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Numerical Analysis of the Effects of Propeller High Thrust Distribution on Propulsion System Performance

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Abstract

High ship propulsion performance is the main goal of designers, propeller is one component of the propulsion system that also affects the performance of the propulsion. In propeller planning, it is necessary to pay attention to the efficiency of the propeller, in addition to reducing ship operating costs and reducing CO2 gas emissions which is one of the requirements for ships built above 2013, the rules have been made into the Energy Efficiency Design Index (EEDI) standard. At this time the propeller that is widely used is the B Series propeller including the propeller design used on mini LNG ships, namely the B6.40 propeller, the B Series propeller has a pitch character from the Wageningen Propeller Series study. Innovations are made to get better propeller efficiency by varying the pitch distribution. The B6.40 propeller of the standard constant pitch type was modified to B6.40 variable pitch (high thrust). Propellers with high thrust have better efficiency especially for non-fast boats. This study was conducted to obtain the best propeller efficiency of a constant pitch propeller and three high thrust propeller units using Numeca's Computational Fluid Dynamics (CFD) numerical self-propulsion test. For validation of the simulation program by comparing the results of the open water test B6.40 Wageningen while resistance validation by comparing the ship resistance model test. The results of the self-propulsion test using Disc Actuator show that the propulsion coefficient (PC) of Modified-2 and Modified-3 high thrust propellers is better when compared to constant pitch. The magnitude of the increase in PC value reaches ± 4% higher than the constant pitch type on the Modified-3 propeller.

1. Introduction

The selection of propellers in the ship propulsion system design process is very important to obtain efficiency in ship operations, especially to minimize fuel use, a decrease in fuel usage will also reduce combustion gas emissions, it should be noted that the highest cost incurred to operate the ship on the fuel budget can reach 42% [1], although ships are the most economical mode of transportation but ships are the largest contributor to air pollution [2]. These two factors are a challenge for designers to build cost-efficient and environmentally friendly ships by limiting exhaust emissions from engines [3] which have been endorsed by IMO in 2011 through the Energy Efficiency Design Index (EEDI) standard for ships built in 2013 and above [4,5]. The amount of gas emissions and fuel efficiency is also influenced by the type of fuel used, alternative use of environmentally friendly fuels such as LNG which has advantages when compared to fossil fuels. Fuel use efficiency can be done by minimising the thrust of the ship [6] as well as the selection of the efficiency of the propulsor system that converts power into thrust. Propeller is one part of the propulsor system, to get a propeller that has high efficiency there are several factors that affect it, including the diameter, number, and pitch of the propeller [7], both from the pitch ratio and pitch distribution [8]. Others, the efficiency value is influenced by the diameter, number, and pitch of the propeller [7], both from the pitch ratio and pitch distribution [8].

Some studies to get better propeller efficiency such as: Installing Energy Saving Devices (ESD) by installing Pre-duct, which is placed between the stern and the propeller to increase the flow to the propeller, Pre-duct can increase the propulsion coefficient by about 1.72% [6]. Installing a Pre-Swirl Stator (PSS) to regulate the flow into the propeller can also increase the Propulsion Coefficient (PC) by 10.3% [9,10]. Another form of ESD by reduce cavitation events by installing fins on the propeller hub (PBCF), this method can increase propeller efficiency by 3-7% [11], another form by concentrating the flow towards the propeller to increase the efficiency of the propulsion system by modifying the shape of the stern of the stern tunnel [12]. However, in this study, to increase the efficiency of the propeller, we do not install other components as above but modify the character of the propeller, namely modifying the pitch distribution of the propeller. PTRIM-BPPT (now BRIN) in its activities in 2020-2021 has carried out the design of the Mini LNG Ship, in these activities hull optimization and model testing have been carried out (Figure 1), while for propeller optimization the pitch ratio (P/D) [13], blade area ratio (BAR) and optimization of determining the number of propeller blades [14].

This research is conducted on the B6.40 propeller which is designed for propellers on Mini LNG Carrier Ship. This propeller has a constant-pitch pitch distribution[15] to be modified into a variable-pitch or high-thrust propeller where high thrust propellers have better efficiency, especially for non-fast vessels, compared to the constant-pitch type[8]. Constant-pitch is the axial distance travelled by the propeller in a fixed range of values, while high-thrust propeller is the axial distance travelled by the propeller in a non-fixed range of values. The positive effect of pitch distribution on propeller efficiency, especially for non-fast vessels, is very good because it can increase its efficiency.

