Analysis of Stern Shape Effect on Pre-Duct Propeller Performance Based on Numerical Simulation

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Abstract. In process and development of ship building, it always lead to the design that is environmentally friendly and has high efficiency values on the energy and economic side. The factor is the selection and determination of the propulsion system. In propulsion system, propeller and its flow is very influential, such as flow at the stern, the flow that will enter the propeller, and the propeller design used. This can increase the propulsive coefficient of the propulsion system. For single screw ship, the hull efficiency is usually between 1.1 - 1.4, while for twin-screw with conventional hull forms, the hull efficiency is around 0.95 - 1.05. The value of relative rotative efficiency is between 1.0 - 1.07 and the efficiency of the shaft is between 0.96 - 0.995. Meanwhile, the value of open water efficiency and hull efficiency greatly affect to ship performance. From the simulation, with the additional of pre-duct The hull efficiency value has increased by 2.2% - 4.3%, this is due to the increase of wake fraction value higher than the thrust deduction value. The relative rotative efficiency also increases by 0.8% - 1% for each variation of the block coefficient or type of ship. But, for the propulsive coefficient, the resulting gap was decreasing by 2% - 6%. Because of that the distance between the hull and the pre-duct, the design of the propeller, the distance between the pre-duct and the propeller, and the shape of the stern are important references for the pre-duct design.

1. Introduction

In process and development of ship building, it always lead to the design that is environmentally friendly and has high efficiency values on the energy and economic side. The factor is the selection and determination of the propulsion system. In propulsion system, propeller and its flow is very influential, such as flow at the stern, the flow that will enter the propeller, and the propeller design used. So, the addition of a device between the hull and the propeller is important to increase the propulsive coefficient, which will be discussed in this study.

The propulsive coefficient can be obtained by hearing the multiplication of the hull efficiency, the propeller efficiency, and the rotative relative efficiency. Changes in these values will affect the performance of the propulsion system, but each efficiency value has a different vulnerability. For single screw ship, the hull efficiency is usually between 1.1 - 1.4, while for twin-screw with conventional hull forms, the hull efficiency is around 0.95 - 1.05. The propeller efficiency values range from 0.35 - 0.75. The value of relative rotative efficiency is between 1.0 - 1.07 and the efficiency of the shaft is between 0.96 - 0.995[1]. Meanwhile, the value of open water efficiency and hull efficiency greatly affect to ship performance.

Of the three ESD Zones in Figure 1, ESD is needed in zone 1 to improve the performance of the flow and propulsion system at the stern of the ship. This ESD will have several forms, such as Pre-Duct, Pre-Swirl, and a combination of the two. Due to the impact of energy loss from the propeller, hull, and stern form, so that the ESD (Energy Saving Device) placement before the propeller can be used to reduce axial and rotational phenomena that contribute greatly to energy loss in the propulsion system[2].In this
study a circular duct design will be made on several types of vessels or different block coefficients to analysis the hull propeller interaction with circular duct design and without pre-duct for each variation. Based on numerical simulation, it will use computational fluid dynamic method with propeller actuator disk. By comparing the propulsive coefficient and wake flow with and without pre-duct for each variation of ship, the hull-propeller interaction in different coefficient block will be obtained.

Figure 1. Zone classification of ESD [3].

From the previous research, it was explained that adding the length of the parallel middle body for a ship with the same stern will increase the ship's resistance coefficient. The shape of the stern change from U-type to V-type also affects the drag coefficient and wake flow [4]. So that the value of Cb can be an influence on ship resistance, stern shape, and wake flow. However, the addition of ESD does not have a substantial advantage even though the power reduction can occur up to 7%. This happens because the flow conditioning made by the Pre-Duct can increase the efficiency of the propeller [5][6][7]. However, changing the angle of attack can significantly increase propulsive efficiency [6][8]. Therefore the Pre-Duct and hull designs cannot be implemented carelessly. A match between the two is required for better efficiency in the propulsion system.

2. Hull-Propeller Interaction

2.1 Efficiency of Propeller

The propulsive coefficient is the multiplication of hull efficiency, open water efficiency, and relative rotative efficiency. This value is used to calculate the power requirements of the ship to reach a certain speed.

\[ PC = \frac{P_E}{P_D} = \eta_H \times \eta_R \times \eta_O \]  

However, this value is influenced by the value of gastric efficiency, propeller efficiency, and rotative relative efficiency. The efficiency value has a different vulnerability. Hull efficiency (\( \eta_H \)) is defined as the ratio of the effective power and thrust at the propeller or can be defined as follows,

\[ \eta_H = \frac{EHP}{THP} = \frac{Rt \times V}{T \times Va} = \frac{Rt}{T} \times \frac{V}{Va} = 1 - \frac{1}{1 - w} \]  

(2)

For single-screw vessels, the hull efficiency (\( \eta_H \)) is usually between 1.1 and 1.4. For twin-screw boats with a conventional hull shape, the hull efficiency (\( \eta_H \)) is approx. 0.95 to 1.05. The higher the block coefficient value, the higher the hull efficiency value [1].

