Optimization of Propeller Design Through Polynomial Approach to Optimize The Ship Energy Efficiency

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Abstract. In the shipping industry, the problem that often becomes an obstacle is the optimization of energy efficiency in ships. Some aspects of optimizing the energy efficiency of ships are one of them planning propulsion systems related to propeller design. The main thing that is considered in propeller design planning is the propeller efficiency which is a measure of propeller performance on its productivity in generating thrust. The selection of propeller types that are compatible with the main engine power, the power transmission will be more maximum in the effort to move the ship which reducing fuel oil consumption from the main engine. The selection of the optimal propeller type will get more efficient thrust from the main engine power of the ship being used. This research use the object passenger ship MV. Sabuk Nusantara 99, 1200 GT owned by the Director General of Sea Transportation of the Indonesian Ministry of Transportation. The polynomial approach used as the method and the result choose optimal type of propeller is B3,611, diameter 1.493 m. The results use an optimal type of propeller with propeller efficiency 0.482 cavitation does not occur.

1. Introduction

In planning a new shipbuilding there are several aspects that must be considered and taken into account because they can affect the motion of the ship to reach the desired speed. Some of these aspects are hull planning, engine system planning, propulsion system planning and other planning that must be considered in planning new shipbuilding so that later it is in accordance with the objectives and functions in the construction of a ship [1]. Propulsion system planning is one of the most important aspects in planning new shipbuilding. Propulsion system planning is one of them is propeller design planning. Propeller design planning is one aspect that must be planned carefully from the purpose of the ship's function in achieving optimum speed. Good propeller design will affect the thrust obtained to be optimal so that the desired speed of the ship will be achieved in its operations [2].

In the shipping industry it is important to reduce operating costs and introduce new technologies and technical innovations through the application of the Energy Efficiency Design Index (EEDI) and the Operational Energy Efficiency Index (EEOI). For ships that are still using the main engine with conventional technology, certain efforts need to be made so that the energy released by the main engine can be used as efficiently as possible for the motion of the ship to reduce the operational costs of the ship. Because the biggest operational cost of ships is fuel consumption both when the ship is sailing and at the port. This cost can be reduced by optimizing the energy of the ship so that it becomes more efficient which ultimately can save fuel use [3].
The technical innovation research carried out is to optimize the use of propellers so as to get more efficient thrust from the main engine power used. This propeller selection certainly refers to the main engine and gear box that has been installed in the hope of getting a better propeller type than the propeller that is already installed. Many types of research have been conducted by researchers on B Series propellers to get the optimum B Series propeller type on ships that have been operating with the aim of obtaining a better type of propeller so as to produce energy efficient ships which in turn can reduce the consumption of fuel consumption aircraft carrier engine.

2. Study Literature and Constraints

2.1. $K_T$ Propeller
By deriving from the Wageningen propeller formula the final equation for $K_T$ Propeller can be obtained as follows:

$$K_{T_{\text{load}}} = \frac{R_T n^2}{\rho (1-t) V^4 (1-w)^4 J^4}$$  \hfill (1)

From the equation of this formula it can be interpreted the relationship of ship resistance and the speed of the ship can be implemented in the form of rank 4 relationship between $K_T$ and $J$.

2.2. Propeller Efficiency
Propeller efficiency values in this program can be calculated using the formula:

$$\eta_p = \frac{J}{2\pi \frac{K_T}{K_Q}}$$  \hfill (2)

Propeller efficiency values can be calculated after the $K_T$ and $K_Q$ values are obtained based on the $J$ value at the point of intersection between the $K_{T_{\text{load}}}$ graph and the $K_{T_{\text{openwater}}}$ graph in the analysis program. At this point of intersection, can get the diameter of the propeller which is a function of $J$.

