Propeller performance penalty of biofouling: CFD Prediction

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ABSTRACT
The negative effect of biofouling on ship resistance has been investigated since the early days of naval architecture. However, for more precise prediction of fuel consumption of ships, understanding the effect of biofouling on ship propulsion performance is also important. In this study, CFD simulations for the full-scale performance of KP505 propeller in open water, including the presence of marine biofouling, were conducted. To predict the effect of barnacle fouling on the propeller performance, experimentally obtained roughness functions of barnacle fouling were employed in the wall-function of the CFD software. The roughness effect of barnacles of varying sizes and coverages on the propeller open water performance was predicted for advance coefficients ranging from 0.2 to 0.8. From the simulations, drastic effects of barnacle fouling on the propeller open water performance were found. The result suggests that the thrust coefficient decreases while the torque coefficient increases with increasing level of surface fouling, which leads to a reduction of the open water efficiency of the propeller. Using the obtained result, the penalty of propeller fouling on the required shaft power was predicted. Finally, further investigations were made into the roughness effect on the flow characteristics around the propeller and the results were in correspondence with the findings on the propeller open water performance.

1. Introduction

The adverse effects of biofouling on ship performance have been reported from the earliest times [1]. Accordingly, a large number of studies have been devoted to the roughness effect on ship resistance [2-21].

According to the literature, the impact of calcareous (hard shell) fouling is particularly critical and highly dependent on the fouling type and coverage [2, 3, 9, 10]. More recently, there have been studies utilising 3D printed artificial calcareous fouling models, e.g. barnacles, oysters or tubeworms [14, 17-21]. They observed significant increases in skin friction according to the sizes and coverage densities of the artificial fouling models.
While the results of these studies demonstrate the impact of biofouling on frictional drag and thus effective power, focusing only on frictional resistance is not enough to understand the economic and environmental impacts of biofouling. From an operational perspective, the roughness effect on ship propulsion performance is also critical as ship energy consumption does depend on not only the hull resistance but also the propulsion efficiency.

The critical impacts of biofouling on propeller efficiency have long been noted since the early days [24-26]. Taylor [27] further asserted that even the ships operating with a propeller in moderately good condition suffer a power loss in the order of 10%. Mosaad [28] claimed that the effect of the propeller surface condition could be less critical than the hull condition, but it can be more significant in terms of energy loss per unit area.

There have been relatively few experimental studies carried out for the examination of the roughness effect on propeller characteristics. McEntee [24] conducted experiments on artificially roughened model propellers to compare the propeller efficiency with the smooth propeller. Up to 35% loss in propeller efficiency was observed due to the roughened surface. Mutton et al. [29] compared the propeller open water performances in intact and damaged coating conditions and showed reduced propeller efficiency under the damaged scenarios. Korkut and Atlar [30] conducted experiments to examine the roughness effect of foul release coatings on the propeller open water performances. An interesting finding is that whilst the applied foul release coating increased the roughness amplitudes, it also reduced the texture amplitude, which results in slight decreases in both of thrust and torque and hence the overall efficiency.

Although these studies provide the pieces of evidence of roughness effect on performances of marine propellers, relating the model-scale experimental data to the full-scale roughness effect is not an easy task owing to the unique feature of the roughness effect. That is, the size of surface roughness cannot be scaled up or down [31]. While the roughness effect on skin friction can be extrapolated using the boundary layer similarity law analysis utilised by Granville [32, 33], this method may not be appropriate to predict the roughness effect on the propeller performances, which are highly affected by the pressure field around the blades. The boundary layer similarity law analysis is limited by the assumption of the zero pressure gradient. That is to say; this method cannot consider the three-dimensional effects and inevitably, it cannot properly consider the roughness effect on the pressure distribution in the flow field around the blades, which dominates the thrust and torque of the propeller.

For this reason, the roughness effect on the full-scale propeller performance is not well established yet. Atlar et al. [34] conducted numerical calculations to determine the roughness effect on the propeller open water characteristics, by using a lifting surface based propeller model combined with an empirical skin friction correction. They used a propeller roughness comparator to represent the blade roughness after several years in service. The increment of the blade section drag coefficient due to the roughness was calculated utilising the early work of Mosaad [28] and used in the numerical computation. The result indicated that the loss of the propeller efficiency could be as high as 12% with the increase in torque and decrease in thrust due to the surface roughness of the blades.
Similarly to Atlar et al. [34], Seo et al. [35] also used a lifting surface based propeller model with enhanced empirical correction for the skin friction for the numerical predictions of full-scale propeller efficiency loss due to surface fouling on the blades. The increased drag coefficient of the blade section due to the surface fouling were predicted based on the boundary layer similarity law analysis. Utilising the drag coefficients of different fouling conditions, they estimated a 14.6% loss in propeller efficiency with small calcareous fouling condition.