Propeller efficiency (\( \eta_O \)) is related to the Open Water Test, which is a propeller that works on a homogeneous wake field without any hull or barrier in front of it. Propeller efficiency depends on the flow, design, rotation speed, and size of the propeller itself. The propeller efficiency values range from
0.35 - 0.75. The value of propeller efficiency can be seen by conducting an open water test and reading the KT KQ J diagram [1]

\[ \eta = \frac{TV_a}{2\pi nQ} = \frac{KT_o J}{KQ_o 2\pi} \]  

(3)

The actual velocity of the water flow to the propeller behind the hull is not constant or always at a right angle to the propeller area, but has a kind of rotational flow. Therefore, compared to the open water test conditions, propeller efficiency is also influenced by the propeller relative rotative efficiency (\(\eta_R\)). It can be defined as efficiency behind hull (\(\eta_B\)).

\[ \eta_B = \eta_R \times \eta_O \]  

(4)

If resistance and propulsion model tests are performed, then the relative rotative efficiency is determined at model scale from the measurements of thrust and torque with the propeller operating behind the model. Using the non-dimensional thrust coefficient as input data, the values J and torque coefficient are read off from the open water curve of the model propeller used in the propulsion test. The torque coefficient of the propeller working behind the model is derived from

\[ KQ_b = \frac{Q_m}{\rho n^2 D^5} \]  

(5)

\[ \eta_R = \frac{KQ_o}{KQ_b} \]  

(6)

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 of ships with conventional hull shapes and on twin-screw will usually be smaller, approximately 0.98 [1].

From the various efficiencies that affect the propulsive coefficient, it can be concluded that the efficiency value of the hull and propeller has the widest susceptibility, so this value will greatly affect the propeller design. Wake Fraction (w) and Thrust Deduction (t). For single-screw vessels, the wake fraction coefficient is usually between 0.20 to 0.45. The bigger the block coefficient, the bigger the wake fraction coefficient. In a twin-screw vessel with a conventional hull shape, the propeller will be positioned outside the stern centerline of the hull, which will lower the wake fraction coefficient [1]. The wake fraction coefficient will increase the risk of cavitation on the propeller because the water velocity distribution on the propeller is generally not homogeneous. The more homogeneous the wake fraction coefficient is, the higher the advance velocity will be so that a design modification on the stern of the hull is needed to produce an optimal wake field [1].

\[ Rt = (1 - t)T \]  

(7)

From the perspective of the hull studied, the addition of 3 vortex generators on each side made the ship's vibrations reduce by 50% in the longitudinal and vertical directions. The addition of an energy-saving device (ESD) will affect the shape of the wake field thereby increasing the propeller performance [9], [10]. Wake-adaptation has an impact on propeller performance, both resulting in greater efficiency, vibration, and minimum noise characteristics. But behind-hull accessories will also contribute to wake flow. So, the hull and propeller compatibility must be analyzed to get the best efficiency.

In general, the thrust deduction coefficient size increases as the wake friction coefficient increases. The shape of the hull may have a significant effect, as in the bulbous bow, under certain conditions (low ship speed), reducing the thrust deduction coefficient. The thrust deduction coefficient for single-screw vessels is usually between 0.12 and 0.30. Ships with a large block coefficient have a large thrust deduction coefficient. For twin-screw vessels and conventional hull forms, the thrust
deduction coefficient will be much lower because the suction process from the propeller occurs further from the stern centerline of the hull [1].

\[ V_a = (1 - t)V_s \] (8)

2.2 Energy Saving Device

Energy-saving devices (ESD) are devices used to recover and minimize energy losses and reduce ship resistance or improve the propulsion efficiency of ships [8]. In some existing ESD, the source of energy loss to the propeller and hull is based on axial, rotational, and friction losses. The use of the ESD device near the propeller is mainly aimed at reducing axial and rotational phenomena which do contribute to energy losses. Several ESD models are grouped into certain zones as in Table 2.1.

