A Design Concept of Composite Marine Propeller for Long Stroke Slow Speed Main Engine

Hyounsuk Lee¹, Jaewook Hur¹, Jin Hyoun Park², Zoo Hwan Hah³, Min-Churl Song¹, Bong-Jun Chang²

¹Maritime Research Institute, Hyundai Heavy Industries, Co., Ltd., Seoul, Korea
²Initial Design Department, Hyundai Heavy Industries, Co., Ltd., Seoul, Korea
³Industrial Research Institute, Hyundai Heavy Industries, Co., Ltd., Ulsan, Korea

ABSTRACT
In this study, design methodology is considered to not only maximize a propulsion efficiency at design operating condition for satisfaction of EEDI regulation by keeping large diameter propeller and long stroke slow speed main engine, but also to maximize power margin at heavy loading condition of a propeller by optimizing passive adaptation of composite propeller. According to this, power margin is improved at low engine speed range and low advance ratio condition by ply lamination optimization for KRISO VLCC with KP458 propeller using BEM-FEM and CFD-FEM based fluid-structure interaction analysis. The BEM-FEM FSI and CFD-FEM FSI methodology is applied to select optimum ply lamination to achieve the design objective

Keywords
Composite marine propeller, Long stroke slow speed main engine (LSSS M/E), energy efficiency design index (EEDI)

1 INTRODUCTION
A composite material has been widely used in the whole industries because of its outstanding material benefits such as light weight, high strength, high stiffness and fatigue resistance. For these reasons, the fiber reinforced plastic (FRP), a representative composite material, has been in the spotlight as a novel material for marine propellers. Furthermore, the composite material propeller can improve propulsion efficiency because the FRP can control passively its flexible (bend and twist) behavior characteristics by the combination of base materials and lamination method.

Meanwhile, the strong demands for the maximization of the propulsion efficiency and the minimization of main engine (M/E) fuel oil consumption (FOC) have been increased after the energy efficiency design index (EEDI) was introduced from Jan. 2013 by the International Maritime Organization (IMO). The long stroke slow speed (LSSS) type engines are applied for M/E of commercial vessels in general, which are designed to maximize efficiency by matching with the large diameter and slow revolution speed propeller. Even though this type M/E has profits for good efficiency, it also has some problems like dissatisfaction of the minimum propulsion power requirements and lack of M/E power margin at low and middle speed range due to the characteristics of low speed M/E. Acceleration delay problems of few LSSS M/E ships at heavy weather condition have been reported, and some major engine makers recommend increase of propeller light running margin (LRM) to solve these problems. However it necessarily accompanies with the degradation of propulsion performance according to the reduced propeller optimum diameter.

In this study, a composite marine propeller design concept to improve the propeller performance at low speed / heavy load condition with optimum (large) diameter is suggested by optimization of composite lay-up.

For this purpose, steady and unsteady 2-way iteratively coupled BEM-FEM based FSI analyses are applied to evaluate the minimum power requirement and structural safety respectively. A CFD-FEM FSI analysis using co-simulation of Abaqus Standard and StarCCM+ is applied to evaluate acceleration performance at a barred speed range (BSR). The BEM-FEM FSI and CFD-FEM FSI methodology used in this study were presented in the author’s previous study. (Lee et al 2014, Lee et al 2015 and Lee at al 2016)

2 TARGET VESSEL (KVLCC2)
KP458 is applied as the target and the original propeller for KRISO KVLCC2, the well-known benchmark ship. (Table 1)

If we build a real vessel based on the opened information of KVLCC (23,125 kW x 75.7 RPM) and assume the propeller light running margin (LRM) is 3%, then we can select M/E as MAN Diesel and Turbo (MDT)’s 2-stroke engine, 7S80ME-C9.5 (low load tuning) with MCR 25,270 kW x 78.0 RPM.

In this case, the selected M/E satisfies EEDI minimum power requirement level 1 because of high MCR power.
The highest RPM in the BSR is 38 and the lowest power margin of 15.3% at that RPM. (Figure 1) According to the engine maker’s recommendation, it is expected there is no acceleration problem because of there is more than 10% power margin at the BSR range.