However, these studies are still limited by the fact that the roughness effect on the propeller is only considered by using increased blade section drag coefficients rather than imitating the roughness effect on the fluid field around the propeller, which is closely related to the surface pressure distribution on the blades. In consequence, they could not observe a considerable roughness effect on thrust, while significant increases in the torque were observed from the calculation results.

Recently, as asserted by Atlar et al. [36], the use of Computational Fluid Dynamics (CFD) is seen as an effective alternative to overcome the above-mentioned limitations of the boundary layer similarity law analysis. In CFD simulations, the roughness effect on the pressure field around the propeller can be predicted as well as other hydrodynamic characteristics. One of the most effective methods is employing the roughness functions of the surface in the wall-function of the CFD model (i.e. modified wall-function approach), which has been used by [12, 15, 16, 20]. Recently, Song et al. [37] extended the validation of the modified wall-function approach by comparing their method with a model ship towing test of Song et al. [38]. Owen et al. [39] investigated the roughness effect of biofouling on propeller characteristics using the modified wall-function approach. The simulation results indicated that severe calcareous fouling could result in 30.3% of efficiency loss compared to the smooth case. However, as the simulations were conducted in the model-scale only, it is still questionable if the simulation results can realistically represent the full-scale effect of biofouling on real marine propellers.

To the best of the authors' knowledge, there exists no specific study to predict the effect of biofouling on the full-scale marine propeller characteristics using CFD. Therefore, this study aims to fill this gap by developing a CFD model to simulate a realistic surface roughness of biofouling through employing a roughness function model to represent the surface roughness of barnacle fouling and performing a comprehensive investigation on the roughness effect of barnacle fouling on propeller characteristics in open water.

In this study, a roughness function model was employed in the wall-function of the CFD model to simulate the surface roughness of barnacles of varying sizes and coverage densities. A validation study was performed by comparing the smooth propeller open water curves obtained from the CFD simulations with the experimental results of the benchmark propeller KP505 [40]. The CFD simulations then conducted under different fouling conditions. The changes in the open water performance of the propeller were examined as well as the power penalties due to the propeller fouling. Finally, the roughness effects on the flow characteristics around the propeller were investigated.
2. Background

2.1. Propeller efficiency

Propeller open water characteristics are useful indicators of the performance for propellers in undisturbed uniform flows with steady loads. The thrust and torque, $T$ and $Q$, can be non-dimensionalised as

$$K_T = \frac{T}{\rho n^2 D^4}$$ (1)

$$K_Q = \frac{Q}{\rho n^2 D^5}$$ (2)

where $D$ is the propeller diameter, $\rho$ is the density of water, and $n$ represents the revolutions per second of the propeller. The thrust and torque coefficients, $K_T$ and $K_Q$, are generally plotted against a range of advance coefficient, $J$, which is defined as

$$J = \frac{V_A}{nD}$$ (3)

in which, $V_A$ is the advance velocity of the propeller. Then, the open water efficiency of the propeller, which is also known as the propeller efficiency, $\eta_O$, can be expressed as

$$\eta_O = \frac{K_T J}{K_Q 2\pi}$$ (4)

2.2. Roughness function

The surface roughness causes an increase in turbulence. As a consequence, the turbulent stress, wall shear stress and finally the skin friction increase. The roughness effect can also be observed in the velocity profile in the log-law region. Clauser [41] showed that the roughness effect results in a downward shift in the velocity profile in the log-law region. This downward shift is termed as ‘Roughness Function’, $\Delta U^+$. The generalised velocity profile in the log-law region for a rough surface is then given as

$$U^+ = \frac{1}{\kappa} \ln y^+ + B - \Delta U^+$$ (5)

where $U$ is the mean velocity at the normal distance of $y$ from the wall, $U_\tau$ is the friction velocity defined as $\sqrt{\tau_w/\rho}$. $\tau_w$ is the wall shear stress, and $\nu$ is the kinematic viscosity.
defined as the ratio of kinetic viscosity and the fluid density, $\mu/\rho$. $k$ is the von Karman constant and $B$ is the log-low intercept.