| Energy-Saving Device                          | Zone(s) of Operation |
|-----------------------------------------------|----------------------|
| Wake equalizing duct                          | I                    |
| Asymmetric stern                              | I                    |
| Grothues spoilers                             | I                    |
| Stern tunnels, semi- or partial ducts          | I                    |
| Mewis duct                                    | I                    |
| Reaction fins                                 | I/II                 |
| Mitsui integrated ducted propellers           | I/II                 |
| Hitachi Zosen nozzle                          | I/II                 |
| Increased diameter/low rpm propellers         | II                   |
| Grim vane wheels                              | II                   |
| Propellers with end plates                    | II                   |
| Propeller boss fins                           | II/III               |
| Additional thrusting fins                     | III                  |
| Rudder-bulb fins                              | III                  |

Of the three existing zones, zone I is the zone that is most closely related to hull propeller interaction. In concept, the flow in the back of the ship will converge towards the propeller, besides that the propeller also absorbs the incoming flow to the propeller. So that the flow from the hull gathers at the stern and is utilized by the propeller. The faster the flow that enters the propeller, the better the propeller performance. By installing the Pre-Duct as in Figure 2, the flow will be used as an addition to the force of the push because of the foil shape on the Pre-Duct. With the trailing edge or tail foil size of 0.7R propeller for radius ducting, the water flow can be focused on the part of the propeller that is most constrained to produce thrust. As in Figure 2.
Figure 2. Pre-Duct addition refers to the distance of the propeller; (a) position; (b) water flow.

3. Validation
Due to simulation-based model testing, it is necessary to validate the comparison of experimental results with simulation results. The allowable error value cannot be more than 5%-7%. To get this value, the simulation is carried out at the model size so that the parameters being compared can have the same value. The following are the model parameters used on each ship.

Table 2. General Parameter of ships.

| Main particulars                  | JBC    | KCS   | Tanker |
|-----------------------------------|--------|-------|--------|
| Length between perpendiculars L<sub>pp</sub> (m) | 280    | 230   | 100.9  |
| Length of waterline L<sub>WL</sub> (m)     | 285    | 232.5 | 103.5  |
| Maximum beam of waterline B<sub>WL</sub> (m) | 45     | 32.2  | 19.2   |
| Depth D (m)                        | 25     | 19    | 9.3    |
| Draft T (m)                        | 16.5   | 10.8  | 6      |
| Displacement volume V (m<sup>3</sup>) | 178369.9 | 52030 | 9291.97 |
| Wetted surface area w/o rudder S<sub>W</sub> (m<sup>2</sup>) | 19556.1 | 9424  | 2753.83 |
Simulations were performed using the CFD method. The size of domain is adjusted to the distance from the AP of the ship. Forward 2.5 L, backward 4.75 L with a depth of 1.8 L over 1.3 L, and Sides 2 L as in Figure 3. Simulations are carried out with the same domain size and meshing settings for each type of vessel with or without Pre-Duct. This is to get a minimal error when adding Pre-Ducts. The meshing density is carried out on the propeller as shown in Figure 4.

From these parameters, a simulation is carried out and the following are the results of the simulations that have been carried out for model validation. Validation is done on JBC, Tanker and KCS without Pre-Duct as Table 3-5.

### Table 3. Error Simulation Japan Bulk Carrier.

| Type of Vessels          | Name | n   | J     | KT   | KQ     | 1-w   | 1-t   |
|--------------------------|------|-----|-------|------|--------|-------|-------|
| Japan Bulk Carrier (JBC) | EFD  | 7.8 | 0.405 | 0.217| 0.0279 | 0.552 | 0.812 |
|                          | CFD  | 7.52| 0.403 | 0.220| 0.0286 | 0.522 | 0.831 |
|                          | Err. | 3.6%| 0.4%  | -1.5%| -2.5%  | 5.4%  | -2.4% |
4. Comparison and Analysis

From the simulation results that have been carried out on 3 types of ships with different block coefficients, with and without pre-ducts, the following is a comparison of the results.

### Table 6. Simulation Model.

| Type of Vessels (Cb)   | Name       | \( I_w \) | \( I_t \) | \( \eta_H \) | \( \eta_R \) | \( \eta_O \) | PC  |
|-----------------------|------------|-----------|-----------|-------------|-------------|-------------|-----|
| Japan Bulk Carrier (JBC) (0.858) | Without Pre-Duct | 0.572     | 0.830     | 1.452       | 1.054       | 0.415       | 0.635 |
|                        | With Pre-Duct | 0.527     | 0.781     | 1.484       | 1.065       | 0.386       | 0.610 |
|                        | Gap        | -7.9%     | -5.9%     | 2.2%        | 1.0%        | -6.9%       | -3.9% |
| Tanker (0.779)         | Without Pre-Duct | 0.548     | 0.832     | 1.519       | 1.026       | 0.379       | 0.591 |
|                        | With Pre-Duct | 0.509     | 0.803     | 1.578       | 1.034       | 0.355       | 0.579 |
|                        | Gap        | -7.2%     | -3.6%     | 3.9%        | 0.8%        | -6.4%       | -2.0% |
| KRISO Container Ship (KCS) (0.6505) | Without Pre-Duct | 0.793     | 0.892     | 1.125       | 1.016       | 0.627       | 0.716 |
|                        | With Pre-Duct | 0.676     | 0.793     | 1.174       | 1.026       | 0.559       | 0.674 |
|                        | Gap        | -14.8%    | -11.1%    | 4.3%        | 1.0%        | -10.8%      | -6.0% |

