Open Water and Performance Analysis of Marine Propeller with PBCF Based CFD Method

Achdri Fauzi Nugraha Oloan, I Made Ariana, Achmad Baidowi
Institut Teknologi Sepuluh Nopember, Marine Technology, Surabaya

Achdri16@mhs.ne.its.ac.id, ariana@its.ac.id, ahmadbai@gmail.com

Abstract. Improving marine propeller performance can use ESD (Energy Saving Devices), especially located at zone 2 area installation ESD. Focus of this research using PBCF (Propeller Boss Cap Fins) as ESD and marine propeller from Japanese Bulk Carrier as object. This research studies marine propeller MP687 with and without PBCF. To obtain data solver, using single domain method and multi domain method. Simulation based on Advanced Ratio (J) = 0.30, 0.40 and 0.50. PBCF at multi domain can improve up to ±4.174% for thrust, -0.769% reduce torque value and 1.114% for efficiency increase. Using DES-SST model turbulence, PBCF can influence propeller MP687 flow to prevent making hub vortex from trailing edge from each propeller blade.

1. Introduction
Environmentally friendly design in the development of shipbuilding has the main objective of having an economical, reliable and low operating cost. One of the factors that can be designed in addition to the shape of the hull is the propulsion system. The propulsion system itself can be modified starting from the fuel, combustion system, exhaust gas system and propeller in order to create environmentally friendly technology and increase ship efficiency. Marine propeller has one of the characteristics, which is to produce tip vortex and hub vortex. ESD (Energy Saving Devices) can reduce or eliminate the hub vortex, namely PBCF by changing the fluid flow around the boss cap and increasing propeller efficiency [1]. This is also reinforced in subsequent studies that the simple concept of increasing propeller efficiency using PBCF on the original ship averaged around 4% [2]. ESD operating at 3 basic zone of installation, there are: first zone (hull area), second zone (propulsion area) and third zone (rudder area). ESD device didn’t describe from this zone installation, but usually describe at 3 zone and have to be standard group of zone installation [3].

In previous studies, it was explained that PBCF can be used by all type of ships. According to research for container ships with 3800 TEU until 5500 TEU with average increase propeller efficiency ±4.850%. Bulk Carriers have an average propeller efficiency increase of ±5.025%, while for the type of ship chemical, cement carrier, LNG, Product and Multi Purpose has an average increase in propeller efficiency ±2.900%. There are many object configurations as described in [4]. DES – SST turbulence model with CFD method to see propeller hub vortex. Total 4 model that test with openwater test with single domain and multi domain. All of this test depend on Velocity advance ratio each J position. Propeller MP687 in this case used scale geometry model that give by NMRI (D = 0.203 m) then using propeller revolution 7.8 rps. To know the impact of PBCF with detailed performance, helicity and vortex flow.
2. Methods
For making experiment of marine propeller with openwater test method, it can be solve with value thrust coefficient \( (K_T) \) and torque coefficient \( (K_Q) \) based on position advance ratio \( (J) \) [5]. Detail can be follow this equation (1):

\[
J = \frac{V_A}{nD}
\] (1)

2.1. Efficiency Openwater Test (\( \eta_o \))
Propeller efficiency related with openwater test. Propeller work on homogen object without hull at at fore. Propeller efficiency depend on speed of advance \( (V_a) \), thrust force \( (T) \), propeller revolution \( (n) \), diameter \( (D) \) and propeller design depend on amount blade \( (Z) \), disk area ratio \( (A_e/A_o) \), pitch / diameter ratio \( (P/D) \). Propeller efficiency have value between 0.35 until 0.75 depend on speed of advance ratio variation [6]. For detailed for search propeller efficiency can be follow equation (2) and openwater test graph can refer to Figure 1.

\[
\eta_o = \frac{J}{2\pi} + \frac{K_T}{K_Q}
\] (2)

![Figure 1. MP687 Propeller Openwater Test](image)

