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# Design of Kaplan-Series Propeller for Commercial Submarine by Varying Rake Angle and Number of the Blade to Obtain the Highest Thrust and Efficiency

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**Abstract** The use of submarines has covered various fields, for instance, is the exploration and exploitation of offshore petroleum. Submarine production and operation costs are still very expensive. The efficient use of fuel can reduce operating costs and increase cruising time for submarines. It is necessary to design the most optimal propeller with the highest and most efficient thrust. In this study, a commercial submarine is applied with the Kaplan-series propeller and nozzle intended to increase propeller thrust. Based on previous research it is recommended that propeller design should involve the hull itself. Therefore, the submarine hull form will be simulated together with the propeller. By varying the number of blades and rake angles of each propeller, it is expected to obtain the highest thrust. There are 3 types of the number of a blade that used in this study i.e. 6, 8, and 10 blades. While the variation rake angles are 5°, 10°, and 15°. The present study uses computational fluid dynamics to predict thrust and torque in open water conditions. The turbulence flow k-epsilon model was used in the simulation. The results revealed that Ka1080 Propeller with 5° rake angle has the highest thrust and torque, which is 201 kN and 181 kN.m. on the other hand, propeller Ka680 with 15° rake angle has the highest efficiency reaching 50.9%.

## Introduction

Nowadays, the submarine is not only used for the military but also for the oil and gas industry[1]. Therefore, the need for a submarine is increasing year by year. The submarine's capability to operate beneath the ocean depends on air-independent propulsion. This kind of propulsion cannot consume ordinary fuel. Poly-electrolyte membrane fuel cells are arranged on board. This kind of fuel is much more expensive than the usual marine fuel. Furthermore, there is a demand to design the propeller that has the highest thrust and efficiency to reduce the fuel of submarine, as a result, we can save the lifetime of the fuel cell.

There is a limitation of time how long submarine could dive in, with a better propeller efficiency it could expand the time. This paper presents a simulation of a submarine in a fully submerged condition which represents the highest force needed [2]. To get the realistic result, the propeller is simulated with its submarine hull form [3].

Propulsion is one of the determinants of the hydrodynamic performance of submarines. With so many choices of propeller types [4,5]. Kaplan-type propellers are chosen because they tend to have



higher thrust [6]. The number of blades were used 6, 8, and 10. This difference aims to find the biggest thrust. Rake angles are also divided into 5°, 10° and 15°.

The design of the propeller considers the submarines hull that has been obtained from previous studies. The hull form from the previous study was used in the present study. The submarine resistance was obtained, 40.7 kN in of 8.2 knots based on the previous study. There is another study compared to B-Series and Kaplan-Series. Based on this study the highest thrust was obtained by the Kaplan propeller at 100 RPM. Kaplan propellers are operated in a nozzle, as a result, type 19A is chosen for the nozzle. NACA foil 0018 was chosen for connecting strut with the nozzle. From previous studies propeller with nozzle has higher thrust [7,8].

This research will carry out a computational fluid dynamics simulation on Kaplan-series propellers arranged with its submarine hull to capture the behavior that produced due to the changes in the number of blades and rake angles on the submarine propeller and know the performance of thrust, torque and propeller efficiency ( $\eta_0$ ) after the change of propeller rake angles and the number of blades.

## Theoretical Background

### 1.1. Governing Equation

Computational fluid dynamic (CFD) is consists of fundamental equations in fluid dynamics such as continuity equation, momentum equation, and energy conservation equation. In this study, CFD solver is based on incompressible Reynolds Averaged Navier-Stokes equation which is the solver applied the finite Volume Method (FVM) for representing the inflow and outflow areas.