The roughness function, $\Delta U^+$ can be expressed as a function of the roughness Reynolds number, $k^+$, defined as

$$k^+ = \frac{k U_t}{v} \quad (6)$$

where, $k$ is the roughness height. It is of note that $\Delta U^+$ simply vanishes in the case of a smooth condition. Once the roughness function, $\Delta U^+ = f(k^+)$, of the given roughness surface is known, it can be utilised in the boundary layer similarity law analysis established by Granville [32, 33] or directly embedded into a CFD solver to predict the roughness effect on the frictional resistance of a ship covered with the given roughness [15].

Demirel et al. [14] used an experimental approach to obtain the roughness functions of barnacles of varying sizes and coverages. Different sizes of real barnacles, categorised as small, medium and big regarding their size, were digitised using 3D scanning technology and 3D printed into the artificial barnacle tiles. The barnacle patches were then glued onto the flat plates by differing the coverage area, and the plates were towed at a range of speeds.

From the analysis of the experimental results, they showed that the roughness functions of the test surfaces could be defined by the roughness function model of Grigson [42], as

$$\Delta U^+ = \frac{1}{\kappa} \ln(1 + k^+) \quad (7)$$

Table 1 shows the representative roughness heights, $k_G$, for the fouling conditions of different barnacle sizes and coverage densities and Figure 1 shows the roughness functions obtained from the experiment and the roughness function calculated using Equation 7. It is of note that $k_G$ is a parameter in length dimension used to represent the hydrodynamic behaviours of rough surfaces. In this case, the $k_G$ values were determined by Demirel et al. [14] according to the barnacle heights, $h$, and the surface coverages, $SC$, such that the roughness function values collapse on top of the Grigson’s roughness function model. The $k_G$ value can also be used to quantify the fouling severity. For example, B20% case is the most severe fouling condition due to the highest $k_G$ value.

Recently, Song et al. [16] employed this roughness function into the wall-function in the CFD model for the investigation of the roughness effect on full-scale ship hydrodynamic characteristics. For validation, they conducted model-scale flat plate simulations using the modified wall-function approach and showed excellent agreements comparing the simulation results with the experimental data. In this study, the same approach was used as Song et al. [16]. In other words, to represent the roughness function of the barnacle surfaces of Demirel et al [14], Grigson’s roughness function model was used with the $k_G$-based $k^+$ values ($k^+ = k_G U_t/v$). And this roughness function model was embedded into
the wall-function in the CFD model to simulate the roughness effect of the barnacle surfaces.

3. Numerical modelling

3.1. Mathematical Formulations

The proposed CFD model was developed based on the Reynolds-averaged Navier-Stokes (RANS) method using a commercial CFD software package, STAR-CCM+ [43]. The averaged continuity and momentum equations for incompressible flows may be given in tensor notation and Cartesian coordinates as in the following two equations [44].

\[
\frac{\partial (\rho \bar{u}_i)}{\partial x_i} = 0
\]

\[
\frac{\partial (\rho \bar{u}_i)}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho \bar{u}_i \bar{u}_j + \rho \bar{u}_i' \bar{u}_j' \right) = - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \bar{\tau}_{ij}}{\partial x_j}
\]

in which, \( \rho \) is density, \( \bar{u}_i \) is the averaged velocity vector, \( \rho \bar{u}_i \bar{u}_j + \rho \bar{u}_i' \bar{u}_j' \) is the Reynolds stress, \( \bar{p} \) is the averaged pressure, \( \bar{\tau}_{ij} \) is the mean viscous stress tensor components. This viscous stress for a Newtonian fluid can be expressed as

\[
\bar{\tau}_{ij} = \mu \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)
\]

where \( \mu \) is the dynamic viscosity.

In the CFD solver, the computational domains were discretised and solved using a finite volume method. The second-order upwind convection scheme was used for the momentum equations. The overall solution procedure was based on a Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) type algorithm. The shear stress transport (SST) \( k-\omega \) turbulence model, presented by Menter in 1994 [45], was used to predict the effects of turbulence, which combines the advantages of the \( k-\omega \) and the \( k-\varepsilon \) turbulence model. This model uses a \( k-\omega \) formulation in the inner parts of the boundary layer and a \( k-\varepsilon \) behaviour in the free-stream for a more accurate near-wall treatment with less sensitivity of inlet turbulence properties, which brings a better prediction in adverse pressure gradients and separating flow [45].