2.3. Propeller Maximum Diameter
The maximum diameter ($D_{\text{max}}$) of the propeller become constrain when the ship is unloaded. Based on the Preliminary Stability documents, the draft of ship when empty or unloaded, which is 2.256 m as shown in Figure 1

![Figure 1. Draft of ship unloaded](Source : Ship drawing design, SN 99)
From the explanation of the picture above it can also be obtained that the maximum diameter of the propeller \((D_{\text{max}})\) is 1,071 x 2 = 2.14 m. The distance between the center of the shaft and the surface of the sea water on the condition of the empty ship \((h) = 1.071\) m

**Cavitation**

To achieve optimal propeller work, the propeller must be avoided from cavitation as constraint. Cavitation can cause the ship to not reach the desired speed. Cavitation on ship propellers has some damaging effects. First, propeller efficiency will be reduced. With cavitation the propeller will not work in homogeneous water but in a liquid that mixed with steam and gas, so this decreases the propulsion power. Secondly, cavitation can cause erosion of the material. Third, cavitation can cause vibrations and sounds, and this is often a major source of problems [4]. Cavitation calculations need to be done in order to ensure that the propeller used does not experience cavitation which causes a decrease in propeller efficiency and damage to the propeller. This cavitation calculation is done out using Burril’s diagram [5]. By deriving from Burril's formula on the cavitation boundary on the burril's diagram, so get the final equation:

\[
\frac{P}{D_{\text{max}}} \leq \frac{1.067 - \left(\frac{A_p}{A_d}\right)}{0.229} \tag{3}
\]

then \(A_p\) is formulated to function \(J\) (advance coefficient)

\[
A_p = \frac{T}{\tau_c \times 0.5 \times \rho \times \left(V_a^2 + \frac{4.84 \times V_a^2}{J^2}\right)} \tag{4}
\]

and \(A_d\) is also formulated to function \(J\) (advance coefficient)

\[
A_d = \frac{A_{E}}{A_0} \times 0.25 \times \frac{V_a^2}{n^2 J^2} \tag{5}
\]

**3. Polynomial Method**

The purposes of study in the initial design of a new ship the B series propeller design can be applied with using the Polynomial method. This is because by using the Polynomial method in designing propellers for new ships, a good analysis test has been conducted, the results are quite convincing, especially for ships using B Series propeller types. The Polynomial method expresses the coefficient of thrust and the torque coefficient in this case includes the number of blades \((Z)\), blade area ratio \((A_E/A_0)\), pitch-diameter ratio \((P/D)\), and advance coefficient \((J)\) [6].

\(K_T, K_Q\) open water Polynomial for \(Rn < 2 \times 10^6\)

\[
K_T = \sum_{s,t,u,v} C^T_{s,t,u,v} \cdot (J)^s \cdot (P/D)^t \cdot (A_E/A_0)^u \cdot (Z)^v \tag{6}
\]

\[
K_Q = \sum_{s,t,u,v} C^Q_{s,t,u,v} \cdot (J)^s \cdot (P/D)^t \cdot (A_E/A_0)^u \cdot (Z)^v \tag{7}
\]

If the value of \(Rn > 2 \times 10^6\), then the value of \(K_T\) and \(K_Q\) polynomial is required to add a correction factor with the value of Delta \(K_T\) \((\Delta K_T)\) and Delta \(K_Q\) \((\Delta K_Q)\).

The Reynold Number value in relation to propeller analysis must be corrected properly. This is because it relates to the value of the trust coefficient and torque coefficient on the B Series propeller type
analyzed. The formula for Reynold Number (Re) that is related to the propeller analysis program is as follows [7]:

$$R_n = 5.3 \frac{A_p/A_v}{Z} \frac{nD^2}{u}$$

This formula is then formulated to function $J$ (advance coefficient)