This study simulates one constant-pitch propeller and three high thrust propellers with distribution patterns according to Adam Kaplan [16] to analyse the effect of pitch distribution type on Propulsion Efficiency (PC) and Delivered Horse Power (DHP) of each propeller using Numeca CFD simulation. The process of using CFD simulation provides advantages because it reduces the number of model tests, the process is shorter and cheaper [15,16].

In the previous study to obtain propeller efficiency by increasing or streamlining the flow towards the propeller, where in this step to achieve this goal by adding components installed on the hull or propeller of a finished ship, while in the study to take the other side of the influence of propeller characteristics such as diameter optimisation, BAR and pitch ratio, namely the possible effect of changes in pitch distribution on propeller efficiency.

In the previous study to obtain propeller efficiency by increasing or streamlining the flow towards the propeller, where in this step to achieve this goal by adding components installed on the hull or propeller of a finished ship, while in the study to take the other side of the influence of propeller characteristics such as diameter optimisation, BAR and pitch ratio, the effect of changing pitch distribution on its propeller efficiency increases up to 4%

2. Methods

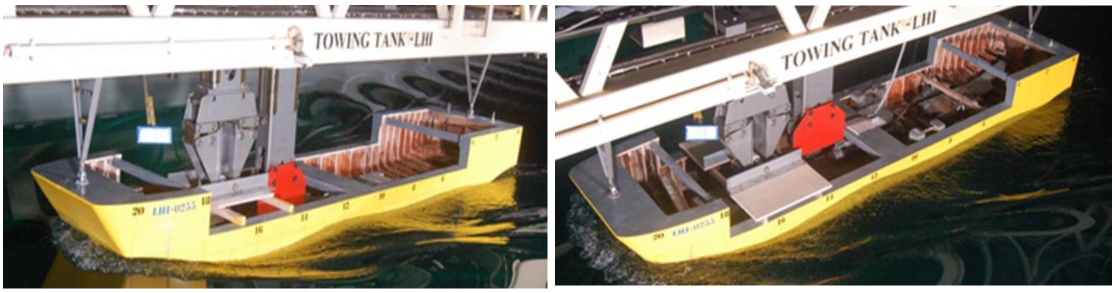
Literature study to obtain data/information related to the object of research. Data or information can be obtained from journals, books, scientific papers and from research that has been done such as data from resistance tests and self propulsion tests from hulls with B4.40 propellers in Table 1 and Table 2.

Table 1. Propeller data

Name	Notation	Propeller	Model	Unit
Propeller Diameter	D	1.5	0.131	m
Blade Area Ratio	BAR	0.4	0,4	-
Pitch Ratio	P/D	1.144	1.144	-
Number of Blade	Z	6	6	Blade

Table 2. Principal dimension ship

Name	Notation	Ship		Model
Length of	LWL	46.44	4.064	m
Breadth	B	11.4	0.997	m
Draught	T	2.5	0.218	m
Block Coefficient	Cb	0.793	0.793	-
Service Speed	Vs	5.144	1.522	m/s



(a) (b)

Figure 1. (a) resistance model test, (b) self propulsion model test

Table 3. Resistance model test result

Result of resistance extrapolation

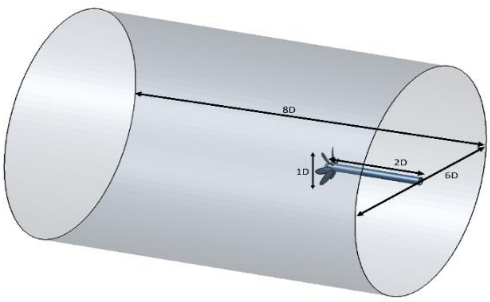
Resistance test Mini LNG Vessel-Full Load							Draft FWD		2.5		m
Ship model No. LHI-255							Draft AFT		2.5		m
V_S	V_M	R_M	CTm	CFm	Cres	CFs	CTs	FD	Rs	PE	CE
Knots	m/s	m/s	*10^-5	*10^-5	*10^-5	*10^-5	*10^-5	N	KN	KW	
5	0.761	7.64	512	361	53	199	371	2.11	8.5	21.8	445
6	0.913	11.00	512	349	68	194	380	2.84	12.5	38.5	434
7	1.065	15.10	516	339	85	190	391	3.65	17.5	63	422
8	1.217	20.77	544	331	123	186	425	4.54	24.8	102	388
9	1.370	29.11	602	324	190	183	488	5.50	36.1	167	338
10	1.522	39.41	661	318	256	181	551	6.53	50.3	259	299
11	1.674	52.34	725	312	327	178	619	7.62	68.4	387	266
12	1.826	70.10	816	308	424	176	714	8.77	93.8	579	231