3.2. Geometry and Boundary Condition

In this study, a full-scale CFD model of the KP505 propeller was developed to examine the effect of biofouling on the propeller performance. The KP505 was designed by Korea Research Institute of Ships and Ocean Engineering (KRISO) to be used for the KRISO Container Ship (KCS). Table 2 and Figure 2 show the principal particulars and geometry of the KP505 propeller.
Figure 3 depicts an overview of the computational domain with the selected boundary conditions in the CFD simulations. The boundary conditions of the simulations were selected to represent the propeller which is completely submerged in an infinite ocean. The computational domain consists of a stationary region (outer zone) and a rotating region (inner zone).

For the opposite faces at the $x$-direction, a velocity inlet boundary condition was applied for the inlet free-stream boundary condition, and a pressure outlet was chosen for the outlet boundary condition while the far-field boundaries were defined as symmetry planes. The inlet, outlet and far-field boundaries were placed at $5D$, $13D$ and $3.5D$ distance from the propeller to avoid any reflections downstream of the propeller and to ensure uniform incoming flow upstream of the propeller. The surface boundary condition of the propeller was defined as the no-slip condition. For smooth cases, the smooth type wall-function was used (i.e. Equation 5 without $\Delta U^+$) while the fouled cases used the rough type wall-function containing the roughness function model, corresponding Equation 5 and 7. It is of note that for the fouled propeller simulations, the rough surface conditions were applied to both the propeller hub and blades.

In this study, the Moving Reference Frame (MRF) approach was used to simulate the rotating propeller [46]. The MRF approach, also known as ‘Multiple Reference Frame’ or ‘Frozen Rotor Approach’, is a steady-state approximation. In this approach, individual cell zones can be assigned different translational and/or rotational motions and solved using the corresponding equations of the reference frames, e.g. the inner zone (yellow cylinder in Figure 3) using a rotating frame and the outer zone associated with a stationary frame in this study. Since the MRF approach does not require complicated mesh motion and can use a steady-state solver, it is simpler and computationally cheaper compared to other unsteady approaches (e.g. the Sliding Mesh). As proven by other studies [39, 47], the authors believe that the MRF method does not bring any significant difference in the results compared to other unsteady methods.

### 3.3. Mesh Generation

Mesh generation was performed using the built-in automated meshing tool of STAR-CCM+. Trimmed hexahedral meshes were used for the high-quality grid for the complex domains. Local refinements were made for finer grids in the critical regions, such as blade edges and areas where the tip and hub vortices are expected to occur as shown in Figure 4. The prism layer meshes were used for near-wall refinement, and the thickness of the first layer cell on the surface was chosen such that the $y^+$ value is always higher than 30 and $k^+$, as suggested by Demirel et al. [15] and CD-Adapco [48].

### 3.4. Verification study
A verification study was conducted to assess the numerical uncertainties of the CFD models and to determine sufficient grid-spacing. The Grid Convergence Index (GCI) method based on the extrapolation of Richardson [49] was used to estimate the order of accuracy of the simulations, as similarly used by [50-53].

According to Celik et al. [54] the apparent order of the method, \( p_a \), is determined by

\[
p_a = \frac{1}{\ln(r_{21})} \left| \ln \frac{\varepsilon_{32}}{\varepsilon_{21}} + q(p_a) \right|
\]  

\[
q(p_a) = \ln \left( \frac{r_{21}^p \phi_1 - s}{r_{32}^p \phi_2 - s} \right)
\]  

\[
s = \text{sign} \left( \frac{\varepsilon_{32}}{\varepsilon_{21}} \right)
\]

where \( r_{21} \) and \( r_{32} \) are refinement factors given by \( r_{21} = \sqrt[3]{N_1/N_2} \) for a spatial convergence study of a 3D model. \( N \) denotes the cell number of the numerical domain. \( \varepsilon_{32} = \phi_3 - \phi_2 \), \( \varepsilon_{21} = \phi_2 - \phi_1 \), and \( \phi_k \) denote the key variables, e.g. \( K_T, K_Q \), or \( \eta_O \) in this study.

