SHAPE-ADAPTIVE COMPOSITE MARINE PROPELLERS – ANALYSIS AND OPTIMIZATION

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1 Introduction

The knowledge and technology behind design and manufacturing of marine propellers has been in existence for several centuries. This is predominantly for alloys such as using Nickel Aluminium Bronze (NAB) and Manganese Nickel Aluminium Bronze (MAB). However, the increasing demand for high efficiency, high strength-to and high stiffness-to-weight ratio has led marine propeller research in a new direction towards engineered materials. Recently, the use of such engineered materials, especially laminated composites, to manufacture marine propellers has received considerable attention equally among researchers and industry. This is due to the favourable qualities of composites over metal alloys such as light weight, reduced corrosion, reduced noise generation, no magnetic signature and passive shape adaptability [1-3].

From a mechanical design and optimisation perspective, efficiency improvement through passive shape adaptability is one of the most attractive capabilities of a composite marine propeller. Passive shape adaptability refers to the capability of composites to deform, without the involvement of external mechanisms based on incoming flow conditions and rotational speeds. This can be achieved by exploiting the intrinsic extension-shear, bend-twist and bend-extension coupling effects of anisotropic composites [4]. Such deformations can potentially be used to enhance the efficiency of a marine propeller especially at off-design conditions. In this paper it is proposed to achieve this by optimising the fibre layup angles and layup materials of the composite, such that the propeller has an optimum bend-twist coupling performance.

Bend-twist coupling refers to the special characteristic of anisotropic materials where out of plane bending moments can cause twisting strains. With correct layup arrangements this effect can be optimised for a certain application using layered composites. Various researchers in the past [1, 2, 4-6] have used flexibility and bend-twist coupling characteristics of composites to design marine propellers that have the capability of self-varying pitch (shape adaptable) based on out of plane bending moments caused by the incoming flow.

The approach taken by Lin and Lee [5, 7, 8] was to minimize the change of torque coefficient of the propeller when moving from the design advance ratio to one other off-design advance ratio. The reason behind this strategy was maintaining the torque, thrust and efficiency the same as the design value when moving away from the design point. However, only one off-design point was considered. The optimization process used by Liu, et al. [4], Motley, et al. [6], Pluciński, et al. [9] attempted to ensure that the ply configuration was chosen such that the blade can achieve the maximum possible pitch variation when moving from unloaded to loaded state. Essentially, the optimization technique attempted to make the blade more flexible while maintaining strain and shape limitations.

A framework to design laminated composite marine propellers with enhanced performance by utilizing bend-twist coupling characteristics is proposed in this paper. The framework consists of iso-geometric analysis combined with a Genetic Algorithm (GA) to optimise layup arrangement of laminated composites. The key requirement for the optimization technique proposed here is to achieve an efficiency curve for the composite propeller that is tangential to all efficiency curves in the vicinity of design (cruise) advance ratio of the vessel. In contrast to the approaches taken by previous researchers, the proposed method attempts to achieve exact pitch angles derived from propeller
efficiency curves based on many off-design points. It also gives the freedom to specify weightages to off-design points based on the probability the blade is likely to operate at that point over others. In addition, non-uniform rational B-splines (NURBS) based finite element method (FEM) has the potential to make the optimization process more accurate, with faster mesh convergence and less demanding in terms of computational time [10], as NURBS based FEM has the capability of representing the exact geometry of complex shapes with a much smaller number of elements, compared to standard FEM, without any defeaturing.

2 Iso-Geometric Analysis

Existing approaches use conventional FEM combined with optimization schemes [1, 11, 12]. Due to the complex shape of propellers, conventional FEM based approaches can only approximate the geometry. In this paper, an attempt is made to use an iso-geometric FEM [13] algorithm to model a composite propeller. The main advantage of the proposed approach is that the geometry can be accurately modeled and the CAD and the FE analysis can be seamlessly integrated. The finite element approximation uses NURBS as the basis functions. The key ingredients in the construction of NURBS basis functions are: the knot vector, the control points, the degree of the curve and the weight associated to a control point. The \( i^{th} \) B-spline basis function of degree \( p \), denoted by \( N_{i,p} \), is defined as:

\[
N_{i,0}(\xi) = \begin{cases} 
1 & \text{if } \xi_i \leq \xi \leq \xi_{i+1} \\
0 & \text{else}
\end{cases}
\]

\[
N_{i,p}(\xi) = \left( \frac{\xi - \xi_i}{\xi_{i+p} - \xi_i} \right)N_{i,p-1}(\xi) + \left( \frac{\xi_{i+p} - \xi}{\xi_{i+p+1} - \xi_{i+1}} \right)N_{i+1,p-1}(\xi)
\]