#### 1.1.1. The Continuity Equation

To apply the conservative form of the Navier-Stokes equation in the Finite Volume Method, the Boundary-bound model volume is considered constant in the dynamic fluid simulation domain. The continuity equation of the mass in the form of conservation based on the density that remains on the Incompressible flow is explained in Equation (1). Where  $\rho$  is the density,  $U$  is the velocity vector and  $t$  is time.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho U_j) = 0 \quad (1)$$

#### 1.1.2. The Momentum Equation

Newton's 2nd law is applied to the finite volume methods in models with fluid flow. When the fluid moves, the force on the fluid element is equal to the mass multiplied by the acceleration of the element itself, as expressed in Equation (2).

$$\frac{\partial \rho U_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho U_i U_j) = -\frac{\partial p'}{\partial x_i} + \frac{\partial}{\partial x_i} \left[ \mu_{eff} \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right] + S_M \quad (2)$$

### 1.2. Hydrodynamic of Propeller

The propeller model has a characteristic that describes its hydrodynamic ability. The result that has been computed by CFD usually refers to thrust ( $T$ ), torque ( $Q$ ), and efficiency ( $\eta_0$ ). Therefore, the performance data are given as the coefficient of thrust ( $K_t$ ) and torque ( $K_q$ ) to be plotted against the advance ratio ( $J$ ). those are defined as Eq. (3)-(6)[9].

$$K_t = \frac{T}{\rho n^2 D^4} \quad (3)$$

$$K_q = \frac{Q}{\rho \cdot n^2 D^5} \quad (4)$$

$$J = \frac{V_a}{nD} \quad (5)$$

$$\eta_0 = \left( \frac{Kt}{Kq} \right) * (J/2\pi) \quad (6)$$

Where  $\rho$  is water density,  $n$  is the number of propeller revolution per second (RPS),  $D$  is propeller diameter, and  $Va$  represents water advance velocity (m/s).

## Simulation Condition

### 1.3. Principal Dimension of Submarine

The dimension of the submarine hull form is presented in Table 1.

**Table 1.** Principal dimension.

Geom. Parameter	Value
Length Overall (m)	71.3
Maximum Height (m)	12.7
Outer hull Diameter (m)	9.2
Velocity (knots)	8.2
RPM Propeller	100
Total Resistance (kN)	40.7
WSA (m <sup>2</sup> )	1910.7
Reynold Number	2.51 x 10 <sup>8</sup>

### 1.4. The principal dimension of the propeller

The propeller dimension is presented in Table 2.

**Table 2.** Propeller principal dimension.

Geom. Parameter	Value
Pitch length (m)	4
Diameter (m)	4.123
AE/AO	0.8
Hub diameter (m)	0.8

### 1.5. Parametric studies

It is mentioned in section 1 that, several blade numbers and rake angles have been taken into consideration. Table 3 is the details of the simulation parameter.

**Table 3.** Propeller principal dimension.

Geom. Parameter	Value
Rake (degree)	5,10,15
Blade number	6,8,10

### 1.6. Fluid condition

The water conditions are adjusted to the waters where the submarine has been designed and tested before. The fluid conditions are presented in Table 4.

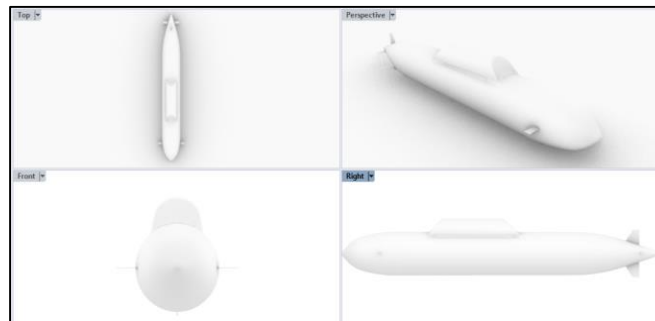
**Table 4.** Fluid condition.

Parameter	Value
Density (kg/m <sup>3</sup> )	1025
Kinematic viscosity (m <sup>2</sup> /s)	1.20. 10 <sup>-6</sup>
Dynamic viscosity (kg/m.s)	1.23. 10 <sup>-3</sup>

## Modelling

### 1.7. Hull Form Modelling

Based on the principal dimensions in Table 1, the 3-D model was made. Figure 1 shows of the 3-D model drawing of submarine that used in present study. The submarine is without propeller model, the next stage draws the propeller model in CAD software.