The extrapolated value is calculated by

\[
\phi_{\text{ext}}^{21} = \frac{r_{21}^p \phi_1 - \phi_2}{r_{21}^p - 1}
\]

The approximate relative error, \( e_a^{21} \), and extrapolated relative error, \( e_{\text{ext}}^{21} \), are then obtained by

\[
e_a^{21} = \left| \frac{\phi_1 - \phi_2}{\phi_1} \right|
\]

\[
e_{\text{ext}}^{21} = \left| \frac{\phi_{\text{ext}}^{21} - \phi_1}{\phi_{\text{ext}}^{21}} \right|
\]

Finally, the fine-grid convergence index is found by

\[
GCI_{\text{fine}}^{21} = \frac{1.25 e_a^{21}}{r_{21}^p - 1}
\]

For the grid convergence study, three different resolutions of grid structures were generated, which are referred to as fine, medium, and coarse meshes corresponding cell numbers of \( N_1, N_2 \), and \( N_3 \). Table 3 shows the required parameters for the calculation of the spatial discretization error. The propeller open water characteristics, \( K_T, K_Q \) and \( \eta_O \), of the smooth case at the advance coefficient of \( J = 0.7 \) were used as the key variables. As indicated in the table, the GCI values of \( K_T, K_Q \) and \( \eta_O \) using the fine mesh is 0.0002%, 0.38%, and 0.89%, respectively. For accurate prediction, the fine mesh was used to simulate the roughness effect of barnacle fouling on the propeller performance. It is of note that the changes in the \( K_T, K_Q \) and \( \eta_O \) values due to the propeller fouling observed in this study are larger than these uncertainties.

3.5. Validation study
The propeller open water curves computed in the full-scale CFD simulations were compared with the model-scale Experimental Fluid Dynamics (EFD) of Fujisawa et al. [40]. As presented in Figure 5, a good agreement was achieved between the CFD and EFD results. There is a slight overestimation of $K_T$ and $K_Q$ at low $J$ values and conversely, a slight underestimation of them at high $J$ values as similarly observed from the full-scale KP505 simulations by Castro et al. [55]. It is of note that the propeller Reynolds numbers, based on chord length at 0.7R and the relative flow velocity ($V_R = \sqrt{V_A^2 + (0.7\pi n D)^2}$) of the current full-scale CFD were $5.6 - 5.8 \times 10^7$, at $J = 0.2 - 0.8$, while these for the model-scale EFD were $6.5 - 6.9 \times 10^5$.

4. Results

4.1. Roughness effect on propeller performance

For the investigation into the effect of barnacle fouling on the propeller performance characteristics, full-scale simulations of the propeller performance in open water were conducted in the different fouling conditions. The simulations were conducted at the advance coefficients, $J$, ranging from 0.2 to 0.8, where the corresponding propeller Reynolds numbers are $5.6 \times 10^7$ to $5.8 \times 10^7$.

Figure 6-8 compare the propeller open water characteristics computed from the CFD simulations in the different surface conditions of barnacle fouling. In the figures, the $K_T$, $10K_Q$ and $\eta_O$ values are plotted against the representative roughness heights of the corresponding fouling conditions, which are depicted in Table 1.

As shown in Figure 6, the thrust coefficients, $K_T$, were observed to decrease with increasing fouling severity. The relative differences in $K_T$ between the smooth case and the most severe fouling case (B20%) were -3.7% at $J=0.2$ to -11.1% at $J=0.8$. It is of note that while the absolute differences between the smooth and rough cases remain similar among the different advance coefficients, the relative differences were observed to be larger at higher advance coefficients due to the smaller smooth $K_T$ values at high advance coefficients.

Figure 7 compares the torque coefficients, $10K_Q$, values against the representative roughness heights. Contrary to the case of $K_T$, there is a tendency for the $10K_Q$ values to increase with the increasing level of fouling. The relative differences in $10K_Q$ between the smooth case and the most severe fouling case (B20%) were 2.6% at $J=0.2$ to 10.2% at $J=0.8$. Similarly, to the thrust coefficients, the relative differences were larger at high advance coefficients while the absolute differences remained similar.

The decrease in thrust coefficients and the increase in torque coefficients result in a reduction of propeller open water efficiencies, $\eta_O$, as shown in Figure 8. The relative differences in $\eta_O$ between the smooth case and the most severe fouling case (B20%) were -6.2% at $J=0.2$ to -19.3% at $J=0.8$. Unlike the cases of $K_T$ and $10K_Q$, both of the absolute and relative differences of $\eta_O$ between the smooth and rough cases were observed to be
larger at high advance coefficients, due to the fact that $\eta_O$ indicates the ratio of $K_T$ and $10K_Q$.

It is interesting to note that, as shown in Figure 6-8, the rate of the change in $K_T$, $K_Q$, and $\eta_O$ become smaller as the fouling severity increases, which is in agreement with the behaviour of the full-scale measurements as discussed by Atlar et al. [34].