2.2. Thrust Coefficient \( (K_T) \) and Toque Coefficient \( (K_Q) \)
Thrust coefficient and torque coefficient plot at advance ratio \( (J) \) when it ratio between speed of advance \( (V_a) \) and rotative speed \( (nD) \). Many problems from propeller with screw type using open water test diagram that mention at Figure 1. Va value and rotative speed with \( n \) is known. Then thrust and torque value can be chosen. If \( V_a \) and \( Q \) is known, value rotative speed can be known. If this 2 parameter \( (V_a \) and \( Q) \) is important to have from 4 parameter \( (V_a, n, T \) and \( Q) \), then other parameter can be found from open water test graph [6]. To search value \( K_T \) and \( K_Q \) can be found at equation (3).

\[
K_T = \frac{T}{\rho n^5 n D^4}
\] (3)

2.3. Detached Eddy Simulation Turbulence Model (DES)
Turbulence model for this research using hyrid RANS-LES models. DES turbulence can be determine based on splitting two zone from computational domain. Conventional RANS are solved at the first region near solid wall. Governing equation filtered by Navier – Stokes equations of LES approach at second region. DES model based on Spalart – Allmaras one equation RANS turbulence model [7].
Hybrid DES not link to any turbulence model [8] and the model at present based on SST $K - \omega$ turbulence model [9].

For Equation, DES is modification from SST model and applied to the dissipation in $k$ transport equation. Dissipation term can be follow:

$$\rho \varepsilon = \beta^* \rho K \omega$$

(4)

Where $\varepsilon$ dissipation rate, $\beta^*$ is constant of the SST model. For SST-DES, can be mention bellow:

$$\rho \varepsilon = \beta^* \rho K \omega F_{DES}$$

(5)

When

$$F_{DES} = \max \left( \frac{Lt}{CDES \Delta} (1 - FSST), 1 \right)$$

(6)

$$\Delta = \max (\Delta x, \Delta y, \Delta z)$$

(7)

$$Lt = \sqrt{K / (\beta * \omega)}$$

(8)

Where $FSST = 0, F1 or F2$ and $\Delta = local$ grid spacing. $Lt$ is turbulence length scale, $CDES$ value constant. $CDES = 0.61$ [10]. $FSST = 0$ sterlets model [8]. F1 & F2 two blend function from SST $\kappa - \omega$ model [9]. blending function designed to the near wall region and zero away from surface. F1 function in wake region area of boundary layer where F2 extend out into boundary layer than F1. For function F1 and F2 can be follow:

$$F1 = \tanh (arg \ 1^4)$$

(9)

$$F2 = \tanh (arg \ 2^2)$$

(10)

3. Analysis and Result

3.1. Domain Parameter

For this research, each model analyse with 2 method of domain. There are single domain and multi domain. The part of boundary consist of 3 primary area, there are inlet zone cylinder zone and outlet zone. Single domain (all body propeller consist of shaft, propeller and hub) parameter for this research can be detailed at Figure 2. Domain size from center propeller hub using 6D distance from maximum outlet domain to center hub propeller. 3D distance from center hub to upper zone and lower zone. 2D distance from center hub to inlet domain. Then for multi domain size based on single domain but have small domain (propeller and hub) in propeller area. Multi domain analysis using non matching connection technique while small domain (propeller and hub) linked into bigger domain (single domain + propeller shaft).
3.2. Validation and Mesh Properties
For validation propeller MP687 model using real model propeller from MP687 based on NMRI JBC. Table 1 represent multi domain result. The experiment take range between $J = 0.10$ until $J = 0.50$. result of average KTErrror between KT EFD vs KT CFD is 4.174 % and 10*KQError between 10*KQ EFD vs 10*KQ CFD is 3.648 %. Table 2 represent single domain open water test. Single domain have bigger error than multi domain. Average KTErrror between KT EFD vs KT CFD is 7.329 % and 10*KQError between 10*KQ EFD vs 10*KQ CFD is 4.094 %.