A \( p^{th} \) degree NURBS curve and NURBS surface is defined by:

\[
C(\xi) = \frac{\sum_{i=0}^{m} N_{i,p}(\xi) w_i P_i}{\sum_{i=0}^{m} N_{i,p}(\xi) w_i}
\]

\[
S(\xi, \eta) = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} N_{i,j}(\xi) M_{i,j}(\eta) P_{i,j} w_i w_j}{W(\xi, \eta)}
\]

It should also be noted that the continuity of the NURBS functions could be custom tailored to suit the needs of the problem. Iso-geometric analysis uses the same basis functions for the geometry and the field variables, representing the accurate geometry without any defeaturing introduced due to meshing.

3 Proposed design and optimisation scheme

The proposed propeller design scheme consists of two stages. The first stage attempts to optimize the ply angles of the layers such that optimum bend-twist coupling performance can be achieved around the standard operating condition. The standard operating condition is defined as the cruise speed of the vessel. Once the required ply configuration to enable pitch change is obtained, the second stage of the design scheme is to determine the unloaded shape of the propeller blade. This is an iterative process where the pre-twist of the blade is changed such that it reaches the required pitch at the cruise speed under cruise speed fluid loadings. A popular propeller series, the Wageningen-B series [14], will be used as the reference for shape and performance characteristics of the composite propeller. The use of Wageningen-B series is also due to the availability of extensive experimental data in open literature.

3.1 Stage One: Ply angle optimisation

In stage one, it is proposed to construct a “difference-scheme” relative to the operating point in terms of pressure and twist. To achieve this, first it is intended to use a standard fluid solver (preferably a panel solver that is optimized for propellers) to obtain a pressure map on the propeller blade surface for various speeds in the vicinity of operating/cruise condition. The shape of the popular Wageningen-B series propellers will be used to construct the geometry of the blade. Pressure difference functions will then be constructed with respect to the operating condition for every chosen point around the operating point. The pressure difference functions will then be converted to nodal force differences to be used in the finite element based optimization process. The required ideal pitch variation to maintain the optimum efficiency will also be assessed relative to the pitch at operating condition. These pitch differences will be obtained using standard propeller efficiency curves for the
propeller series which the composite propeller is based upon.

The objective function of optimization will attempt to minimize the total difference (corresponding to the respective pressure difference) between the optimum pitch that is required and the pitch that was obtained by the chosen ply configuration (Eq. (4)) at each iteration step in the Genetic Algorithm.

\[
\min_{\theta} f(\theta) = \sum_{i=1}^{n} |\Delta \phi_{tip,required}^{i} (\Delta P_{i}) - \Delta \phi_{tip,GA}^{i} (\Delta P_{i})|
\]  

Here, \( n \) is the total number of points chosen above and below the operating condition. Although this paper will present the optimization task as an unconstrained optimization problem, constraints will be based on composite failure theories that are yet to be extensively investigated for this application.

3.2 Stage Two: Unloaded shape

Unlike rigid alloy propellers, composite propellers cannot be manufactured at their optimum shape due to the shape change over the transition from unloaded to optimally loaded condition. Thus, the objective of stage two is to achieve the pre-deformation required for the blade, such that it reaches the optimal shape at the operating condition. The proposed methodology is iterative as summarized in Fig. 2. The basic idea is to apply negative strains to the blade and iterate the shape until the required shape at the design point under design loadings. A similar methodology was also used by Pluciński, et al. [9], Mulcahy, et al. [15].
4 Optimisation tools and technique

The optimisation process was achieved using the Genetic Algorithm (GA). Being an iterative evolutionary algorithm, the GA is dependent upon an accurate method that can evaluate the deflection and twist achieved by each ply angle configuration. Thus, in-house shell based (using first-order shear deformation theory) FEM codes were developed and coupled with the GA. FEM codes were developed based on both standard Lagrange based FEM and Iso-Geometric NURBS basis functions. All coding were performed using the commercially available technical computing software Matlab™.