**Table 1** Geometric details of original KVLCC propeller, KP458

<table>
<thead>
<tr>
<th>Diameter, D (m)</th>
<th>9.86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub ratio</td>
<td>0.1550</td>
</tr>
<tr>
<td>P/D at blade root</td>
<td>0.5765</td>
</tr>
<tr>
<td>P/D at ( r = 0.7R )</td>
<td>0.7212</td>
</tr>
<tr>
<td>P/D at blade tip</td>
<td>0.6510</td>
</tr>
<tr>
<td>((P/D)_{\text{mean}})</td>
<td>0.6900</td>
</tr>
<tr>
<td>Expanded Area Ratio, EAR</td>
<td>0.431</td>
</tr>
<tr>
<td>No. of blades, Z</td>
<td>4</td>
</tr>
<tr>
<td>Tip skew angle, ( \theta ) (degree)</td>
<td>16.75</td>
</tr>
<tr>
<td>Tip rake (mm)</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Figure 1** Evaluation of acceleration through BSR, original KP458

3 APPLICATION OF LONG-STROKE SLOW SPEED M/E

To improve EEDI, the de-rated LSSS M/E and larger diameter (slow revolution speed) propeller is applied. If 7G80ME-C9.5 M/E (high load tuning) is selected and de-rated from 21,500 kW \( \times 61.2 \) RPM MCR power to 17,760 kW \( \times 57.4 \) RPM NCR power, 10.6m diameter propeller can be selected as optimum at design target 14.8 knots ship speed w/ 15% sea margin. The propeller with 10.6m diameter has the same geometry with KP458 except for diameter and mean pitch ratio for precise comparison. The specified fuel oil consumption (SFOC) which represents engine efficiency is improved about 2% and daily fuel oil consumption (DFOC) which represents total efficiency is remarkably decreased from 88.6 MT to 66.7MT. (Table 2)

Even though the ‘modified’ case (LSSS M/E) can improve EEDI dramatically by DFOC improvement, this case does not meet the minimum power requirement level 1 due to the selection of low MCR power. Therefore the modified case should be satisfied the minimum power requirement level 2. In this study, the simplified assessment methodology (PrimeShip-GREEN/MinPower) offered from ClassNK to judge the minimum power requirement level 2. The performance of POW (Propeller Open Water) at low advance ratio is required to apply the simplified assessment. Thus, the BEM code (KPA14 which will be applied in the FSI analysis is used to predict the POW performance.

**Table 2** Comparison between original and modified M/E selection (KVLCC2)

<table>
<thead>
<tr>
<th>Original</th>
<th>Modified (LSSS M/E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M/E</td>
<td>7S80ME-C9.5</td>
</tr>
<tr>
<td>Tuning</td>
<td>LOW</td>
</tr>
<tr>
<td>MCR</td>
<td>25,270 kW ( \times 78.0 ) RPM</td>
</tr>
<tr>
<td>NCR</td>
<td>23,125 kW ( \times 75.7 ) RPM</td>
</tr>
<tr>
<td>Speed</td>
<td>16.0 knots</td>
</tr>
<tr>
<td>Propeller</td>
<td>9.86 m x 4 blades</td>
</tr>
<tr>
<td>SFOC</td>
<td>159.6 g/kW·hr</td>
</tr>
<tr>
<td>DFOC</td>
<td>88.6 MT</td>
</tr>
</tbody>
</table>

**Figure 2** Simplified assessments of level 2 for modified case

**Figure 3** Evaluation of acceleration through BSR, modified

The assessment result of the minimum power requirement level 2 for the modified case is presented in the Figure 2 and Table 3. To satisfy the minimum power requirement...
level 2, the required power should be less than 100% of power on load diagram, and considering analysis error, it required power should be controlled less than 98%. But the modified case does not satisfied with level 2 for conditions that peak wave period is longer than 13 seconds.

There is also concern about acceleration problem because the minimum barred speed power margin is 8%. (Figure 3)

4 APPLICATION OF COMPOSITE PROPELLER
To solve the problem of power shortage at heavy load operation condition without basic design concept (M/E selection, propeller diameter, etc.), a composite material propeller can be introduced by utilizing its bend-twisting characteristics.

4.1 Design Procedure
A proposed design procedure of the design optimization of composite propeller for LSSS M/E is composed of 10 steps as follows:

1) Optimum M/E selection considering the design (contract and EEDI) condition.
2) Optimum propeller diameter selection and propeller design for the design condition.
3) Composite lay-up design (material composition, lamination sequence and angle, etc.) and initial geometry design to achieve target blade geometry at design condition.
4) If the minimum power requirement level 1 is satisfied by the selected M/E, do propeller efficiency maximization at the off-design condition by ply lamination optimization. (Lee et al, 2015 and Lee et al 2016) And then step to 7).
5) Evaluate the minimum power requirement level 2 with variation of skin thickness and orientation angle.