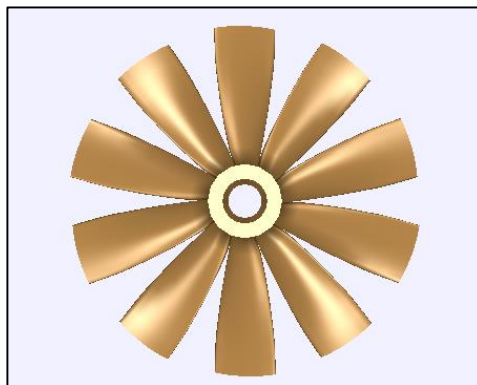
**Figure 1.** Hull form model in 3-D

### 1.8. Propeller model

The propeller, as the main object in this study has been drawn into 3-D based on the principal dimensions in Table 2 and Table 3 shows the variation that used in this study. Figure 2 is an example from the several propeller model. The propeller is designed as the criteria shown below.

**Table 5.** Propeller characteristics.

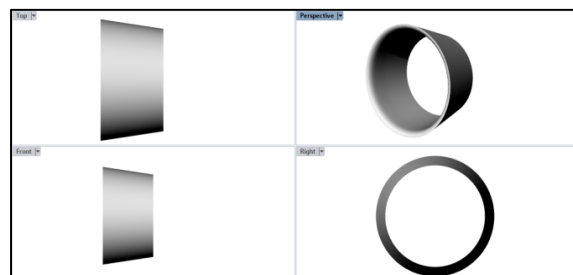
Geometry	Value/Type
Propeller Type	Fix pitch propeller
Rotation	Right
Blades	6, 8 and 10
Diameter (m)	4.123
Nominal Pitch (m)	4
Rake angle (degree)	5 10 and 15
Expanded Bar	0.8
skew angle (degree)	3.1
Sections	Kaplan
Outline	Kaplan
Rake distribution	Linear
Skew distribution	Kaplan
Hub Diameter/D (m)	0.2
Thickness rule	Kaplan
Thickness distribution	Kaplan



**Figure 2.** Propeller Ka1080-5

*1.9. Nozzle model*

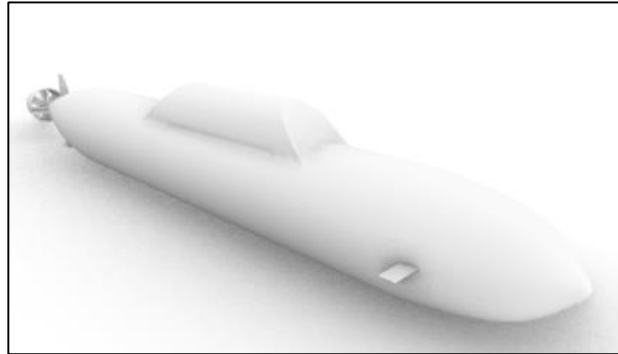
The propeller is designed to be arranged with a nozzle. The previous study concludes that ducts 19A has a desirable hydrodynamic feature and easy to fabricate[9]. As a result, Nozzle 19A is chosen to use in simulation. Figure 3 is presented the nozzle 19A 3D model.



**Figure 3.** Nozzle 19A

1.10. Assembled model

After the component had been drawn, the propeller and its nozzle need to be joined to hull form. The hull form of a submarine is presented in Figure 4.



**Figure 4.** Complete submarine hull body

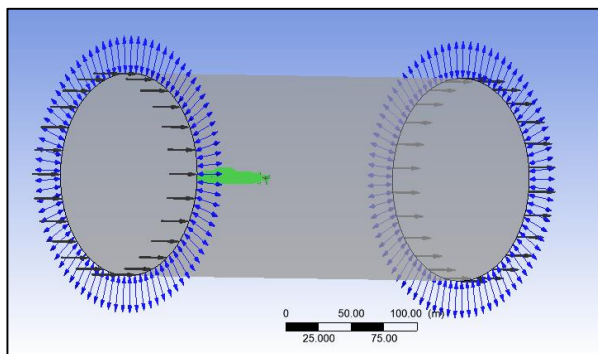
**Computational domain**

CFD simulations are followed by the criteria of ITTC CFD guidelines. For the case of the propeller domain, 2 fluid domains need to be created, which is the fluid domain and the propeller domain. This simulation uses a steady-state condition. The fluid domain is created with a dimension that suggests by ITTC. Table 5 is presented the dimensions[10].