4.1 NURBS mesh convergence and stability

A mesh convergence study was conducted to ensure that the NURBS based finite element technique is stable and provides accurate results with the increase in the number of degrees of freedom. Typically, NURBS meshes can be refined in three ways: h-refinement (knot insertion), p-refinement (elevation of degree of NURBS bases) and k-refinement (a combination of both h and p-refinements) [16]. It is beyond the scope of this paper to discuss these refinement techniques in detail and interested readers are referred to the literature on the applications of NURBS based partition of unity method to analyse plate structures Shojaee, et al. [17], Valizadeh, et al. [18], Scott, et al. [19]. However, for the purposes of mesh convergence and stability, h-refinement and p-refinement will be presented and the convergence of maximum displacement was investigated.

For the study, a simple rectangular plate with dimensions: 0.4 m (L) x 0.2 m (W) x 3 mm (t) was considered. It was assumed that the plate was made out of unidirectional CFRP (Table 3) and has 24 plies all having a fibre orientation of 40° counter clockwise from x-axis towards y-axis. The plate was assumed to be clamped at the left edge and a uniform pressure loading of 100 Pa (upwards) was applied on the top surface. The mesh was created for NURBS orders 2 and 3 with a varying number of control points for each order. Details of the meshes that were validated and their results are given in Table 1. Fig. 3 illustrates the mesh, including control points (squares), of the first model with NURBS order 3. For verification purposes maximum deflection obtained using standard FEM (using the commercial software ANSYS™, 8-noded shell 281) is also presented.

<table>
<thead>
<tr>
<th>Control Points</th>
<th>Physical mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Lattice (DOFs)</td>
<td>Max. Displacement</td>
</tr>
<tr>
<td>Mesh 1</td>
<td>5×5 (150)</td>
</tr>
<tr>
<td>Mesh 2</td>
<td>8×8 (384)</td>
</tr>
<tr>
<td>Mesh 3</td>
<td>16×16 (1536)</td>
</tr>
<tr>
<td>Mesh 4</td>
<td>32×32 (6144)</td>
</tr>
<tr>
<td>ANSYS™ FEM: Q8 shell 9841 nodes (59046 DOFs)</td>
<td>6.2119</td>
</tr>
</tbody>
</table>

Table 1. Mesh statistics and convergence results
As expected, it was observed that higher order NURBS converged faster with a smaller number of control points. Further higher orders were also investigated and were found to have rapid convergence. For the sake of brevity, results for higher order basis functions are not shown here.

Based on the results obtained, it was clear that the in-house solver has good stability and convergence. Thus, it can be used for complex shapes with confidence.

### 4.2 Genetic Algorithm

Genetic Algorithms fall into the category of Evolutionary Algorithms and is widely used in many practical applications. The GA scheme is iteration based and is inspired by the natural gene selection of species. In summary, GA evaluates fitness of the input variables and attempts to converge at the best variable combination that can optimize the objective function [20]. GA has been used by authors in various composite ply optimisation tasks [5, 7, 9, 21, 22], proving its attractiveness and credibility. Awad, et al. [23] provided a comprehensive comparison between various optimization techniques and their applicability in composite design, summarizing the many advantages of GA. Some of these advantages are the capability of handling non-linear objective functions, non-linear constraints and both discrete and continuous variables. Moreover, GA provides a “best” solution for the problem under the given constraints. This is another desirable aspect of GA that improves its practicality over most other algorithms that terminate when an exact solution does not exist for the problem. However, one disadvantage of GA is that it may at times converge to local/false minima instead of the global minimum.

One simple strategy to overcome this is performing GA initialized using different initial search ranges. In the context of marine propellers, although objective functions of optimization were different, many authors have used GA as the optimization algorithm [1, 4, 5, 9].

### 5 NURBS coupled GA validation study

A demonstration of the proposed optimization technique using GA coupled with NURBS based FEM was attempted. The proposed optimization approach gives the highest priority to ensure that the shape of the propeller at the design point is achieved and the required twist was attempted to be maintained in the vicinity of the design point. A rectangular plate with similar dimensions to the convergence test (0.4 m (L) x 0.2 m (W) x 3 mm (t)) with uniform pressure distributions normal to the surface was considered.

Required (ideal) slopes at the tip (\(\phi\)) for various uniform pressure distributions (P) were arbitrarily chosen for this example as given in Table 2. An applied pressure of 1000 Pa with 5° nominal tip angle was taken as the operating/cruise condition. Pressure distributions and tip angle requirements were chosen such that there are no obvious relationships between each other in order to maintain generality. In the case of a propeller, the pressure values will be found by performing CFD analysis at the required velocities in the vicinity of the design point.