(Applying steady BEM-FEM based FSI analysis to obtain POW performance of low advance ratio)
6) If fail to satisfy the minimum power requirement level 2, return to 4) and change the composite lay-up design.
7) Calculation of bollard-pull power at the maximum BSR propeller revolution speed and evaluation of acceleration performance. (Applying CFD-FEM based FSI analysis to obtain POW performance of bollard-pull condition)
8) If the power margin is slightly deficient at BSR range, return to 4) and change the composite lay-up design.
9) Even though applying new composite lay-up design, if fail to satisfy the minimum power requirement level 2 or to achieve sufficient power margin at the BSR range, return to 1) or 2) and change the M/E or propeller design.
10) Evaluate structural safety at MCR condition by applying unsteady 2-way coupled BEM-FEM FSI method

Figure 4 Definition of fiber reference directions of the blade
4.2 Composite Lay-up
Propeller blades consist of CFRP skin and foam core are applied in this study. There are many parameters for composite blade design such as CFRP material composition, orientation angle (α), ply stack angle (θ), repeated stacking sequence, skin thickness (skin-core ratio), etc. Among these design parameters, the orientation angle of CFRP skin and skin thickness are selected as design parameter because of the convenience of application at design and manufacturing stage.

Material properties of CFRP skin and core are presented in Table 4. The repeated stacking sequence is [−30°, 0°, +30°]s and each skin ply thickness is 0.6 mm.

To design composite lay-up, the orientation angle varies from -30 deg. to +30 deg. and skin thickness varies between 36mm, 54mm and 72 mm.

Table 4 Material properties of CFRP skin and foam core

<table>
<thead>
<tr>
<th></th>
<th>HCW6019 (skin, ply)</th>
<th>Foam (core)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_{11} (MPa)</td>
<td>117,000</td>
<td>70</td>
</tr>
<tr>
<td>E_{22} (MPa)</td>
<td>7,800</td>
<td>ν</td>
</tr>
<tr>
<td>G_{12} (MPa)</td>
<td>0.320</td>
<td>0.3</td>
</tr>
<tr>
<td>G_{13} (MPa)</td>
<td>4.660</td>
<td></td>
</tr>
<tr>
<td>G_{23} (MPa)</td>
<td>4.660</td>
<td></td>
</tr>
<tr>
<td>X_{12} (MPa)</td>
<td>2,202</td>
<td></td>
</tr>
<tr>
<td>X_{13} (MPa)</td>
<td>-1,384</td>
<td></td>
</tr>
<tr>
<td>S_{12} (MPa)</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>Y_{12} (MPa)</td>
<td>-186</td>
<td></td>
</tr>
<tr>
<td>Y_{13} (MPa)</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>X_{C} (MPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S_{C} (MPa)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) S.T. = 36 mm   (b) S.T. = 54 mm   (c) S.T. = 72 mm

Figure 5 Material composition (Green : pure skin, Red : pure core and core+skin)

4.3 Initial Geometry Prediction
The pattern of blade bend-twist deformation depends on the composite lay-up design, as well as the loads acting on the blade. Thus the prediction of the initial blade geometry should be determined at given propeller design conditions with consideration of wake effect. Figure 6, 7 and 8 shows predicted initial geometry according to orientation change of skin thickness 36 mm, 54 mm and 72 mm, respectively. Figure 9 and 10 presents comparison of initial pitch ratio and initial rake ratio at 0.9 r/R.

Figure 6 Initial geometry of skin thickness 36mm
Figure 7 Initial geometry of skin thickness 54mm
Figure 8 Initial geometry of skin thickness 72mm
Figure 9 Initial pitch ratio at 0.9 r/R
Figure 10 Initial rake ratio at 0.9 r/R

The propeller pitch, is related to the propeller performance directly according to the orientation angle,
but it has relatively less relationship with the skin thickness. On the other hand, rake, which represents bend deformation characteristic, is directly affected from the skin thickness variation. Differences between target geometry and each of initial geometries at design condition are shown in Figure 11. (P/D : -0.0068 - 0.0047, x/D : -0.0002 - 0.0008) Efficiency differences between target and attained values are -0.13 - 0.16%.

Figure 11 Difference between target and attained geometry

(a) pitch difference

(b) rake difference

Figure 12 Difference between target and attained efficiency

4.4 Review on Minimum Power Requirement
To evaluate the minimum power requirement level 2, steady FSI calculation to predict POW performance at low advance ratio region for each composite lay-ups with predicted initial geometry. (eg. Figure 13 for J=0.2 case)

The simplified assessment methodology is applied by calculated POW results at low advance ratio, then we can get the results (Table 5) to determine the minimum power requirement.