Table 1. Validation Propeller MP687 Multi Domain

| Advance Ratio | KT EFD | KT CFD | KTErrror % | 10*KQ EFD | 10*KQ CFD | KQError % |
|---------------|--------|--------|------------|-----------|-----------|-----------|
| J             | Multi  | Multi  | Multi      | Multi     | Multi     | Multi     |
| 0.10          | 0.3267 | 0.3095 | 5.272      | 0.3748    | 0.3802    | 1.432     |
| 0.20          | 0.2949 | 0.2809 | 4.749      | 0.3500    | 0.3571    | 2.032     |
| 0.30          | 0.2598 | 0.2490 | 4.144      | 0.3210    | 0.3311    | 3.132     |
| 0.40          | 0.2214 | 0.2135 | 3.560      | 0.2871    | 0.3008    | 4.786     |
| 0.50          | 0.1798 | 0.1741 | 3.146      | 0.2479    | 0.2649    | 6.857     |
| Average       | 0.2565 | 0.2454 | 4.174      | 0.3162    | 0.3268    | 3.648     |

Table 2. Validation Propeller MP687 Single Domain

| Advance Ratio | KT EFD | KT CFD | KTErrror % | 10*KQ EFD | 10*KQ CFD | KQError % |
|---------------|--------|--------|------------|-----------|-----------|-----------|
| J             | Single | Single | Single     | Single    | Single    | Single    |
| 0.10          | 0.3267 | 0.2995 | 8.327      | 0.3748    | 0.3864    | 3.087     |
| 0.20          | 0.2949 | 0.2724 | 7.615      | 0.3500    | 0.3593    | 2.660     |
| 0.30          | 0.2598 | 0.2414 | 7.085      | 0.3210    | 0.3327    | 3.652     |
| 0.40          | 0.2214 | 0.2064 | 6.764      | 0.2871    | 0.3004    | 4.636     |
| 0.50          | 0.1798 | 0.1675 | 6.852      | 0.2479    | 0.2638    | 6.434     |
| Average       | 0.2565 | 0.2374 | 7.329      | 0.3162    | 0.3285    | 4.094     |
Table 3. Mesh Properties

| No | Model       | Domain | Cell    |
|----|-------------|--------|---------|
| 1  | MP687       | Single | 3,732,419 |
| 2  | MP687       | Multi  | 4,900,388 |
| 3  | MP687+PBCF | Single | 5,270,856 |
| 4  | MP687+PBCF | Multi  | 5,368,345 |

After comparing multi domain vs single domain validation model, we can see advance ratio J = 0.10 until J = 0.50 multi domain have low margin error for KT and 10*KQ. In this research, using propeller scaled geometry from NMRI and turbulence model using DES – SST. Table 3 represent mesh quality depend on model and domain. Cell size for multi domain is bigger than single domain. It can be increased slightly if PBCF installed at propeller hub.

3.3. Impact of Thrust and Torque PBCF at MP687 Multi Domain vs Single Domain

After validation model propeller MP687, PBCF was installed and analyse with multi domain and single domain. For detail can see at Table 4 for effect of installation PBCF multi domain and Table 5 for effect installation PBCF single domain. Then Table 7 for comparation effect installation PBCF between multi domain vs single domain.

Table 4. Effect Propeller MP687 Multi Domain + PBCF

| Advance Ratio | KT CFD | KT PBCF | KTGap % | 10*KQ CFD | 10*KQ PBCF | KQGap % |
|---------------|--------|---------|---------|-----------|------------|---------|
| J             | Multi Multi Multi Multi Multi | Multi Multi Multi Multi Multi Multi | Multi Multi Multi Multi Multi Multi |
| 0.30          | 0.2490 0.2503 +0.500 0.3311 | 0.3291 -0.591 |
| 0.40          | 0.2135 0.2142 +0.324 0.3008 | 0.2985 -0.762 |
| 0.50          | 0.1741 0.1745 +0.185 0.2649 | 0.2624 -0.955 |
| Average       | 0.2122 0.1926 +0.336 0.2989 | 0.2967 -0.769 |

Detail Table 4 for effect of installation PBCF multi domain propeller MP687 with PBCF from advanced ratio J = 0.30 until J = 0.50. Average increase for KT +0.336 % and decrease 10*KQ -0.769 %. Bigger increase effect for KT located at J = 0.30 is +0.500 % and J = 0.50 for bigger decrease 10*KQ is -0.955 %. Table 6 for result single domain analysis. Average increase propeller MP687 with PBCF from advanced ratio J = 0.30 until J = 0.50 for KT is +0.912 % and 10*KQ is -0.065%. Bigger increase effect for KT at J = 0.50 is +1.022 % then 10*KQ bigger decrease at J = 0.50 is -0.201 %.

