Analysis of The Effect of Pitch Angle on Propeller Modification by Considering Wake Distribution on Propeller Performance

Maful Suranto, I Made Ariana and Achmad Baidowi
Marine Engineering Department, Institut Teknologi Sepuluh Nopember, Surabaya

maful.19042@mhs.its.ac.id; ariana@its.ac.id; ahmadbai@gmail.com

Abstract. The propeller is an important component of the ship's propulsion system, and its design related to the safety and ship’s cost. The propeller is operated in an uneven flow field behind the ship so it has an important influence on the cavity, vibration and hydrodynamic performance. Therefore, optimization calculations are needed to get the most economical in addition to meeting the provisions of the Energy Efficiency Design Index. Optimization software through polynomial regression values can be used for selecting propeller. However, when the propeller is installed on the hull, the Velocity Advance (Va) on the propeller will change from the distribution at the time of the open water test because of the shape of the hull. This reduces the performance of propeller. So it is necessary to calculate the engine propeller hull matching to get a match on each propulsion component. Blade element theory concept can be used in designing the propeller for the engine hull matching, with the hypothesis that if the pitch angle is greater than Va, cavitation will occur. This condition is not allowed and if the pitch angle is too small for Va, the thrust cannot be maximized against flow, then it must adjust to the Velocity Advance (Va) distribution on the ship's hull, because increasing the thrust value will also increase the propeller's relative rotative efficiency (ηR) and open water efficiency (ηO) and hull efficiency (ηH). This situation makes a proportional increase in the value of the propulsive coefficient. The simulations are carried out on the size of the model with a dual domain (single-hull) by turning the propeller while the ship is stationary and seeing the convergent speed generated by the ship. The simulation data that will be taken are propeller thrust and torque because these values are considered sufficient to compare the simulation results. It's getting the thrust foil value that making model S_T, S_eta and S_KomL. S_T model is done by looking at the highest thrust, S_eta model with highest efficiency method and on S_KomL with highest thrust and efficiency by looking at the streamlined model, the thrust and efficiency values are equal to or higher of the MP687. It is showed that open water efficiency value in the two modified models has decreased, namely S_T model of 0.341, S_KomL of 0.345 and S_eta of 0.301 with original MP687 model of 0.371. While the hull efficiency of S_T model has decreased to 1.449 and S_KomL model increased by 1.591 and S_eta model increased by 3.8 but in MP687 model was 1.526, and the relative rotate efficiency of S_T model increased to 1.096, S_KomL model also increased by 1.099 and also S_eta model of 1.08 which originally on the MP687 1.055 model. This will result in the Propulsive Coefficient (PC) value in S_T model of 0.543 with decreasing, S_KomL 0.604 and S_eta 1.25 with an increase from the original MP687 0.597

1. Introduction
The propeller is an important component of the ship's propulsion system, and its design related to the safety and ship’s cost. The propeller is operated in an uneven flow field behind the ship so it has an
important influence on the cavity, vibration and hydrodynamic performance. Therefore, optimization calculations are needed to get most economical in addition to meeting the provisions of the Energy Efficiency Design Index.

The total efficiency is the product of the shaft efficiency, hull efficiency, relative rotative efficiency, and propeller efficiency – open water. On a single propeller ship, the hull efficiency value is between 1.1 – 1.4 but for twin-screw hull efficiency is around 0.95 - 1.05. The value of the relative efficiency of rotation has a value of 1.0 - 1.07, while the efficiency of the shaft is between 0.96 - 0.995. The open water efficiency has a value of between 0.35 - 0.75 [1]. From various efficiency values, the open water efficiency value, relative rotational efficiency and hull efficiency will affect the performance of the ship.

Propeller selection can be done using software optimization through polynomial regression values for propeller selection [2]. However, when the propeller is mounted on the hull, the wake distribution on the propeller will change. This reduces the performance of the propeller. So it is necessary to calculate the engine propeller hull matching to get the suitability of each propulsion component.