Table 5 Assessment of the minimum power requirement level 2

<table>
<thead>
<tr>
<th>Orientation angle</th>
<th>Required power / Power on load diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>36mm shell thick.</td>
</tr>
<tr>
<td>-30 deg.</td>
<td>96.5%</td>
</tr>
<tr>
<td>-20 deg.</td>
<td>98.8%</td>
</tr>
<tr>
<td>-10 deg.</td>
<td>98.2%</td>
</tr>
<tr>
<td>0 deg.</td>
<td>99.4%</td>
</tr>
<tr>
<td>10 deg.</td>
<td>101.9%</td>
</tr>
<tr>
<td>20 deg.</td>
<td>104.5%</td>
</tr>
<tr>
<td>30 deg.</td>
<td>106.4%</td>
</tr>
<tr>
<td>NAB</td>
<td>106.3%</td>
</tr>
</tbody>
</table>

4.5 Acceleration Performance Evaluation at BSR
A composite propeller has different thrust and torque coefficients at each RPM even though the advance ratio are same because its blade geometry is closely connected from rotational body forces (the Coriolis force and centrifugal force). Therefore bollard-pull power should be calculated at the highest RPM of BSR and checked that the bollard-pull power is less than M/E lay out with more than 10% margin. For the bollard-pull calculation with consideration of hydro-elastic behavior of the composite propeller, the CFD-FEM FSI analysis is applied because the BEM code used in prior to FSI analysis could not support bollard-pull calculation as wake alignment at J=0 condition is not possible.

As the result of the acceleration performance evaluation at BSR for modified KP458 composite propeller (10.6m diameter, 54mm shell thickness and α = -20 deg.), the minimum power margin at BSR is 13%.
4.6 Structural Evaluation

In this study, the structural integrity of the composite propeller blade is evaluated by Tsai-Hill failure criterion (Tsai, 1965): an extension of von Mises yield criterion to anisotropic composite materials. In the criterion, failure is avoided if a failure index is less than unity (1), while failure is predicted if it is equal to or larger than 1.

Figure 14 Evaluation of acceleration through BSR, composite

During the revolution of the blade, the most critical region is the trailing edge around 0.5 r/R and it shows that the maximum failure index values are distributed between 0.23 and 0.45 ranges. Figure 15, shows that the present composite lay-up design is assuring the factor of safety of 2.2.

Figure 15 Maximum Tsai-Hill failure index (one revolution)

Maximum value is 0.45 on the trailing edge when the blade is at 12° position as shown in Figure 16.

Figure 16 Tsai-Hill failure index distribution (12° blade position)

During the revolution of the blade, the most critical region is the trailing edge around 0.5 r/R and it shows that the maximum failure index values are distributed between 0.23 and 0.45 ranges. Figure 15, shows that the present composite lay-up design is assuring the factor of safety of 2.2.

5 CONCLUSION

Application of LSSS M/E and de-rated engine setting leads to improve EEDI remarkably by reduction of SFOC and maximization propeller efficiency. But these also lead to dissatisfaction of the minimum propulsion power requirements and shortage of M/E power margin at low and middle speed range due to LSSS M/E characteristics.

Composite marine propellers can be an alternative solution. A design concept of composite marine propeller is suggested by consideration of LSSS M/E and composite propeller characteristic.

KVLCC2 and modified KP458 propeller is selected as a sample design target. The minimum power requirement is evaluated by applying the simplified assessment methodology offered from ClassNK, and the heavy load acceleration performance at the BSR is evaluated by comparison of the M/E lay-out and the bollard-pull power. These two heavy load characteristics are unable to satisfy the requirements. To resolve the problems, a composite material propeller is proposed as an alternative and proposed design concept is applied by composite lay-up optimization using BEM-FEM FSI and CFD-FEM FSI analyses. The selected composite design satisfies all requirements and the inner structure is evaluated to be safe.

REFERENCES


ClassNK, ‘PrimeShip-GREEN/MinPower Software for Assessment of Minimum Propulsion Power’


Jang, H-G, Noh, I-S, Hong, C-H. & Lee, C-S. (2013). ‘Design Algorithm of Flexible Propeller by Fluid-


DISCUSSION

Question from Ian Godfrey
I was keen to understand what geometric parameters of the propeller most affected performance in the speaker’s experience. The speaker explained that variation in pitch distribution had a more significant impact than rake.

Author’s closure
Yes, as shown in the presentation, the deformation related to pitch (twist) affects propeller performance more than the deformation related to rake (bend).

Questions from Serkan Turkman
Was it model scale or full scale in the coupled CFD and FEM simulation?

Author’s closure
All the fluid-structure interaction simulations including CFD-FEM coupled analysis in this study were carried out based on full scale.