Figure 9 compares the overall propeller open water curves computed in the smooth condition and the most severe fouling condition (B20%). The consistent decreases in $K_T$ and the increase in $K_Q$ along with the advance coefficients can be seen in the figure. An interesting feature from the figure is that the optimum $J$ point where the maximum efficiency is found was moved with the presence of surface fouling (i.e. the smooth case shows the maximum $\eta_O$ at $J=0.8$, while that of the rough case is found around $J=0.7$).

Figure 10 and 11 illustrate the contributions of the pressure and shear (frictional) components in the thrust and torque coefficients (i.e. $T_{total} = T_{shear} + T_{pressure}$ and $Q_{total} = Q_{shear} + Q_{pressure}$) at $J=0.7$. The surface conditions were arranged in the order of increasing fouling severity (i.e. representative roughness height, $k_G$, from Table 1).

As can be seen in Figure 10, the shear components of the thrust always act in the negative direction and increase with the level of surface fouling (by 154%), while the pressure components decrease with the increased surface roughness (by -8.1%). Accordingly, the total thrust coefficient decreases with the presence of surface fouling.

On the other hand, an interesting feature was observed in the torque coefficients. As can be seen in Figure 11, the pressure torque components decrease with increasing surface fouling (by -5.1%), which is desirable for propeller efficiency. However, the rate of increase in frictional torque component is much higher (by 168%) than that of pressure torque such that the overall torque coefficients show an increasing trend with the level of surface fouling. It is of note that the decrease in the pressure torque can be related to the decreased pressure thrust as shown in Figure 10.

4.2. Power penalty

In order to investigate the impact of propeller fouling in a more practical point of view, the required shaft powers, $SP$, to maintain the design speed of KCS (24 knots) for different fouling cases were predicted using the obtained $K_T$ and $K_Q$ curves together with the resistance predictions of Song et al. [16]. The $SP$ values were calculated under two different scenarios, namely ‘clean-hull/fouled-propeller’ scenario and ‘fouled-hull/fouled-propeller’ scenario. The required $SP$ values were determined as follows: i) the required thrust, $T_{req}$, is calculated as $T_{req} = R_T/(1 - t)$, where $R_T$ is the total resistance of KCS under the corresponding hull condition, determined by Song et al. [16], and $1 - t$ is the thrust deduction factor (1 - $t = 0.853$, available at [56]); ii) then the advance coefficient values, $J$, used for the open water curves are converted to the propeller rotational speeds, $n = V_s(1 - w_n)/(JD)$, where $1 - w_n$ is wake fraction for the hull fouling determined by Song et al. [16] and $V_s$ is the ship speed; iii) the $K_T$ curve (Fig. 6) is converted to thrust values as, $T = K_T\rho n^2D^4$, and then a $n$ vs $T$ curve is obtained; iv) from the $n$ vs $T$ curve, the required $n$ value is determined to satisfy $T = T_{req}$. v) $K_Q$ value for
the corresponding \( n \) (and hence \( J \)) is read from the \( K_Q \) curve (Fig. 7). vi) finally the required shaft power, \( SP \), is calculated as

\[
SP = 2\pi \rho K_Q n^3 D^5
\]  

(18)

Table 4 shows the increase in required shaft power, \( SP \), to maintain the design speed in the ‘clean-hull/fouled-propeller’ scenario. As indicated in the table, the corresponding rotational speeds, \( n \), and torque coefficients, \( K_Q \) increase with the presence of surface fouling, resulting in increases in the shaft powers to maintain the design speeds. It is of note that these significant increases in power (up to 20\% at B20\%) were caused only by the fouled propeller while the entire hull remained smooth.

When the hull fouling is considered together, i.e. ‘fouled-hull/fouled-propeller’ scenario, the increase in the required power becomes more dramatic. As depicted in Table 5, the increase in required shaft power reaches to 84\% at the most severe fouling condition (B20\%).

4.3. Flow characteristics

4.3.1. Pressure distribution

Figure 12 compares the pressure fields on the \( y = 0 \) plane in the smooth and fouled (B20\%) surface conditions. The pressure was non-dimensionalised by dividing it by the dynamic pressure, \( 1/2 \rho V^2 \). It can be seen from the figure that the fouled case has a less vivid colour map of the pressure distribution, which results in a smaller pressure difference between the pressure and suction sides of the propeller, as depicted in Figure 13. This observation is in accordance with the decreased pressure components in the thrust and torque due to the surface fouling observed in the previous section.

Interestingly a remarkable reduction was observed in the pressure drop downstream of the propeller hub by the fouled surface. This can be seen as a positive effect of the surface roughness as opposed to its unfavourable effect on the propeller blades. The change in pressure distribution can be explained by the reduced strength of the hub vortex, which can be found in Figure 17 and 18.