$$R_n = 5.3 \frac{A_p/A_v}{Z} \frac{nJ^2}{u}$$

Delta Value of $K_T$

$$\Delta K_T = ((0.000353485) + (-0.00333785 x (A_p/A_v) x (J^2))$$

$$+ (0.004478125 x (A_p/A_v) x (P/D) x (J^2))$$

$$+ (0.00643192 x ((log10(R_n)-0.301) x (P/D) x (J^2)))$$

$$+ (0.000110636 x ((log10(R_n)-0.301) x (P/D) x (J^2)))$$

$$+ (0.0000276305 x ((log10(R_n)-0.301) x (Z) x (A_p/A_v) x (J^2)))$$

$$+ (0.0000954 x ((log10(R_n)-0.301) x (Z) x (A_p/A_v) x (P/D) x (J^2)))$$

| $K_T$ | $C$ | s | t | u | v | $K_T$ | $C$ | s | t | u | v |
|------|-----|---|---|---|---|------|-----|---|---|---|---|
| 1    | 0.0080496 | 0 | 0 | 0 | 0 | 21 | 0.010465 | 1 | 6 | 2 | 0 |
| 2    | -0.204554 | 1 | 0 | 0 | 0 | 22 | -0.00648272 | 2 | 6 | 2 | 0 |
| 3    | 0.166351 | 0 | 1 | 0 | 0 | 23 | -0.00841728 | 0 | 3 | 0 | 1 |
| 4    | 0.158114 | 0 | 2 | 0 | 0 | 24 | 0.0168424 | 1 | 3 | 0 | 1 |
| 5    | -0.147581 | 2 | 0 | 1 | 0 | 25 | -0.00102296 | 3 | 3 | 0 | 1 |
| 6    | -0.481497 | 1 | 1 | 1 | 0 | 26 | -0.0317791 | 0 | 3 | 1 | 1 |
| 7    | 0.415437 | 0 | 2 | 1 | 0 | 27 | 0.0186404 | 1 | 0 | 2 | 1 |
| 8    | 0.0144043 | 0 | 0 | 0 | 1 | 28 | -0.00410798 | 0 | 2 | 2 | 1 |
| 9    | -0.0530054 | 2 | 0 | 0 | 1 | 29 | -0.000606848 | 0 | 0 | 0 | 2 |
| 10   | 0.0143481 | 0 | 1 | 0 | 1 | 30 | -0.0049819 | 1 | 0 | 0 | 2 |
| 11   | 0.0606826 | 1 | 1 | 0 | 1 | 31 | 0.0025983 | 2 | 0 | 0 | 2 |
| 12   | -0.0125894 | 0 | 0 | 1 | 1 | 32 | -0.000560528 | 3 | 0 | 0 | 2 |
| 13   | 0.0109689 | 1 | 0 | 1 | 1 | 33 | -0.00163652 | 1 | 2 | 0 | 2 |
| 14   | -0.133698 | 0 | 3 | 0 | 0 | 34 | -0.000328787 | 1 | 6 | 0 | 2 |
| 15   | 0.00638407 | 0 | 6 | 0 | 0 | 35 | 0.000116502 | 2 | 6 | 0 | 2 |
| 16   | -0.00132718 | 2 | 6 | 0 | 0 | 36 | 0.000690904 | 0 | 0 | 1 | 2 |
| 17   | 0.168496 | 3 | 0 | 1 | 0 | 37 | 0.00421749 | 0 | 3 | 1 | 2 |
| 18   | -0.0507214 | 0 | 0 | 2 | 0 | 38 | 0.0000565229 | 3 | 6 | 1 | 2 |
| 19   | 0.0854559 | 2 | 0 | 2 | 0 | 39 | -0.00146564 | 0 | 3 | 2 | 2 |
| 20   | -0.0504475 | 3 | 0 | 2 | 0 | 3 | -0.000539412 | 0 | 3 | 0 | 2 |

Delta Value of $K_0$

$$\Delta K_0 = ((-0.000591412))$$

$$+ (0.00696898 x (P/D))$$

$$+ (0.0000636654 x (Z) x (P/D))$$
propeller is obtained. This optimum propeller analysis program is specifically used to obtain the optimal propeller type of predetermined limits.