The use of the concept of blade element theory can be accepted as the basis for the design of the propeller [3]. Changes in camber, rake and pitch will affect the optimization of the wake-adapted propeller design [4]. The results of their research shows that the optimized leaf propeller design will be shaped like a Controllable Pitch Propeller (CPP), which has a low pitch and rake distribution value if you ignore the propeller skew value. In addition, CPP also plays a role in saving SFOC with the flexibility of the propeller pitch that can be adjusted to the engine power output.

So in this study, optimization of the MP687 propeller design was carried out on certain ships that would be redesigned using the concept of blade element theory and wake-adapted to adjust the stern design, with the hypothesis that if the pitch angle is greater than the Va flow, cavitation will occur, this condition is not allowed. and if the pitch angle is too small with respect to the Va thrust that is obtained not maximally for the Va flow, then it must adjust to the Velocity Advance (Va) distribution on the hull, because increasing the thrust value will result in an increase in the relative rotational efficiency of the propeller (ηR) and allowing the efficiency of open water (ηO) and hull efficiency (ηH) will increase in proportion to the increase in the value of the propulsive coefficient, resulting in better and more efficient propulsion performance to meet EEDI.

The simulation is carried out at the actual size with a dual domain (single-hull) by turning the propeller while the ship is stationary and seeing the convergent speed generated by the ship. The simulation data that will be taken are propeller thrust and torque because these values are considered sufficient to compare the simulation results. Where it will be done how the design and performance of the MP687 propeller modification using the concept of blade element theory with the CFD method, as well as the propulsion performance of the ship with the modification of the propeller.

2. Methods

2.1. Blade Element Theory

Blade element theory is a combination of the first momentum theory proposed by Rankine-Froude in 1878[5]. Blade Element (BE) theory uses these geometrical properties to determine the forces exerted by a propeller on the flow-field [6,7]. The theory of momentum commonly abbreviated as MT (momentum theory), proposed by Rankine and Froude was first modified by Betz in 1921 and then refined by Glauert in 1926. The theory contains a mathematical model for calculating the ideal power of a wind turbine, the thrust of the wind and the effect of turbine operation on ambient wind conditions by applying the principle of calculating linear momentum to the actuator disk model. While the blade element theory or known as BET explains the principle of calculating the aerodynamic blade forces in an elemental manner. Calculated parameters are integrated to get the total value. BEMT is combination of MT and BET, states that the value of the thrust and torque of MT is the same as BET. The similarity of parameter values will provide an overview of the linear and rotational factor values for the flow that entering the propeller.

A relatively simple and effective method for predicting propeller performance is using MBET in conjunction with momentum theory (MT), as described in the early work by Rankine, Froude,
Lanchester and Prandtl. The result is usually called “the combined blade-momentum element theory” (CMBET). As is well known, in this method the propeller is divided into a number of elementary stream tubes (called 'strips') along the radius, where the balance of forces applied involves lifting the two-dimensional profile and drag along with the thrust and torque generated within the strip. At the same time, a balance of axial and angular momentum is applied. This results in a set of non-linear equations that can be solved iteratively for each blade strip. The resulting values of base thrust and torque are finally integrated along the spokes to predict the overall propeller performance. It should be noted that strip theory is completely analytical in its formulation, and this makes the model easy to implement and almost inexpensive to run.

CMBET follows the approach presented by Goldstein (1929), Betz (1919, 1920) and Tachmindji and Milan (1957), however, there are important differences regarding the estimation of profile characteristics. The significance of the combined element momentum-blade theory approach (CMBET) is quite large, compared to other more complex analytical techniques, for marine propeller design purposes because it is very simple, fast and almost inexpensive to implement and run on ordinary personal computers [3].

It is assumed that the propeller is attached to an aircraft that is moving forward along its longitudinal axis. Therefore, the lifting line theory, which is applicable for the analysis of an aircraft wing, must be modified accordingly and is known as the blade element theory [8,9,10]. Usually blade-element models are developed for a propeller in axial flight (the axis of rotation is parallel to the free stream direction), that has straight blades. The blades are divided into small elements in the radial direction. It is assumed that each element behaves as a two dimensional wing. Another assumption is the absence of interaction between neighbour elements [13,14,15].