**Table 6.** Fluid domain’s dimension.

Distance from hull to	Value
Inlet boundary	1 x Lpp
Outer Tubular wall boundary	1 x Lpp
Outlet boundary	3 x Lpp.

As the dimension is shown, the fluid domain was made for the simulation. This dimension should be applied to prevent wave reflection. The fluid condition was made as Figure 5 presented.



**Figure 5.** Fluid Domain

1.11. Fluid Domain

The fluid domain is a room for fluid. This domain contents some boundary conditions, which are shown in Table 7 below.

**Table 7.** Boundary Condition in the fluid domain.

Boundary	Type	
Inlet	Velocity-Inlet (subsonic)	$P=0$ , $v=4,218$ m/s
Hull wall	No-slip wall	$v=0$ at surface
Outlet	Pressure-Outlet	$P=0$
Outer Tubular Wall	Opening	$P=0$

The inlet boundary is defined as velocity-inlet which has speed the same as submarines speed, 8,2 knots. The outer tubular wall is defined as an opening. It allows the fluid to cross the boundary surface in either direction. The outlet boundary is defined as outlet-pressure. The submarine itself is defined as a no-slip wall, so the velocity of the fluid at the wall set to zero.

#### 1.12. Propeller domain

The propeller domain is defined as a rotating domain that has rotational speed 100 RPM. In the rotating propeller domain, there is only one boundary condition, the propeller itself. the surfaces of the propeller are defined as no-slip wall.

#### Mesh Independent

The next step after geometry completed is the discretization of geometry, where the domain of analysis is discretized into elements. These elements will affect the calculation. The discretization strategy must be as accurate as possible to be able to represent the geometry of the propeller and the hull. In the propeller domain, smaller size is used, on the other hand, the large size is used to a fluid. Table 8 shows set up in the meshing stage.

**Table 8.** Setup of numerical simulation.

Parameter	Option
Mesh type	Unstructured
element shape	Tetrahedrons
Sizing quality	Fine
Sizing function	Curvature
Skewness	0,4
Smoothing	High
Total element	$2,0 \cdot 10^6$

This mesh independence has been generated to ensure an adequate number of cells meshing that were sufficiently used for all simulations to obtain accuracy and steadiness in the computational result regardless of the longer CPU time. However, the total number of cells meshing with 2,086,131 was selected for all simulations due to reliability mesh result in capturing the flow field and pressure distribution on the blade's surface.



Table 9. Total meshing in 6 cases.

No	Element	Kt	Kq
1	367630	0.25	0.043
2	744011	0.27	0.046
3	1205952	0.28	0.048
4	2086131	0.27	0.048
5	3035029	0.27	0.048
6	3206052	0.27	0.048