\[
K_0 = (0.0160818 \times (A_d/A_o))^2 + (-0.000938091 \times ((\log_{10}(R_n)) - 0.301)) \times (P/D) \\
+ (-0.00059593 \times ((\log_{10}(R_n)) - 0.301)) \times (P/D^3) \\
+ (0.0000782099 \times ((\log_{10}(R_n)) - 0.301)^2) \times (P/D^3) \\
+ (-0.0000052199 \times ((\log_{10}(R_n)) - 0.301)) \times (Z) \times (A_d/A_o) \times (J^2) \\
+ (-0.00000088528 \times ((\log_{10}(R_n)) - 0.301)^2) \times (Z) \times (A_d/A_o) \times (P/D) \times (J) \\
+ (0.0000230171 \times ((\log_{10}(R_n)) - 0.301)) \times (Z) \times (P/D^3) \\
+ (+0.00000184341 \times ((\log_{10}(R_n)) - 0.301)^3) \times (Z) \times (P/D^3) \\
+ (-0.00400252 \times ((\log_{10}(R_n)) - 0.301)) \times (A_d/A_o^2) \\
+ (+0.000220915 \times ((\log_{10}(R_n)) - 0.301)^3) \times (A_d/A_o^2))
\]

| $K_0$ | $C$ | $s$ | $t$ | $u$ | $v$ | $K_0$ | $C$ | $s$ | $t$ | $u$ | $v$ |
|-------|-----|-----|-----|-----|-----|-------|-----|-----|-----|-----|-----|
| 1     | 0.00379368 | 0 | 0 | 0 | 0 | 0.0397722 | 0 | 3 | 2 | 0 |
| 2     | 0.00886523 | 2 | 0 | 0 | 0 | 0.00350024 | 0 | 6 | 2 | 0 |
| 3     | -0.032241 | 1 | 1 | 0 | 0 | -0.0106854 | 3 | 0 | 0 | 1 |
| 4     | 0.00344778 | 0 | 2 | 0 | 0 | 0.00110903 | 3 | 3 | 0 | 1 |
| 5     | -0.0408811 | 0 | 1 | 1 | 0 | -0.000313912 | 0 | 6 | 0 | 1 |
| 6     | -0.108809 | 1 | 1 | 1 | 0 | 0.0035985 | 3 | 0 | 1 | 1 |
| 7     | -0.0885381 | 2 | 1 | 1 | 0 | -0.00142121 | 0 | 6 | 1 | 1 |
| 8     | 0.188561 | 0 | 2 | 1 | 0 | -0.00383637 | 1 | 0 | 2 | 1 |
| 9     | -0.00370871 | 1 | 0 | 0 | 1 | 0.0126803 | 0 | 2 | 2 | 1 |
| 10    | 0.00513696 | 0 | 1 | 0 | 1 | -0.00318278 | 2 | 3 | 2 | 1 |
| 11    | 0.0209449 | 1 | 1 | 0 | 1 | 0.00334268 | 0 | 6 | 2 | 1 |
| 12    | 0.00474319 | 2 | 1 | 0 | 1 | -0.00183491 | 1 | 1 | 0 | 2 |
| 13    | -0.00723408 | 2 | 0 | 1 | 1 | 0.000112451 | 3 | 2 | 0 | 2 |
| 14    | 0.00438388 | 1 | 1 | 1 | 1 | -0.000029722 | 3 | 6 | 0 | 2 |
| 15    | -0.0269403 | 0 | 2 | 1 | 1 | 0.000269551 | 1 | 0 | 1 | 2 |
| 16    | 0.0558082 | 3 | 0 | 1 | 0 | 0.00083265 | 2 | 0 | 1 | 2 |
| 17    | 0.0161886 | 0 | 3 | 1 | 0 | 0.00155334 | 0 | 2 | 1 | 2 |
| 18    | 0.00318086 | 1 | 3 | 1 | 0 | 0.000302683 | 0 | 6 | 1 | 2 |
| 19    | 0.015896 | 0 | 0 | 2 | 0 | -0.0001843 | 0 | 0 | 2 | 2 |
| 20    | 0.0471729 | 1 | 0 | 2 | 0 | -0.000425399 | 0 | 3 | 2 | 2 |
| 21    | 0.0196283 | 3 | 0 | 2 | 0 | 0.000869243 | 3 | 3 | 2 | 2 |
| 22    | -0.0502782 | 0 | 1 | 2 | 0 | -0.0004659 | 0 | 6 | 2 | 2 |
| 23    | -0.030055 | 3 | 1 | 2 | 0 | 0.000554194 | 1 | 6 | 2 | 2 |
| 24    | 0.0417122 | 2 | 2 | 2 | 0 |