Table 4. Performance prediction

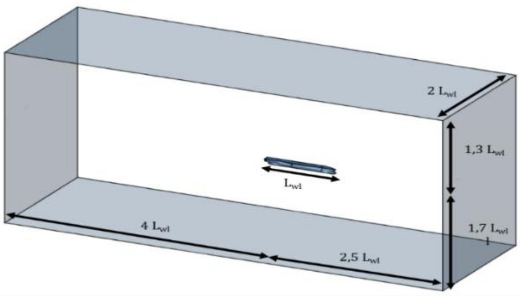
Propulsion test Mini LNG ISO Tank						Draft FWD		2.50 m
Ship model No. LHI-255						Draft AFT		2.50 m
Model propeller No. P-083								
V_S	N	N	PS	PE	ETA-D	TH	R	THFD
Knots	RPM	Hz	KW	KW	PE/PD	KN	KN	1-R/TH
5.0	120.0	1.999	35.7	21.7	0.640	10.9	8.4	0.229
6.0	145.2	2.420	63.7	38.4	0.636	16.1	12.5	0.228
7.0	171.2	2.853	105	62.9	0.630	22.6	17.5	0.228
8.0	201.4	3.357	175	102	0.615	32.1	24.8	0.227
9.0	238.3	3.972	297	167	0.591	46.6	36.1	0.226
10.0	276.9	4.614	475	258	0.572	64.8	50.2	0.225
11.0	318.2	5.303	732	387	0.556	88.0	68.3	0.223
12.0	366.3	6.106	1133	579	0.538	120	93.7	0221

The hull and propeller modelling is used for CFD simulation of resistance test, open water test and self propulsion test. Based on Table 1 and Table 2, 3D models of the hull and propeller are created to make the simulation domain. The dimensions of the simulation domain can be seen in Figure 2 [18,19].

To validate the simulation model used as a reference, the model used is the same 3D design made in two stages, namely grid independent and error gap (Figure 5). The Grid Independent process is the determination of the number of meshes used by comparing the simulation results at each increase in the number of cells. The amount of meshing taken is about 3-4 million for the hull, while for the propeller about 2-3 million mesh (Figure 3 and Figure 4.). Since there is no significant change in the results under these conditions, the simulation can be carried out with a faster duration [17] at this mesh count. Validation of the error gap of the CFD simulation results can be seen by comparing it with the model test in Figure 1. The CFD simulation of the ship's hull simulation results are validated by comparing them with the results of the resistance test in Table 4. In contrast, the CFD simulation validation for the ship propeller generated as shown in Table 5 is compared with the open water test results of B series B6.40 Wageningen, as shown in Table 6, while the allowable tolerance value in validation is ≤ 5% [20] of the CFD simulation results against the model result.



(a)



(b)