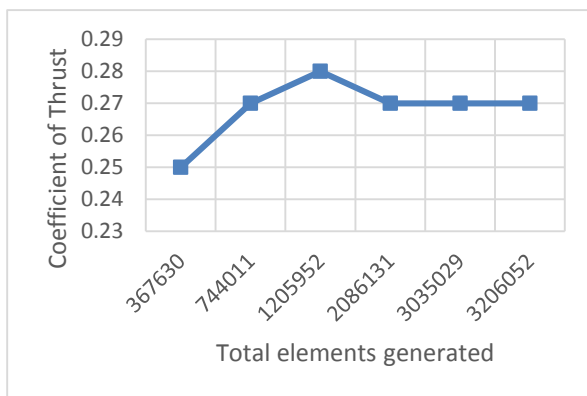


Figure 6. Mesh Independency on Thrust Coefficient

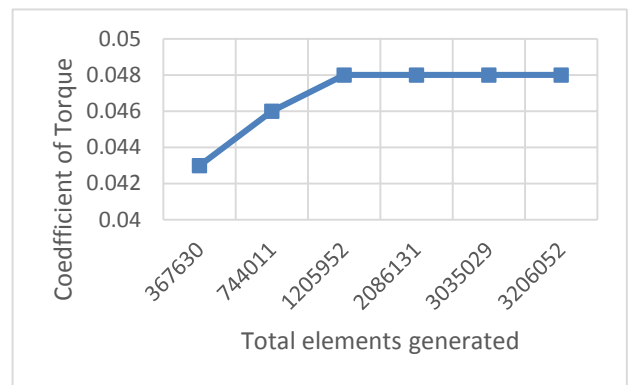


Figure 7. Mesh Independency on Torque Coefficient

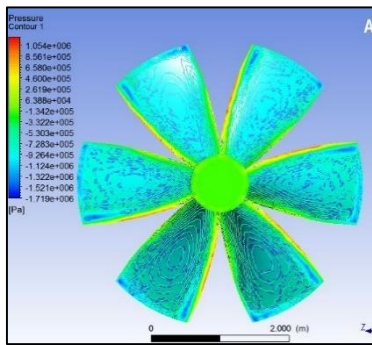
**Results and discussion**

From the simulations that have been carried out on 9 propellers, the mesh results shown in Table 10.

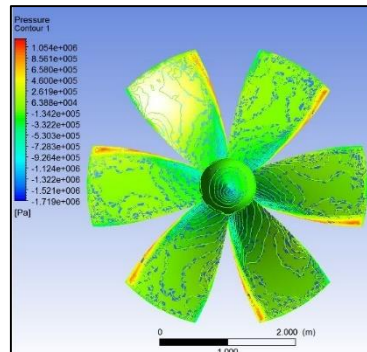
Table 10. Total meshing in 9 cases.

Propeller	Element
Ka680-5	2040053
Ka680-10	2018683
Ka680-15	2033120
Ka880-5	2017159
Ka880-10	2018005
Ka880-15	2286649
Ka1080-5	2012042
Ka1080-10	2011560
Ka1080-15	2077026

As the propeller is rotating on its shaft, pressure occurs on the propeller blade. This hydrodynamic phenomenon creates higher pressure on the back propeller. The difference pressure between face and back creates a lift force. In this case, the lift force of the propeller is acting as thrust. The pressure contour is shown in Figure 8 and Figure 9.

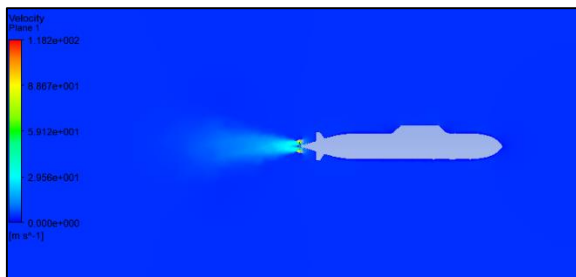


**Figure 8.** Pressure contour on propeller face

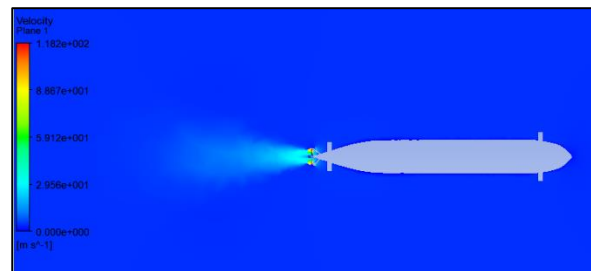


**Figure 9.** Pressure contour on propeller back

As the fluid flows through the submarine hull form, it creates a drag force. This drag force occurs at around of wetted surface area of the submarine. Figures 10 and 11 showed fluid velocity on a submarine.

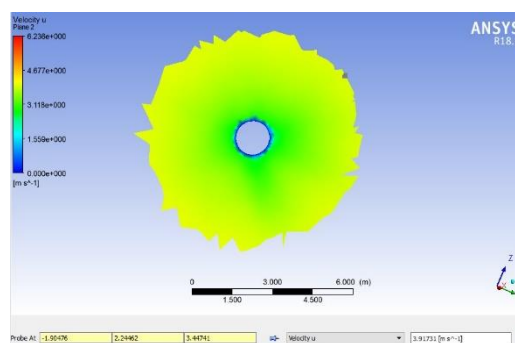


**Figure 10.** Flow on submarine (sideview)



**Figure 11.** Flow on submarine (topview)

Based on the simulations, the velocity of advance ( $V_a$ ) occurred then  $V_a$  value is acquired from the average velocity in front of the propeller.