**Table 2. Regression coefficients and exponents of $K_0$**

4. Optimum Propeller Analysis Program

This optimum propeller analysis program is specifically used to obtain the optimal propeller type of each type of B-series propeller. This analysis program starts by entering the values that have been obtained previously. The application used is the academic version of the Mat Lab software. The process of optimum propeller analysis program by iterating the values of $Z$, $A_d/A_o$, $P/D$, and $J$ according to predetermined limits. Looping of the variation of $Z$, $A_d/A_o$, $P/D$ values until get the optimum or best propeller is obtained. The steps in the optimum propeller analysis program are more detailed explained in the flow chart shown in Fig 2.
Figure 2. Propeller Analysis Flow Chart

Input data: $R_T, V_s, t, w, D_{max}, n, h, \phi_r, \rho_e, A_e/A_0$

1. $J_{min} = \frac{V_a}{nD_{max}}$

2. $J = J_{min} ; 0.01; 0.5$

Cavitation Constraints

$$P / D_{max} = \frac{1.067 - (\frac{A_p}{A_d})}{0.229}$$

NumbZ = 2 s/d 7
PD = 0.5 s/d P/D_{max}

$+ (\Delta K_T & \Delta K_Q)$

$K_{Topen}, K_{Qopen}$

$$R_n = 5.3 \frac{A_e/A_0}{nJ^2} \frac{V_a^2}{Z}$$

If $R_n < 2 \times 10^6$

yes

$$K_{Tload} = \frac{R_n n^3}{\rho(1-t) V s^2 (1-w)^4 J^4}$$

no

$K_{Tload} - K_{Topen} \leq 0.001$

Graph

$$\eta_p = \frac{J \ K_T}{2 \pi \ K_Q}$$

Propeller: $\eta_{propeller}, K_T, K_Q, A_e/A_0, P/D, J, T, Q$
5. Results and Discussion
In this research, the ship used as the object of analysis is a ship with twin screw propellers. Because in this case the Main Engine and Gear box are already installed, the propeller revolutions (n), ship speed (Vs) has been obtained. Ship's of resistance is calculated by using the academic version of the Maxsurf of the ship's drawing design. The maximum diameter of the propeller (Dmax) has been determined. Wake Factor (w), trust deduction factor (t) is calculated using the Heckscher formula from the book "Ship Design for Efficiency and Economy" [7]. Distance of the center of the shaft to the surface of sea water (h) has been obtained.

| Table 3. Input Data | Item                          | Value     |
|---------------------|-------------------------------|-----------|
|                     | Total ship resistance (R_T)  | 85215 kN  |
|                     | Service speed (Vs)            | 12 knt    |
|                     | Thrust deduction factor (t)   | 0.187     |
|                     | Wake Factor (w)               | 0.214     |
|                     | Maximum Diameter (Dmax)       | 2.14 m    |
|                     | Propeller revolutions (n)     | 573 rpm   |
|                     | Distance of the center of the shaft to the surface of sea water (h) | 1.071 m |
|                     | Phi                           | 22/7      |
|                     | Rho                           | 1.025 t/m³|