<table>
<thead>
<tr>
<th>(P(x,y)) (Pa)</th>
<th>750</th>
<th>800</th>
<th>1000 (Cruise)</th>
<th>1300</th>
<th>1400</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\phi) (deg)</td>
<td>3.5</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>6.5</td>
</tr>
<tr>
<td>(\Delta P(x,y)) (Pa)</td>
<td>-250</td>
<td>-200</td>
<td>0</td>
<td>+300</td>
<td>+400</td>
</tr>
<tr>
<td>(\Delta \phi) (deg)</td>
<td>-1.5</td>
<td>-1</td>
<td>0</td>
<td>+1</td>
<td>+1.5</td>
</tr>
</tbody>
</table>

Table 2. Optimum tip angles required for various pressure distributions (only uniform pressures were considered for this example)

The composite plate was made out of AS4/3501-6 (prepreg) CFRP layers (Table 3) with a nominal thickness of 0.125 mm. The GA coupled with NURBS based FEM, was used to minimise the objective function (Eq. (4)) for four different cases – continuous ply angles, ply angles constrained to integer increments, 5 degree increments and 10 degree increments. The derived optimal ply configuration results are presented in Table 4. These
results were independently verified using the commercial FEM software ANSYS™.

<table>
<thead>
<tr>
<th>Property</th>
<th>AS4/3501-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kgm⁻³)</td>
<td>1590</td>
</tr>
<tr>
<td>$E_1$ (GPa)</td>
<td>126</td>
</tr>
<tr>
<td>$E_2$ (GPa)</td>
<td>11</td>
</tr>
<tr>
<td>$G_{12}$ (GPa)</td>
<td>6.6</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.28</td>
</tr>
<tr>
<td>$\nu_{23}$</td>
<td>0.4</td>
</tr>
<tr>
<td>Nominal thickness (mm)</td>
<td>0.125</td>
</tr>
</tbody>
</table>

Table 3. Mechanical Properties of CFRP layers [24]

<table>
<thead>
<tr>
<th>Variables</th>
<th>Optimum ply configuration (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>[39.57 / 39.93 / 29.00 / 49.20 / 58.95 / 55.11 / 29.44 / 51.57 / 7.56 / 45.57 / 13.62 / 6.73]</td>
</tr>
<tr>
<td>1° increments</td>
<td>[44 / 40 / 35 / 103 / 88 / 60 / 85 / 22 / 29 / 92 / 94 / 132]</td>
</tr>
<tr>
<td>5° increments</td>
<td>[30 / 35 / 50 / 45 / 80 / 20 / 25 / 90 / 60 / 70 / 90 / 60]</td>
</tr>
<tr>
<td>10° increments</td>
<td>[40 / 70 / 40 / 60 / 50 / 50 / 50 / 10 / 50 / 100 / 50 / 150]</td>
</tr>
</tbody>
</table>

Table 4. Optimum ply angles calculated using the Genetic Algorithm

The final step was to calculate the unloaded tip angle (shape) of the plate. As explained in Section 3.2, the first step of the process is to apply reverse strains or reverse loads. In this example reverse loads were applied. If reverse strains were applied the iteration path will be slightly different, but will eventually converge to the same unloaded shape. By applying reverse loads it was found that the plate needs an initial tip angle of 2.0212°. This yielded the first step of the iteration loop. Summary of iteration values is presented in Table 5. These values are depicted in Figure 5 for better representation.

Table 5. Summary of iteration steps

<table>
<thead>
<tr>
<th>Iteration No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloaded $\phi$ (deg)</td>
<td>2.0212</td>
<td>1.4011</td>
<td>1.3203</td>
</tr>
<tr>
<td>Loaded $\phi$ (deg) at design pressure</td>
<td>5.62</td>
<td>5.0808</td>
<td>5.008</td>
</tr>
<tr>
<td>Difference (deg) w.r.t design requirement</td>
<td>0.62</td>
<td>0.0808</td>
<td>0.008</td>
</tr>
<tr>
<td>% Difference</td>
<td>12.4</td>
<td>1.616</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table 5. Summary of iteration steps

Thus, the plate has to be manufactured with a uniform twist with 0° at root and 1.32° at tip, with a ply layup chosen from Table 4. In order to verify the results, after the unloaded shape was obtained, the geometry was constructed in commercial software ANSYS™ and pressure values (Table 2) were applied. Comparisons made are shown in Fig. 6.