**Figure 12.** Velocity Contour in Front of Propeller

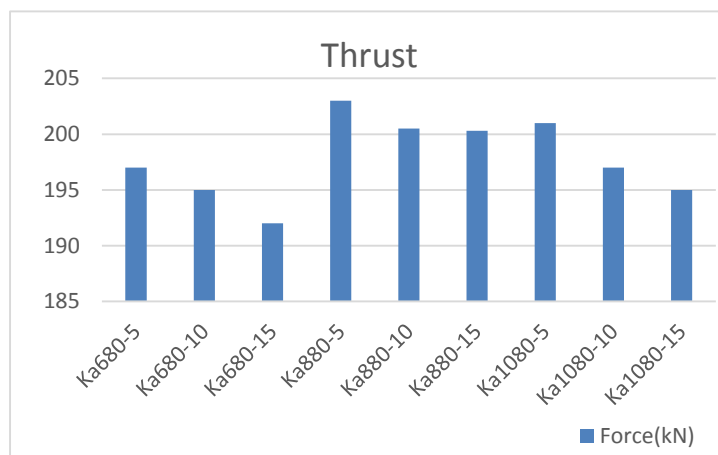
**Table 11.** Averaged Velocity.

No	Va(m/s)
1	3.9172
2	3.95834
3	3.94149
4	3.97975
5	3.96579
6	3.95124
7	3.9272
8	3.88715
9	3.93076
10	3.9201
Mean	3.9379

From the simulation results, we got the thrust values as in Table 12 and the torque listed in Table 13.

**Table 12.** Thrust result from a simulation.

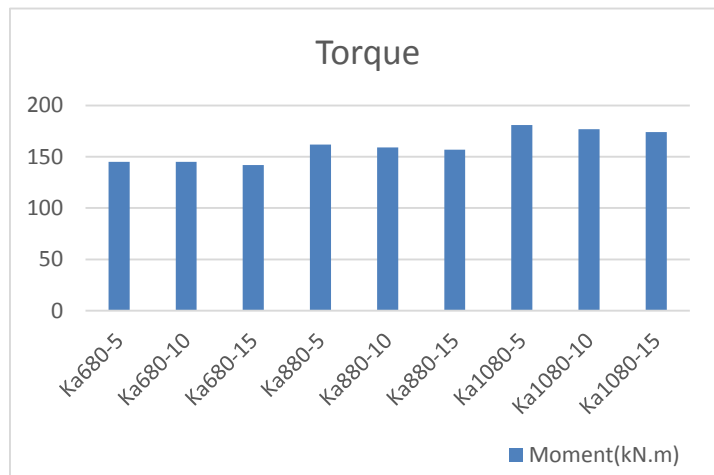
Propeller	Force(kN)
Ka680-5	197
Ka680-10	195
Ka680-15	192
Ka880-5	203
Ka880-10	200.5
Ka880-15	200.3
Ka1080-5	201
Ka1080-10	197
Ka1080-15	195



**Figure 13.** Propeller Thrust (kN)

**Table 13.** Torque result from simulation.

Propeller	Moment(kN.m)
Ka680-5	145
Ka680-10	145
Ka680-15	142
Ka880-5	162
Ka880-10	159
Ka880-15	157
Ka1080-5	181
Ka1080-10	177
Ka1080-15	174



**Figure 14.** Propeller Torque (kN)

Propeller efficiency is also calculated to find the most efficient propeller. The efficiency calculation uses the formula as shown in Equation 7.