4.3.2. Wall shear stress distribution

Figure 14 illustrates the non-dimensional wall shear stress magnitude on the propeller surface in the smooth and fouled (B20\%) surface conditions at \( J = 0.7 \). The wall shear stress was non-dimensionalised by dividing it by the dynamic pressure, \( 1/2 \rho V^2 \). As can be seen in the figure, the wall shear stress values increased significantly due to the increased surface roughness. This observation is in agreement with the increased shear torque components observed in the previous section.

4.3.3. Velocity Distribution
Figure 15 and 16 illustrate the axial and transverse velocity on the $y = 0$ plane in the smooth and fouled (B20%) surface conditions at $J = 0.7$. As shown in Figure 15, the fouled case shows more scattered velocity distributions compared to the smooth case, which is believed to be linked to the pressure distribution resulting in thrust loss. As shown in Figure 16, increases in boundary layer thickness due to the surface fouling on the blades were observed, which can be related to the increased wall stress observed in Figure 14. From this observation, it can also be deduced that the increased boundary layer thickness increases the amount of fluid rotating with the propeller. Therefore, the transverse velocity distribution at the downstream becomes more fluctuating and complicated as can be seen in Figure 16b.

4.3.4. Propeller Vortices

To examine the effect of barnacle fouling on the propeller vortices, the vorticity magnitudes on the $y = 0$ plane for the smooth and fouled (B20%) surface conditions are illustrated in Figure 17. Similar to the features of the pressure and velocity fields observed in the previous sections, the vorticity of the fouled case shows a more dispersed distribution compared to the smooth case. The strengths of tip and hub vortices were observed to be reduced due to the surface roughness and thus dissipate earlier, while the vorticity in between tip and hub vortices increases. This can be seen more clearly using the second invariant of the velocity gradient tensor, Q-Criterion. Figure 18 illustrates the iso-surface of Q-Criterion ($Q = 10 \text{s}^{-2}$) coloured with relative helicity. The tip and hub vortices of the fouled propeller dissipate earlier than those of the smooth propeller, and stronger vortices formed in between the tip and hub vortices can also be found in the figure. It can be inferred that the reduced hub vortex is related to the reduced pressure drop downstream of the propeller hub as shown in Figure 13. This finding is significant since it suggests the possibility that the surface roughness can be used to control the propeller vortices and resolve the problems associated with the propeller vortices, e.g. propeller cavitation. However, this will require a fine compromise between the two conflicting consequences, i.e. the efficiency loss of the blades and mitigation of hub vortex cavitation.

5. Concluding remarks

A CFD model has been proposed for the investigation into the effect of barnacle fouling on the open water performance characteristics of KP505 propeller in full-scale. To represent the surface roughness of barnacle fouling in the simulation, the roughness function of barnacle fouling, which is experimentally obtained by Demirel et al. [14], was
embedded into the wall-function of the CFD software so that the surface boundary
condition of the blade can represent the barnacles of varying sizes and coverages.
A verification study was conducted to assess the numerical uncertainties of the proposed
CFD model and to determine sufficient grid-spacings. The numerical uncertainties of \( K_T \),
\( K_Q \) and \( \eta_o \) values were estimated to be 0.0002%, 0.38%, and 0.89%.
The propeller open water curves obtained from the CFD simulations were compared with
the experimental data [40] and showed a good agreement.
Fully nonlinear RANS simulations of the full-scale KP505 propeller were performed in
different surface conditions to investigate the effect of barnacle fouling on the propeller.
The simulation results showed that with increasing level of surface fouling, the magnitude
of the propeller thrust coefficient decreases while the magnitude of the torque coefficient
increases. This leads to a loss in propeller open water efficiency up to 19.3% at the most
severe fouling conditions.
An interesting finding is that the pressure component in the torque coefficient decreases
with increasing surface fouling. However, the increase in frictional torque component is
much faster such that the overall net torque coefficients show increasing tendencies with
increasing surface fouling rate.
The power penalty due to the propeller fouling was also investigated. The result indicates
that the required delivered power, to maintain the design speed of the ship, increases up
to 19.8% only by the propeller fouling, and it increases up to 96.8% when the hull fouling
is considered together.
The roughness effect on the fluid field downstream of the propeller was also examined.
Less vivid pressure distribution was observed, which leads to the decreased pressure
differences on the pressure side and suction side of the propeller. Another interesting
finding is that the pressure drop behind the propeller cap is remarkably reduced due to
the fouled surface, which can be interpreted as a positive consequence (e.g to
mitigate/reduce hub vortex cavitation), apart from its unfavourable effect on the blades.
The axial and transverse velocity distributions in the smooth and rough surface conditions
were also compared. The axial velocities of the fouled case showed more scattered
distribution than the smooth case as similarly observed in the pressure field. From the
transverse velocity distribution, increased boundary layer thickness on the propeller
blades was found, which can be related to the increased wall shear stress.
Another interesting finding is that the surface roughness reduces the strength of the
propeller hub and tip vortices, which is believed to be one of the reasons for the reduced
pressure drop downstream of the propeller hub. This suggests the possibility that the
surface roughness can be used to control the propeller vortex and the associated
problems.
This study has provided several important findings such as the roughness effect on the
propeller open water characteristics, pressure and velocity distributions, and propeller
vortices. However, the CFD approach has not been experimentally validated for
propellers. Therefore, a piece of future work might be to conduct an open water test of a
model propeller with a rough surface to be compared with the CFD results for validation.
6. Acknowledgements