Based on this simple plate twist optimisation problem it is clear that the proposed two-stage optimisation scheme using FEM coupled with GA provides highly accurate results for optimisation.
6 NURBS propeller blade optimization

The GA coupled NURBS FE solver was used to optimize a Wageningen-B Series propeller blade for various pressure distributions. Similar to the plate example in the preceding section, optimization was carried out to find the ideal ply layup to achieve the required twist variation. Blade optimisation was carried out for uniform and arbitrary pressure distributions. Although the pressure variations were arbitrary, they were chosen sensibly based on the pressure distribution at cruise condition obtained using CFD analysis. The blade was chosen from the Wageningen-B five bladed series having expanded area ratios (EAR) of 0.75. The propeller was chosen to have a diameter of 0.4 m with the hub having a diameter of 0.08 m, respecting the standards of Wageningen-B series. One special characteristic of the Wageningen-B series is all propellers, apart from 4-bladed propellers, have constant pitch distributions in the radial direction, making the blades 2-dimensional on the plane of the blade [14]. Thus, 2-dimensional NURBS meshes were generated. NURBS meshes were generated using the commercial software Rhino and mesh information (knot vectors, control point locations, weightages and orders of NURBS bases) was exported into the FEM solver. Fig. 7 shows the mesh and control points (squares) generated for:

- Control Points i direction = 10
- Control Points j direction = 22
- NURBS order i direction = 3
- NURBS order j direction = 3
- i knot vector (14 elements) = [0, 0, 0, 0, [1:6] × 0.1429, 1, 1, 1, 1]
- j knot vector (26 elements) = [0, 0, 0, 0, [1:18] × 0.0526, 1, 1, 1, 1]

Figure 7 clearly illustrates the capability of a NURBS based FE mesh to accurately discretize a complex geometry with curved boundaries using a minimal number of elements. The NURBS mesh for the blades was created using a 2-dimensional structured mesh. Readers interested in unstructured meshed as encouraged to read Scott, et al. [19].

Based on hypothetical requirements presented in Table 6, continuous variable optimization was carried out using material specifications for CFRP AS4/3501-6 (Table 3).
Table 6. Pressure distributions and pitch angle requirements for propeller blade

<table>
<thead>
<tr>
<th>P (kPa)</th>
<th>∆P (kPa)</th>
<th>Pitch/Dia. (P/D)</th>
<th>(\phi) (deg)</th>
<th>∆(\phi) (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>-70</td>
<td>0.7</td>
<td>12.56</td>
<td>-3.44</td>
</tr>
<tr>
<td>230</td>
<td>-20</td>
<td>0.8</td>
<td>14.3</td>
<td>-1.7</td>
</tr>
<tr>
<td>250</td>
<td>0</td>
<td>0.9</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>285</td>
<td>+35</td>
<td>1.0</td>
<td>17.66</td>
<td>+1.66</td>
</tr>
<tr>
<td>300</td>
<td>+50</td>
<td>1.1</td>
<td>19.3</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Table 7 shows ply angle results obtained using the optimization scheme approximated to one decimal point. A comparison between pitch angle requirement and achieved pitch angle is shown in Fig. 8.

| B5-75 | [35.7 / 0.0 / 0.0 / 141.3 / 121.3 / 30.0 / 42.8 / 121.7 / 57.3 / 41.0 / 0.0 / 0.4 / 26.3 / 0.0 / 78.2 / 0.0 / 12.0 / 55.5 / 60.3 / 56.4] |

Table 7. Ply angle results for B5-75

6. Conclusion

The optimization and tailoring of composite materials for specific requirements has been in existence for several decades. Recently there has been a development in applying this knowledge in the field of marine propeller design. This paper presented an optimization process for composite marine propellers using iso-geometric analysis based FEM and the Genetic Algorithm. The main advantage of iso-geometric based FEA is its capability of representing complex shapes accurately without any mesh defeaturing. Thus, it is seen as an ideal tool for propeller optimization considering its complex shape. The paper discussed about coupling of FEM with GA and the validation for a simple flat composite plate. This was demonstrated through application to a Wageningen-B series propeller blade. The obtained results are in excellent agreement with standard FEA, demonstrating the validity of the proposed approach. It was concluded that this approach could be easily implemented for deriving the laminate design of a composite propellers with confidence.

References