$$\eta_0 = \frac{T \cdot Va}{2 \cdot n \cdot \pi \cdot Q} \tag{7}$$

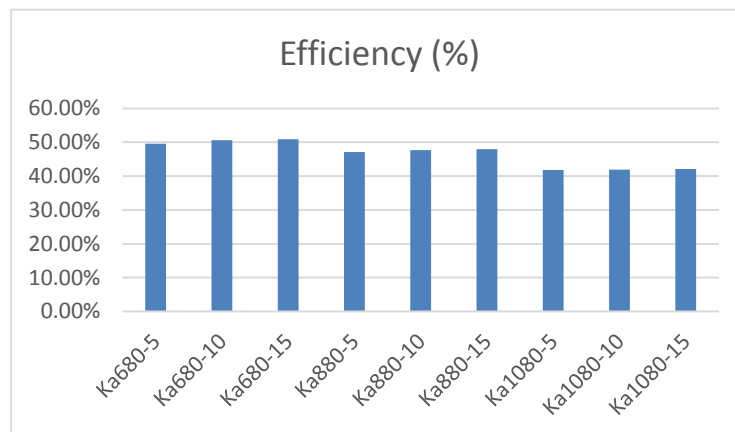
The results of the highest efficiency calculation found on the Ka680 propeller rake 15° are written as follows

$$\begin{aligned} \eta_0 &= \frac{(203000 \times 0.1019) \times 3,94}{2 \times 1,67 \times 3.14 \times 158000(0.1019)} \\ &= 0,5089 \\ \eta_0 &= 50,9 \% \end{aligned}$$

Table 14 shows the efficiency values of each propeller case.

**Table 14.** Propeller efficiency.

Propeller	Efficiency (%)
Ka680-5	49.6%
Ka680-10	50.6%
Ka680-15	50.9%
Ka880-5	47.1%
Ka880-10	47.7%
Ka880-15	48.0%
Ka1080-5	41.8%
Ka1080-10	41.9%
Ka1080-15	42.1%

**Figure 15.** Propeller Efficiency (kN)

### 1.13. Effect of increasing rake angle

The rake angle tends to increase the thrust, torque, and propeller efficiency. As the increasing value of the rake angle, the distance between the hull and propeller will be increased (propeller clearance)[11]. The increasing distance causes the flow at propeller blades have less wake then before. The flow that passes through the hull will rub against the hull when it reaches the end of the hull, the friction will immediately disappear and turbulence will occur, causing a wake. The wake will gradually disappear as it moves far from the hull.

### 1.14. Effect of the increasing number of blades

The results show that the increasing number of blades is in-line with increasing torque. The increasing torque is not accompanied by an equivalent increasing thrust. Even in some propellers, there was a decrease in thrust as the number of blades increased. It can be seen in Equation (5), the efficiency value on a propeller is a ratio between the thrust coefficient ( $K_t$ ) divided by the torque coefficient ( $K_q$ ). Because increased torque is greater than the thrust's, it will decrease the efficiency as the number of blades increase. This is in-line with the results of previous studies, the higher number of propeller blades used the efficiency will be decreased and fuel consumption will be increased [12].

### 1.15. Effect to propeller efficiency

The efficiency of the propellers reaches 50,9 %, this is due to several factors one of the reasons is the propeller revolution. The higher propeller revolves then, the lower the value of  $J$ . This is related to the value of  $Kt$  (coefficient of thrust) and  $Kq$  (torque coefficient).  $Kt$  and  $Kq$  will be higher if  $J$  is lower. On the contrary, thrust and torque will get higher when  $Kt$  and  $Kq$  increasing. Not surprisingly, the highest thrust is achieved at low efficiency. The results show that the higher the propeller revolves, the lower the efficiency is obtained. Because the simulation was done at 100 RPM, it is not surprising the efficiency not high. This condition is described from present results and also the previous reference[9]. The efficiency results are following previous studies where the fewer the number of blades, the better the efficiency will be. From these results, the authors found that as rake increased the efficiency value tended to rise.

### Conclusion

The parameters that have been reviewed in this study using CFD method on submarine propellers showed the propeller characteristics. The increase in rake angle tends to increase thrust, torque, and efficiency. It was also found that increasing the number of propeller blades showed consistent increasing torque and decreasing efficiency. While the thrust tends not to show homogeneous results. The phenomena occur varies by increasing the number of blades. Among all propellers tested, the Ka1080 propeller with a rake angle of  $5^\circ$  is a propeller with the highest thrust and torque of 201 kN and 181 kN.m. On the other hand, the propeller with the highest efficiency is the Ka680 rake  $15^\circ$  with an efficiency reaching 50,9% at 100 revs/min.

### Acknowledgment

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