Table 5. Effect Propeller MP687 Single Domain + PBCF

| Advance Ratio | KT CFD | KT PBCF | KTGap % | 10*KQ CFD | 10*KQ PBCF | KQGap % |
|---------------|--------|---------|---------|-----------|------------|---------|
| J             | Single Single Single Single Single Single | Single Single Single Single Single Single |
| 0.30          | 0.2414 0.2434 +0.822 0.3327 | 0.3321 -0.201 |
| 0.40          | 0.2064 0.2083 +0.892 0.2871 | 0.3003 -0.048 |
| 0.50          | 0.1675 0.1692 +1.022 0.2479 | 0.2638 +0.054 |
| Average       | 0.2051 0.2069 +0.912 0.2990 | 0.2988 -0.065 |
Table 6 and Table 7 for effect multi domain vs single domain KT and 10*KQ. We can see thrust trend line from KT graph, advance ratio J = 0.30 until J = 0.50 have linear decrease value KT from minimum J to maximum J at effect (multi domain) and for 10*KQ (multi domain) have linear decrease value same as KT value. PBCF installation effect for KT value multi domain vs single domain at Table 6. Effect of increasement KT are linear value from J = 0.30 (+0.500 %) until J = 0.50 (+0.185 %). But at single domain, effect of increasement KT value are linear value from J = 0.30 (+0.822 %) until J = 0.50 (+1.022 %). Comparation from effect installation PBCF is value added KT at J = 0.30 until J = 0.50 linear higher to lower trend (multi domain) and difference effect value added KT at J = 0.30 until J = 0.50 lower to higher trend.

Table 6. Effect Thrust (KT) Propeller MP687 Multi Domain Vs Single Domain

| Advance Ratio | KT CFD | KT PBCF | KTGap % | KT CFD | KT PBCF | KTGap % |
|---------------|--------|---------|---------|--------|---------|---------|
| J             | Multi  | Multi   | Multi   | Single | Single  | Single  |
| 0.30          | 0.2490 | 0.2503  | +0.500  | 0.2414 | 0.2434  | +0.822  |
| 0.40          | 0.2135 | 0.2142  | +0.324  | 0.2064 | 0.2083  | +0.892  |
| 0.50          | 0.1741 | 0.1745  | +0.185  | 0.1675 | 0.1692  | +1.022  |
| Average       | 0.2122 | 0.2130  | +0.336  | 0.2051 | 0.2069  | +0.912  |

Table 7. Effect Torque (KQ) Propeller MP687 Multi Domain Vs Single Domain

| Advance Ratio | 10*KQ CFD | 10*KQ PBCF | KQGap % | 10*KQ CFD | 10*KQ PBCF | KQGap % |
|---------------|-----------|------------|---------|-----------|------------|---------|
| J             | Multi     | Multi      | Multi   | Single    | Single     | Single  |
| 0.30          | 0.3311    | 0.3291     | -0.591  | 0.3327    | 0.3321     | -0.201  |
| 0.40          | 0.3008    | 0.2985     | -0.762  | 0.2871    | 0.3003     | -0.048  |
| 0.50          | 0.2649    | 0.2624     | -0.955  | 0.2479    | 0.2640     | +0.054  |
| Average       | 0.2989    | 0.2967     | -0.769  | 0.2990    | 0.2988     | -0.065  |

From Table 7 Effect of PBCF are decrease 10*KT phenomena. Linear decrease value from J = 0.30 (-0.591 %) until J = 0.50 (-0.955 %) at multi domain. But at single domain, effect of decreases 10*KQ value gap at J = 0.30 until J = 0.40. But at J = 0.50 value of 10*KQ gap are increase (+0.054 %). After that from single domain and multi domain, average bigger decrease value gap at multi domain (-0.769 %) and smaller average decrease value gap at single domain (-0.065 %).