This study was presented at the 38th International Conference on Ocean, Offshore & Arctic Engineering (OMAE2019), June 9-14, Glasgow, Scotland, UK. It should be noted that the results were obtained using the ARCHIE-WeSt High-Performance Computer (www.archie-west.ac.uk) based at the University of Strathclyde.

7. References


Fig. 1 Roughness functions for the test surfaces [14]
Fig. 2 KP505 propeller
Fig. 3 Domain and boundary conditions
Fig. 4 Grid system
Fig. 5 comparison of the propeller open water curves obtained from the current CFD (full-scale) and EFD (model-scale) [40]
Fig. 6 Thrust coefficients decreasing with the level of surface fouling
Fig. 7 Torque coefficients increasing with the level of surface fouling
Fig. 8 Propeller efficiency decreasing with the level of surface fouling
Fig. 9 Comparison of the Propeller open water curves in smooth and rough (B20\%) conditions
Fig. 10 Contribution of the thrust coefficient components, at $J=0.7$
Fig. 11 Contribution of the torque coefficient components, at $J=0.7$
Fig. 12 Pressure distribution on y=0 plane, at J=0.7
Fig. 13 Pressure distribution on the propeller surface, at $J=0.7$
Fig. 14 Wall Shear stress coefficients, at $J=0.7$
Fig. 15 Axial velocity on $y = 0$ plane, at $J=0.7$
Fig. 16 Transverse velocity on $y = 0$ plane, at $J=0.7$
Fig. 17 Vorticity magnitude on $y = 0$ plane, at $J=0.7$
Fig. 18 Isosurface of Q-criterion, at $J=0.7$
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<tr>
<th>Surface condition</th>
<th>Barnacle type</th>
<th>Barnacle height, $h$ (mm)</th>
<th>Surface coverage, $SC$ (%)</th>
<th>Representative roughness height, $k_G$ (μm)</th>
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Table 2 Principal particulars of the KP505 propeller [40]

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<td>Ae/Ao</td>
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<td>Rotation</td>
<td>Right Hand</td>
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<tr>
<td>Hub ratio</td>
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Table 3 Discretization error calculation for spatial convergence study

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<td>$r_{32}$</td>
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Table 4 Increases in the required shaft power: ‘clean-hull/fouled-propeller’ scenario

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<th>Surface condition</th>
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<th>$1 - W_n$ [16]</th>
<th>$T_{req}$ (kN)</th>
<th>$n$</th>
<th>$J$</th>
<th>$K_Q$</th>
<th>SP (MW)</th>
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<td>1829.6</td>
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Table 5 Increases in the required shaft power: ‘fouled-hull/fouled-propeller’ scenario

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<th>Surface condition</th>
<th>$R_f$ (kN) [16]</th>
<th>$1 - W_n$ [16]</th>
<th>$T_{req}$ (kN)</th>
<th>$n$</th>
<th>$J$</th>
<th>$K_Q$</th>
<th>SP (MW)</th>
<th>ΔSP (%)</th>
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<td>Smooth</td>
<td>1560.7</td>
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<td>1829.6</td>
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Last: 

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Authors: Soonseok Song, Yigit Kemal Demirel, Mehmet Atlar

ASME Journal Title: Journal of Offshore Mechanics and Arctic Engineering

Volume/Issue: 142/6
Date of Publication (VOR* Online): 27/05/2020

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