller. To limit the extent of this undesirable outcome, one has to draw the line between twist angle and bending rigidities. As discussed in literature, for the analytical model chosen, twist angle has been calculated. All the stacking sequences are assumed to be symmetric. As a result of selecting symmetric laminates, extension-twist coupling is not investigated, i.e. \( B_{16} \) and \( B_{26} = 0 \). For the purpose of understanding the effect of bend-twist coupling on the performance of composite marine propeller, the ply angle of the layer made of R-glass roving UD/epoxy is changed systematically in stacking sequences \( S_1 \) to \( S_{18} \) from \( 90^0 \) to \( -90^0 \). For better understanding the propeller characteristics, the stiffness ratios of \( D_{16}/D_{11}, D_{26}/D_{11}, D_{16}/D_{22}, and D_{26}/D_{22} \) versus \( \theta \) for the laminate \( (45^0_{s2}/-45^0_{s2}/22.5^0_{c}/-22.5^0_{c}/90^0_{c}/45^0_{c}/\theta_{Rg}/0^0_{c}/67.5^0_{c}/-67.5^0_{s2}/90^0_{s2}/60^0_{s2}/-60^0_{s2})_s \) are calculated. The effective rigidities of the beam in global coordinate system [Berthelot] are plotted as a function of sequence number in fig 2, 3, and 4. For choosing the stacking sequence, the twist angle is also plotted as a function of stacking sequence number as shown in fig 5.
From fig 2 and 3, it is seen that the bending rigidities and torsion rigidities are maximum for 8th, 9th, 12th and 13th sequences. From the figure of bending-torsion coupled rigidity in fig 4, the values are positive maximum for 8th and 9th sequences but negative for 12th and 13th sequences. Whereas there is no considerable change in twist angle as predicted in fig 5, for 8th, 9th, 12th and 13th stacking sequences. Conclusively, to enhance the performance of the composite propeller, stacking sequences which have got higher values of rigidities and simultaneously produce high twist angle is selected which is a performance enhancer as understood from the literature. The 14th sequence which has got almost zero twist angle resembles the rigid NAB propeller in characteristics.

The solid 46 element from the Ansys library is chosen for the analysis. The material data and layup sequence is incorporated in hyper-mesh 9.0. 3D composite elements layers are stacked according to the measured thickness of each element. For meshing the composite propeller the solid model is imported in to hyper mesh and the elements are selected for various layup sequences as given by their thickness.

3. Results and discussions

Hydro elastic model is executed for the two stacking sequences as shown below. 8th sequence is taken as S1 and 14th sequence as S2.

\[ S1 = (45_{x2}/-45_{x2}/22.5_{c}/-22.5_{c}/90_{c}/45_{c}/67.5_{ RG}/0_{c}/67.5_{c}/-67.5_{x2}/90_{x2}/60_{x2}/-60_{x2}) \]

\[ S2 = (45_{x2}/-45_{x2}/22.5_{c}/-22.5_{c}/90_{c}/45_{c}/-45_{RG}/0_{c}/67.5_{c}/-67.5_{x2}/90_{x2}/60_{x2}/-60_{x2}) \]

These two stacking sequences are used for modeling a propeller and cavitation inception based on the minimum absolute pressure of 1720 pa, corresponding to 15° c is used. The following table 2, gives the details of the analysis.
Table 2: minimum pressure Vs stacking sequence

<table>
<thead>
<tr>
<th>j</th>
<th>0.934</th>
<th>0.747</th>
<th>0.560</th>
<th>0.448</th>
<th>0.422</th>
<th>0.374</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Pressure @NAB</td>
<td>92240</td>
<td>84600</td>
<td>55500</td>
<td>16000</td>
<td>1720</td>
<td></td>
</tr>
<tr>
<td>Min Pressure @S1</td>
<td>96532</td>
<td>90520</td>
<td>65486</td>
<td>23120</td>
<td>3300</td>
<td>1760</td>
</tr>
<tr>
<td>Min Pressure @S2</td>
<td>90370</td>
<td>82326</td>
<td>53620</td>
<td>15280</td>
<td>1748</td>
<td></td>
</tr>
<tr>
<td>Efficiency @NAB</td>
<td>0.711</td>
<td>0.631</td>
<td>0.512</td>
<td>0.451</td>
<td>0.386</td>
<td>0.251</td>
</tr>
<tr>
<td>Efficiency @S1</td>
<td>0.785</td>
<td>0.693</td>
<td>0.604</td>
<td>0.511</td>
<td>0.46</td>
<td>0.456</td>
</tr>
<tr>
<td>Efficiency @S2</td>
<td>0.70</td>
<td>0.61</td>
<td>0.496</td>
<td>0.42</td>
<td>0.403</td>
<td>0.224</td>
</tr>
</tbody>
</table>

From the above table, it is concluded that, stacking sequence S1, have enhanced cavitation inception speed compared to NAB and S2. As S1, has got relatively high bending, torsion and bending–torsion rigidities with respect to the angle of twist compared to others. Therefore S1 is used for the composite propeller. The minimum pressure Vs advance coefficient, J is plotted in fig 6. It is clearly evident that no cavitation range is more with S2 sequence.

3.1 Fabrication of composite propeller with hand-layup.

Marine composite propeller can be developed by open and closed molding with hand or spray layup reinforcement lamination. Molland and Turnock [6], have successfully produced the hybrid composite of a four bladed propeller type based on wageningen B4-40 series profile using the closed molding by hand layup reinforcement lamination. The same procedure is adopted in this research work. Woznick [67], also adopted an open mould method for reinforcement materials to lay on to a duplication of an YP677 single propeller blade.

The closed molding type suggested a more controllable of a material curing parameters, consistency and quality. In this work a four bladed marine propeller, INSEAN E779a with a diameter of 205mm and , hub diameter of 50mm and hub length of 78.33mm is adopted which has a nominal pitch of 190 mm. A two piece mould type is designed to produce an FRP composite detachable blade by hand lay-up lamination process. The mould design and development is carried out with the help of a computer aided drawing tool, Solid works and manufacturing application tool master CAM. The mould is designed to produce complete propeller geometry with low skew. The upper mold is designed to form a propeller back (suction) section and lower mould is propeller blade face (pressure) section as shown in fig 7.

The lower mould is provided with three bleeding ways to ensure that excess resin and air bubbles can be bled out. The mould parts are fabricated by computer numerical control CNC machining using Computer aided manufacturing (CAM) application tool (Master Cam) for machining tool path planning and generating. The mould for propeller blade is as shown in fig 8.
Efficiency of the propeller with respect to the advance coefficient is plotted in fig 9. Whereas the experimental comparison is made in fig 10.

4. Conclusion
It is concluded that from the results presented above, well designed composite propeller can replace a metallic propeller for enhanced performance from cavitation and efficiency point of view. Hydroelastic model can effectively be used for predicting the behaviour of shape adaptive composite propellers.
5. References

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