3.4. Impact of Efficiency PBCF at MP687 Multi Domain vs Single Domain

Efficiency validation model propeller MP687, factor can influence propeller efficiency is position J, value of KT and KQ. PBCF was installed and analyse with multi domain and single domain. For detail efficiency characteristic, PBCF influence propeller MP687 can see at Table 8 for effect of installation PBCF multi domain and Table 9 for effect installation PBCF single domain. Then Table 10 for comparation effect installation PBCF between multi domain vs single domain.
From Table 8 can explain from multi domain efficiency propeller MP687 before and after PBCF installation. Efficiency take from position J = 0.30 until J = 0.50. Average error between ETA EFD vs ETA CFD are 8.072 %. Then for average validation efficiency error from single domain ETA EFD vs ETA CFD are 11.192 % can see at Table 9. Effect PBCF installation at MP687 propeller in multi domain can gain up to +1.114 % average increasement efficiency and for single domain gain up to +0.977 %. Bigger gain for efficiency at J = 0.50 ( +1.151 % ) in multi domain, but for single domain bigger gain efficiency at J = 0.30 ( +1.025 % ). Detail of comparation can take place at at Table 10. From this result, PBCF with multi domain can be use for next analysis because impact of efficiency are bigger than single domain.

**Table 8. Efficiency Propeller MP687 Multi Domain**

| Advance Ratio | ETA EFD | ETA CFD | ETAError % | ETA PBCF | ETAGap % |
|---------------|---------|---------|-------------|----------|----------|
| J             | Multi   | Multi   | Multi       | Multi    | Multi    |
| 0.30          | 0.3864  | 0.3594  | 7.000       | 0.3633   | +1.097   |
| 0.40          | 0.4909  | 0.4521  | 7.912       | 0.4570   | +1.094   |
| 0.50          | 0.5771  | 0.5234  | 9.305       | 0.5294   | +1.151   |
| Average       | 0.4848  | 0.4449  | 8.072       | 0.4499   | +1.114   |

**Table 9. Efficiency Propeller MP687 Single Domain**

| Advance Ratio | ETA EFD | ETA CFD | ETAError % | ETA PBCF | ETAGap % |
|---------------|---------|---------|-------------|----------|----------|
| J             | Single  | Single  | Single      | Single   | Single   |
| 0.30          | 0.3864  | 0.3466  | 10.306      | 0.3501   | +1.025   |
| 0.40          | 0.4909  | 0.4877  | 10.844      | 0.4418   | +0.940   |
| 0.50          | 0.5771  | 0.5054  | 12.428      | 0.5103   | +0.967   |
| Average       | 0.4848  | 0.4299  | 11.192      | 0.4341   | +0.977   |

**Table 10. Effect Efficiency ( ETA ) Propeller MP687 Multi Domain Vs Single Domain**

| Advance Ratio | ETA CFD | ETA PBCF | ETAGap % | ETA CFD | ETA PBCF | ETAGap % |
|---------------|---------|----------|----------|---------|----------|----------|
| J             | Multi   | Multi    | Multi    | Single  | Single   | Single   |
| 0.30          | 0.3594  | 0.3633   | +1.097   | 0.3466  | 0.3501   | +1.025   |
| 0.40          | 0.4521  | 0.4570   | +1.094   | 0.4877  | 0.4418   | +0.940   |
| 0.50          | 0.5234  | 0.5294   | +1.151   | 0.5054  | 0.5103   | +0.967   |
| Average       | 0.4449  | 0.4499   | +1.114   | 0.4299  | 0.4341   | +0.977   |