After analyzing the propeller by varying the number of blades (Z), A_e / A_o, and P / D in the propeller optimum analysis program, the optimum operating point is found at B3.611, P / D 0.569 with a graph like in Fig 3

![Figure 3. Propeller optimum operating point graph](image)

The output data of the propeller optimum analysis program is as follows

| Table 4. Output Data | J   | Z   | D(m) | Eff | K_T | 10K_Q |
|----------------------|-----|-----|------|-----|-----|-------|
|                      | 0.34| 3   | 1.493| 0.482| 0.1128| 0.1270|

The optimum propeller data from the propeller analysis program, then is verified P / Dmax as a limitation does not cavitation occur. From the optimum program analysis data obtained Diameter and P / Dmax data on each J as follows.
Table 5. D(m) & P/D$_{\text{max}}$

| J   | 0.24 | 0.25 | 0.26 | 0.27 | 0.28 | 0.29 | 0.30 | 0.31 | 0.32 | 0.33 | 0.34 |
|-----|------|------|------|------|------|------|------|------|------|------|------|
| D(m) | 2.115| 2.030| 1.952| 1.880| 1.813| 1.750| 1.692| 1.637| 1.586| 1.538| 1.493|
| P/D$_{\text{max}}$ | 0.858| 1.267| 1.440| 1.491| 1.469| 1.396| 1.286| 1.144| 0.975| 0.783| 0.569|

At the intersection point of KT$_{\text{open}}$ with KT$_{\text{load}}$ at J 0.34, the P / D$_{\text{max}}$ value is 0.569, where the optimum propeller P / D is 0.569 at a diameter of 1,493 m. so it can be concluded that this type of propeller is "no cavitation". The optimum analysis result of propeller as a whole is obtained by B Series propeller type as in table 6.

Table 6. B Series Optimum Data Propeller

| Item                | Explanation         |
|---------------------|---------------------|
| Propeller           | B-Series            |
| Number of Blade (Z) | 3                   |
| Diameter (D)        | 1.493 m             |
| $A_I/A_0$           | 0.611               |
| P/D                 | 0.569               |
| Efficiency          | 0.482               |
| Condition           | No Cavitation       |

6. Conclusion

Based on this research, analyzes using the polynomial method in the optimum propeller analysis program that has been carried out, it can be concluded that the results of analysis by varying the number of blade (Z), $A_I/A_0$, and P / D obtained the most optimum type of propeller is propeller B Series B3.611 with a diameter of 1.493 m, P / D 0.569, and the highest efficiency value is 0.482, "no cavitation"

The results of this optimal propeller analysis are expected to produce better thrust so that can reduce the use of fuel which is ultimately beneficial from an economic term.

References

[1] Bernitsas, M.M., Ray, D., Kinley, P., (1981), “Kt, Kq and Efficiency Curves for the Wageningen B-Series Propellers”, University of Michigan, Michigan.
[2] Dragovis, Branislav., Tzannatos,Ernestos., T Selentis, Vassilis., Venera Todotut,Amalia ., (2016). “Energy Efficiency in the Shipping sector- A Case Study”. Economy Series, Vol II/2016, ISSN 2344-3685/ISSN-1,1844-7007
[3] Harvald, SV. Aa., (1983), “Resistance and Propulsion of ships,” The Technical University of Denmark, Denmark.
[4] Huda, Nurul., (2013), “Analisa Pengaruh Energy Saving Device Pada Propeller Dengan Metode CFD,” Tugas Akhir, Jurusan Teknik Perkapalan, UNDIP Semarang.
[5] Lewis, Edward V., (1988), “Principles of Naval Architecture”, 2nd edition, The Society of Naval Architecture and Marine Engineers, Jersey City
[6] Molland., Antony E, (2010), “The Maritime Engineering Reference Book”, Oxford University, Oxford UK
[7] Schneekluth , H., Bertram ,V , (1998),“Ship Design for Efficiency and Economy”, second edition., Butterworth-Heinemann, Oxford, ISBN 0 7506 4133 9