Propeller Series has its own pitch distribution which has a different angle of attack value for each suction. The angle between the inflow and the nose-tail line / mean line of the foil is the value of the angle of attack of the foil. This value will affect the performance of the foil on each suction propeller so that an adjustment of the angle of attack is needed to get maximum performance. The inflow line angle value must not be equal to the zero lift line value because the foil will not produce lift / thrust. To find out the value of the thrust and torque on the propeller using BET, we can use the L and D formulas with the illustration in Figure 1.

\[ dL = C_L \frac{1}{2} \rho A V r^2 \]  
\[ dD = C_d \frac{1}{2} \rho A V r^2 \]  

While the thrust and torque can be written as follows:

\[ \frac{dT}{z} = dL \cos \beta i - dD \sin \beta i \]
The blade element theory divides the rotor blade into several discrete radial elements (airfoils). This theory relies on two key assumptions: (1) There are no aerodynamic interactions between the 2D airfoil elements in different sections, and (2) the forces acting on the elements are solely determined by the lift and drag characteristics of the airfoils shape and relative inflow [11,12].

2.2. Efficiencies

a. Hull efficiency $\eta_H$

Hull efficiency ($\eta_H$) is the division between effective power and propeller thrust. It can be formulated as:

$$
\eta_H = \frac{E_{HP}}{T_{HP}} = \frac{R_t \times V}{T \times V_a} = \frac{R_t}{T} \times \frac{V}{V_a} = \frac{1 - t}{1 - w}
$$

(6)

On single-screw vessels, the hull efficiency ($\eta_H$) is 1.1 to 1.4. While on twin-screw ships the hull efficiency ($\eta_H$) is 0.95 to 1.05 [1].

b. Open water propeller efficiency $\eta_O$

Propeller efficiency is the reading of KT KQ J open water test diagram where the propeller carried out without a hull or barrier in front of it. This efficiency influenced by the incident flow, design, rotation and diameter of the propeller. Propeller efficiency values range from 0.35 to 0.75 [1].

$$
\eta_O = \frac{TV_a}{2\pi nQ} = \frac{KT_{0J}}{KQ_{0J}2\pi}
$$

(7)

c. Relative rotative efficiency $\eta_R$

The actual velocity of the water flow to the propeller behind the hull is not constant or always at right angles to the propeller area, but has some sort of rotational flow. Therefore, compared to the open...
water test conditions, the propeller efficiency is also affected by the propeller's relative rotative efficiency ($\eta_R$).

In single-screw vessels, the relative rotative efficiency values range from 1.0 to 1.07, in other words, water rotation has a beneficial effect. The relative rotative efficiency in conventional hull and twin-screw vessels will usually be less, approximately 0.98 [1].

$$\eta_R = \frac{KQ_o}{KQ_0} = \frac{Q_o}{Q_0}$$

(8)

2.3. Flowchart

In this study, the problem to be discussed is the analysis of the modification of MP687 propeller design on the hull interaction. The next step is to study the references contained in journals/papers, internet and
books of supporting materials. Literature study was conducted to learn about the basic theories regarding the issues raised. The data needed in this thesis are hull and propeller design data. The next stage is validation by comparing the results of the software simulation with experimental data. If less than 10% error, then CFD results will be re-simulated. From the simulation will get the value Va (Velocity Advance) as result, but the flow that is formed after the hull is not symmetrical it will be taken in 4 conditions or on the positive and minus axes every 2 axes, which the value will be used to modify the propeller using blade element theory method. And if the result of foil angle redesign from simulation are not streamlined or the result of propulsion coefficient are high, a model revision will be carried out. The analysis is based on the results of simulated propeller thrust and torque, so that the comparison of propeller modification changes can be seen more real. The efficiency value can be calculated from the resistance, ship speed and flow in the simulation to produce a propulsion coefficient value. Furthermore, conclusions are drawn to facilitate the readers understanding by using as a reference in the development for future researching.