From Table 8 can explain from multi domain efficiency propeller MP687 before and after PBCF installation. Efficiency take from position J = 0.30 until J = 0.50. Average error between ETA EFD vs ETA CFD are 8.072 %. Then for average validation efficiency error from single domain ETA EFD vs ETA CFD are 11.192 % can see at Table 9. Effect PBCF installation at MP687 propeller in multi domain can gain up to +1.114 % average increasement efficiency and for single domain gain up to +0.977 %. Bigger gain for efficiency at J = 0.50 ( +1.151 % ) in multi domain, but for single domain bigger gain efficiency at J = 0.30 ( +1.025 % ). Detail of comparation can take place at at Table 10. From this result, PBCF with multi domain can be use for next analysis because impact of efficiency are bigger than single domain.
Example validation model EFD vs CFD from multi domain can see at Figure 3. Red line represent KT (EFD), blue line represent 10*KQ (EFD) and green line represent efficiency (EFD). Then for CFD result represent plus (+) symbol. Validation can be compared at \( J = 0.10 \) until \( J = 0.50 \) point. All of validation propeller with open water test depend on geometry. It take geometry data from NMRI. Propeller MP687 take model with diameter \( 0.203 \text{ m} \) and revolution take 7.8 rps. For velocity advance (VA) can various depend on \( J \) advance value, diameter and propeller rotation.

3.5. Visualization of Helicity Pattern at MP687 With and Without PBCF

After gain data result from CFD propeller MP687 with and without PBCF at multi domain vs single domain, propeller MP687 need to be inspect at helicity because we concern at hub vortex that created or formed by combine vortex from each trilling edge. Helicity pattern can see both single domain and multi domain. Star like pattern mean helicity at hub propeller and circular blue mean hub vortex prom propeller. All of this pattern can see detailed at Figure 4. PBCF installed at propeller MP687 can generate difference helicity and hub vortex both from multi domain and single domain vs MP687 without PBCF. Figure 5 PBCF area, both helicity and vortex become different form. Helicity and vortex at hub become turbulence pattern. The colour that represents helicity and vortex hub become mixed each other.
Detailed turbulence can refer to Figure 6 and Figure 7 for propeller MP687 single domain vs multi domain. Strong hub vortex from propeller with single domain analysis are indicated with straight blue at center between wake flow propeller. Same strong hub vortex at multi domain are indicated with straight blue but little bigger than single domain vortex hub. Cutting plane from propeller flow analysis at coordinate 0,0,0 to known turbulence characteristic. Beside that, at Figure 7 for propeller area have some small cylinder that indicated to be sliced, it call multi domain characteristic that difference between Figure 6. Turbulence flow characteristic effect after PBCF was installed can refer to Figure 8 and Figure 9.
Figure 8. Flow Pattern Propeller MP687 with PBCF Single Domain at J = 0.50

Figure 9. Flow Pattern Propeller MP687 with PBCF Multi Domain at J = 0.50

Figure 8 representation turbulence characteristic after PBCF was installed with single domain analysis method. From that phenomenon, PBCF can make straight flow to turbulence flow that eliminate hub vortex. Indicated hub vortex was eliminated can see at unstable flow that represent turbulence. It same phenomena for multi domain turbulence characteristic at Figure 9. All of turbulence multi domain vs single domain using DES – SST model analysis for this experiment.

4. Conclusion
These research show analysis for comparation between propeller MP687 with or without PBCF. Method that used by comparing solver analysis with single domain and multi domain with turbulence model DES – SST. Result for propeller validation MP687, multi domain reach smaller average error KT (4.174 %), 10*KQ (3.648 %) and efficiency (8.072 %) than single domain average error KT (7.329 %), 10*KQ (4.094 %) and efficiency (11.192 %). Impact PBCF for KT, single domain reach average increasement (+0.912 %) than from multi domain (+0.336 %). For PBCF at average 10*KQ bigger decrease from multi domain (-0.769 %) than single domain (-0.065 %). Higher added efficiency for installation PBCF at multi domain (+1.114 %) than single domain (+0.977 %). Helicity effect and vortex from propeller MP687 are same pattern at multi domain and single domain. But at cutting plane flow, hub vortex flow are difference size. After PBCF installed at propeller, Helicity and vortex flow are eliminated and change to turbulence flow. That effect because each PBCF fin’s delayed vortex flow from each trailing edge form into whole vortex flow. Torque decrease indicated from CFD simulation and Thrust increase. Then efficiency can be obtained to improve propeller MP687.

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