Based on the results of the simulations obtained as in Table 4. The hull efficiency value has increased by 2.2% - 4.3%, this is due to the increase of wake fraction value higher than the thrust deduction value. The relative rotative efficiency also increases by 0.8% - 1% for each variation of the block coefficient or type of ship. But, for the propulsive coefficient, the resulting gap was decreasing by 2% - 6%. This is due to the reduction in the efficiency of open water which is not proportional to the increase in hull efficiency. Changes in advance velocity also make the advance coefficient shift. So the advance velocity value and the efficiency of open water is reduced. However, the reduction in propeller efficiency is higher than the increase in hull efficiency, so that the propulsive coefficient value decreases.

The suitability of the Pre-Duct shape and placement for each vessel type is different. The Pre-Duct design must be adjusted accordingly to get a better propulsive coefficient value. The pitch-diameter...
ratio or area ratio can be adjusted to keep open water efficiency in same value for advanced coefficient of propeller with pre-duct

5. Conclusion

CFD method has been feasible to analyse the benefit use of ESD such as the implementation of pre-duct on different type of vessels. It confirm by the validation data from the experiment and the simulation. In general, the addition of the Pre-Duct will increase the hull efficiency by 2.2% - 4.3% and the relative rotative efficiency by 0.8% - 1%. The addition of Pre-Duct has a good impact on the hull efficiency of ships with low coefficient block. but the value of open water efficiency decreases and it is not proportional to the increase in hull efficiency. Therefore the propulsive coefficient value decreases. The distance between the hull and the pre-duct, the design of the propeller, the distance between the pre-duct and the propeller, and the shape of the stern are important references for the pre-duct design.

References

[1] MAN B&W Diesel A/S, “Basic Principles of Ship Propulsion,” *Man Diesel Turbo*, pp. 1–42, 2013, doi: 10.1017/CBO9781107415324.004.

[2] A. S. Olsen, “Energy coefficients for a propeller series,” *Ocean Eng.*, vol. 31, no. 3–4, pp. 401–416, 2004, doi: 10.1016/j.oceaneng.2003.06.002.

[3] J. S. Carlton, *Theoretical and Analytical Methods Relating to Propeller Action*, no. 1865. 2012.

[4] K. Suastika, F. Nugraha, and I. K. A. P. Utama, “Parallel-middle-body and stern-form relative significance in the wake formation of single-screw large ships,” *Int. J. Technol.*, vol. 8, no. 1, pp. 92–101, 2017, doi: 10.14716/ijtech.v8i1.3542.

[5] T. van Terwisga, “On the working principles of Energy Saving Devices,” *Third Int. Symp. Mar. Propulsors*, no. May, pp. 510–518, 2013.

[6] F. Çelik, “A numerical study for effectiveness of a wake equalizing duct,” *Ocean Eng.*, vol. 34, no. 16, pp. 2138–2145, 2007, doi: 10.1016/j.oceaneng.2007.04.006.

[7] H. Schneekluth, “Wake equalizing duct,” *Nav. Archit.*, vol. 102, pp. 147–150, 1986.

[8] A Munazid, J M Ariana, and K A P Utama, “Numerical Study of Pre-Duct on Traditional Fishing Vessels as Energy Saving Device (ESD) Numerical Study of Pre-Duct on Traditional Fishing Vessels as Energy Saving Device (ESD),” in *Maritime Safety International Conference*, 2020, doi: 10.1088/1755-1315/557/1/012049.

[9] L. X. Hou, C. H. Wang, A. K. Hu, and F. L. Han, “Wake-adapted design of fixed guide vane type energy saving device for marine propeller,” *Ocean Eng.*, vol. 110, pp. 11–17, 2015, doi: 10.1016/j.oceaneng.2015.09.036.

[10] J. H. Kim, J. E. Choi, B. J. Choi, S. H. Chung, and H. W. Seo, “Development of Energy-Saving devices for a full Slow-Speed ship through improving propulsion performance,” *Int. J. Nav. Archit. Ocean Eng.*, vol. 7, no. 2, pp. 390–398, 2015, doi: 10.1515/ijnaoe-2015-0027.