3. Analysis and Result

Previously, simulations had to be carried out on the model before the modification stage, it was necessary to validate the model first. This is done to state that the conditions between the test on the towing tank or EFD and the CFD used are the same as the actual conditions and allow simulations to be carried out using CFD. The validation requirements are as follows:

3.1. Validation

a. Validation Propeller MP687

![Validation MP687](image)

| J  | Kt  | 10Kq  | eta  |
|----|-----|-------|------|
| 0.10 | 3.37 | -3.63 | 6.76 |
| 0.20 | 3.25 | -3.60 | 6.61 |
| 0.30 | 3.76 | -3.59 | 7.10 |
| 0.40 | 4.11 | -4.34 | 8.10 |
| 0.50 | 4.31 | -5.80 | 9.56 |
| 0.60 | 4.45 | -8.18 | 11.68 |
| 0.70 | 5.25 | -11.76 | 15.22 |
| 0.80 | 13.46 | -18.79 | 27.15 |

Figure 3. Open Water Tes Validation

From the graphs and data figure 3, the error value in percentage is below 10% at J 0.1 to 0.6 for Kt and 10Kq values, while at J 0.7 and 0.8 the largest error reaches 18%. Meanwhile, the percentage of open water efficiency is below 10% at J 0.1 to J0.5 while the highest is at J0.8 at 27%.
b. Validation Naca0012

Table 1. Validation Naca0012

| Angle | Cl   | Fy      | Fy_numeca | Error |
|-------|------|---------|-----------|-------|
| 0     | 0    | 0       | 0.9951    | 0     |
| 5     | 0.45987 | 5183.78013 | 5326.0161 | 2.743866 |
| 10    | 0.90163 | 10047.247  | 9950.7402 | -0.96053 |
| 15    | 1.13579 | 12413.9241 | 12992.1503 | 4.657884 |

From these data at table 1, the grid used is 70 thousand, while in the validation the smallest error value is at angle 10 with an error of 0.96% while the largest error is at angle 15, which is 4.6%.

c. Validation JBC Sel-Propusi.

Table 2. Validation JBC

| Name | n (rps) | J   | KT   | KQ     | 1-w   | 1-t   |
|------|---------|-----|------|--------|-------|-------|
| EFD  | 7.8000  | 0.4050 | 0.2170 | 0.0279 | 0.5520 | 0.8120 |
| CFD  | 7.7000  | 0.3917 | 0.2220 | 0.0290 | 0.5740446 | 0.8280442 |
| Error| 1.2821  | 3.2840 | -2.3041 | -3.8710 | -3.9936 | -1.9759 |

From the data table 2, it’s found that the error in each value is around 1-3% where KQ has the largest error value, which is 3.8%

3.2. Foil Angle Selection for Modification Model

From the previous simulation, namely at the ship simulation stage, this will be used to determine how big the angle of entry is on each foil. The following is the value of wake flow (Va) obtained.

![Figure 4. Value Velocity Advance](image)

From the Va data figure 4, a value with each positive and negative axis can be taken where the data will be used to find the average Va value for each radius. From this value will be used to find the angle value on the model of each foil, here are the results of the calculation.
Table 3. Angle of foil

From the table 3, a simulation will be carried out on the foil with a speed of each r/R, where the foil model is simulated with an angle of each alpha with the addition of an angle and also simulated by reducing the angle to a angle of 0.

From the table 3, a simulation will be carried out on the foil with a speed of each r/R, where the foil model is simulated with an angle of each alpha with the addition of an angle and also simulated by reducing the angle to a angle of 0.
In the graph figure 5 and 6 are the results of foil simulation every r/R, in Figure 5 shows changing in angle to the amount of thrust, Figure 6 shows changing the angle of foil to the amount of efficiency. That image will be used as basis for modifying the propeller. Namely plotted in figures 5 and 6 for MP687 propeller angle of each r/R is, while for each propeller modification based in the following way:

a. Model S_T

Modeling on S_T is based on the highest thrust value before it goes down and the shape of model is required to be streamlined. An example in Figure 5 in r/R 0.8 graph, the first highest thrust value will occur at an angle of about 16 it will decreasing in thrust and will increasing again with increased angle, then the angle on r/R 0.8 graph is taken at about 16. After taking the angle, a streamline model will be carried out and the S_T model can be seen in Figure 5 with a black triangle symbol, for angle size can be seen in table 4.

b. Model S_eta

The basis for making the S_eta model is by looking at highest efficiency value on condition that the model results are streamlined. With example in Figure 6 in r/R 0.8 graph, the highest thrust value will occur at an angle of about 7, then streamline model is carried out. In S_eta model, it can be seen in Figure 6 with a black diamond symbol and the angle size can be seen in Table 4.

c. Model S_KomL

In making the S_KomL model it is based on the same or higher thrust value and higher efficiency value provided that a streamlined model is carried out with reference to the thrust and efficiency values must be higher than the MP687 model. With example in r/R 0.7 graph on S_KomL model, it is allowed to an angle of about 15 to 19 because angle in Figure 5 will produce a higher thrust value than the MP687 model, and also with the angle value in Figure 6 it produces a higher efficiency value which taller than MP687 models. Then the S_KomL model can be seen in Figure 5 with a black box symbol and the angle size can be seen in table 4.

### Table 4. Angle Result of Each Models

| r/R  | angle pitch | S_T     | S_KomL | S_eta |
|------|-------------|---------|--------|-------|
| 0.2  | 50.003379   | 60.0000 | 60.0000|
| 0.3  | 38.50065    | 43.5000 | 43.5000|
| 0.4  | 30.81992    | 34.5000 | 34.5000|
| 0.5  | 25.51387    | 27.7000 | 28.0000|
| 0.6  | 21.68906    | 22.3000 | 23.2000|
| 0.7  | 18.82473    | 18.7000 | 18.9000|
| 0.8  | 16.6096     | 16.6100 | 16.6100|
| 0.9  | 14.85034    | 16.5000 | 13.0000|
| 0.95 | 14.10073    | 16.4000 | 10.0000|
| 0.99803 | 13.44737 | 15.5000 | 6.0000 |
The results of modified propeller model are as follows:

![Image of propeller models](image)

Figure 7. Result Model (a) S_T, (b) S_KomL and (c) S_eta

With the modified model above, it will be simulated and get an open water test graph as:

![Open water graph](image)

Figure 8. Open Water

From the open water diagram figure 8, it shows that the S_T with the same J will produce a large thrust but with a larger torque resulting in lower efficiency, while in the S_KomL model with the same J there is some low torque but the thrust remains low where the efficiency is still lower and the S_eta model with the same J produces low thrust and low torque with lower efficiency than the MP687.
3.3 Calculation Analysis

a. Efficiency Open Water

From the simulation results, the thrust value is 42,357 N. This will be used for plotting the open water test diagram, then it will be generated as:

\[
KT = \frac{T}{\rho n^2 D^4}
\]

\[
KT = \frac{42.357}{998 \times 10.09^2 \times 0.203^4} = 0.2455
\]

![Figure 9. Open Water MP687]

From the results of the plotting diagram figure 9 of the open water test, the J value is 0.312, 10Kq is 0.328 and the open water efficiency is 0.371.

b. Efficiency Hull

From the simulation results, the resistance value is 35,073 N with a model speed of 1,179 m/s, this results in a thrust value of 42,357 N. To get the value of Va (Velocity Advance) it will be plotted with an open water test diagram to produce a value of J. To get the value of Va used the following formula:

\[
Va = J \times n \times D
\]

\[
Va = 0.312 \times 10.09 \times 0.203 = 0.639
\]

Meanwhile, to get the hull efficiency value is as follows:

\[
\eta_H = \frac{Rt}{T} \times \frac{V}{Va}
\]

\[
\eta_H = \frac{35.073}{42.357} \times \frac{1.179}{0.639} = 1.526
\]

c. Efficiency Relatively Rotative

Rotative relative efficiency is the ratio between torque in open water and torque behind the ship which is 1,091 N.m. and the formula’s:

\[
Qo = KQ \times \rho \times n^2 \times D^5
\]
\[ Q_o = 0.0328 \times 998 \times 10.09^2 \times 0.203^5 \]
\[ Q_o = 1.151 \]

The relative efficiency value of rotation is obtained as follows:

\[ \eta_R = \frac{Q_o}{Q_b} = \frac{1.151}{1.091} = 1.055 \]

**d. Propulsive Coefficient**

Propulsive Coefficient (PC) is the product of efficiency hull, efficiency relative rotative and efficiency open water.

\[ PC = \eta_o \times \eta_H \times \eta_R \]
\[ PC = 0.371 \times 1.526 \times 1.055 = 0.597 \]

Or it can be concluded or simplified the Propulsive Coefficient (PC) formula as follows:

\[ PC = \frac{Rt \times Vs}{Q_b \times n \times 2\pi} \]
\[ PC = \frac{35.073 \times 1.179}{1.091 \times 10.09 \times 2\pi} = 0.597 \]

From the calculation of the Propulsive Coefficient (PC) above, the calculation of the Propulsive Coefficient (PC) on other models will be carried out, for the calculation results are as follows:

**Table 5. Result Propulsive Coefficient**

| Model     | ηO   | ηH   | ηR   | PC   |
|-----------|------|------|------|------|
| MP_687   | 0.371151 | 1.52614 | 1.055027 | 0.597597 |
| S_T      | 0.341867 | 1.44954 | 1.09639 | 0.543315 |
| S_KomL   | 0.345272 | 1.591138 | 1.09973 | 0.604243 |
| S_eta    | 0.301882 | 3.81534 | 1.086486 | 1.251397 |

From the table 5, it is showed that open water efficiency value in the two modified models has decreased, namely S_T model of 0.341, S_KomL of 0.345 and S_eta of 0.301 with original MP687 model of 0.371. While the hull efficiency of S_T model has decreased to 1.449 and S_KomL model increased by 1.591 and S_eta model increased by 3.8 but in MP687 model was 1.526, and the relative rotate efficiency of S_T model increased to 1.096, S_KomL model also increased by 1.099 and also S_eta model of 1.08 which originally on the MP687 1.055 model. This will result in the Propulsive Coefficient (PC) value in S_T model of 0.543 with decreasing, S_KomL 0.604 and S_eta 1.25 with an increase from the original MP687 0.597.
From the figure 10, it can be seen that the pressure value obtained on the MP687 model shows that the pressure value on the leading is almost average between r/R. Whereas in the S_T model the pressure value is redder indicating a higher pressure value, but in the S_KomL model it is almost flat in the leading part. Meanwhile in S_eta model, pressure on the leading does not appear red which indicates a small thrust result.

4. Conclusion
Those data above have concluded that S_T model is done by looking at the highest thrust, S_eta model with highest efficiency method and on S_KomL with highest thrust and efficiency by looking at the streamlined model, the thrust and efficiency values are equal to or higher of the MP687. It is showed that open water efficiency value in the two modified models has decreased, namely S_T model of 0.341, S_KomL of 0.345 and S_eta of 0.301 with original MP687 model of 0.371. While the hull efficiency of S_T model has decreased to 1,449 and S_KomL model increased by 1,591 and S_eta model increased by 3.8 but in MP687 model was 1,526, and the relative rotate efficiency of S_T model increased to 1,096, S_KomL model also increased by 1,099 and also S_eta model of 1.08 which originally on the MP687 1,055 model. This will result in the Propulsive Coefficient (PC) value in S_T model of 0.543 with decreasing, S_KomL 0.604 and S_eta 1.25 with an increase from the original MP687 0.597.

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