Figure 2. Propeller domain

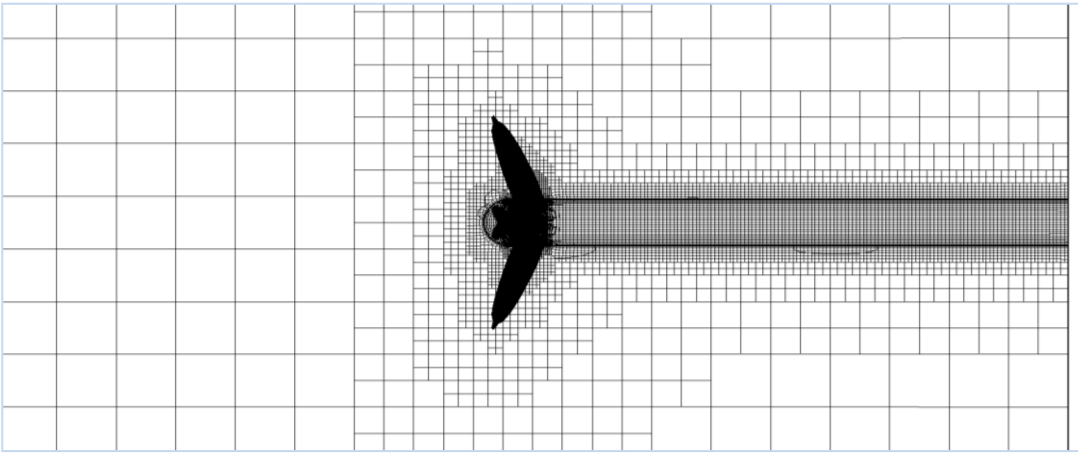


Figure 3. Propeller meshing process

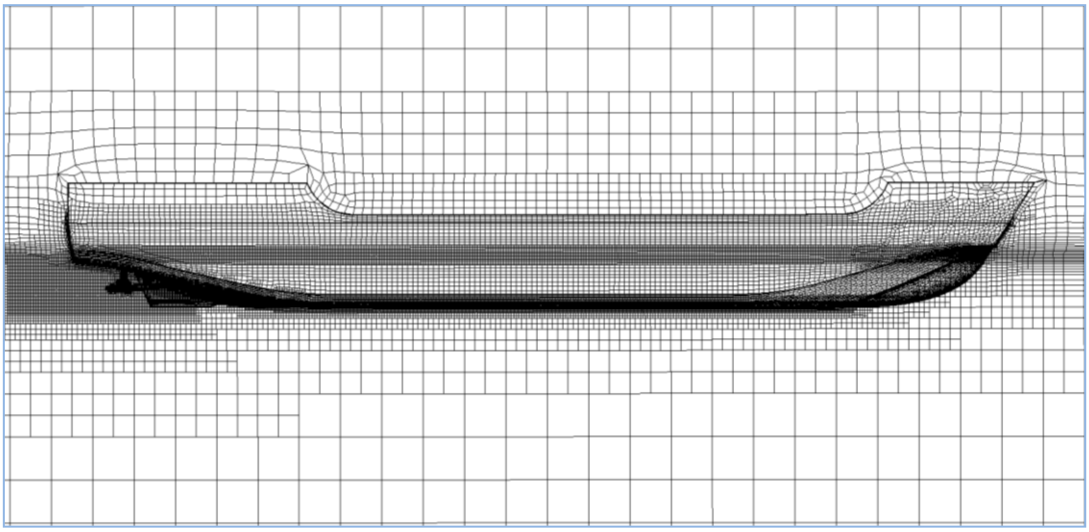


Figure 4. Hull meshing process

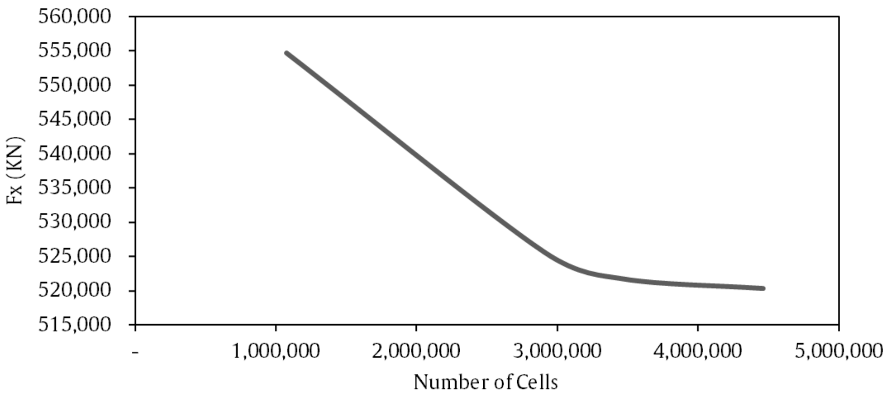


Figure 5. Independence gird

Table 5. Open water test propeller B6.40 standard (Wageningen)

NO.	J	KT	KQ	10 x KQ	η_o
1	0.10	0.4438	0.0689	0.6894	0.1025
2	0.20	0.4269	0.0670	0.6698	0.2030
3	0.30	0.4050	0.0648	0.6475	0.2987
4	0.40	0.3783	0.0621	0.6212	0.3879
5	0.50	0.3471	0.0590	0.5897	0.4687
6	0.60	0.3116	0.0551	0.5514	0.5399

7	0.70	0.2719	0.0505	0.5052	0.5998
8	0.80	0.2282	0.0450	0.4498	0.6462
9	0.90	0.1807	0.0384	0.3838	0.6746
10	1.00	0.1296	0.0306	0.3059	0.6745
11	1.10	0.0751	0.0215	0.2148	0.6122

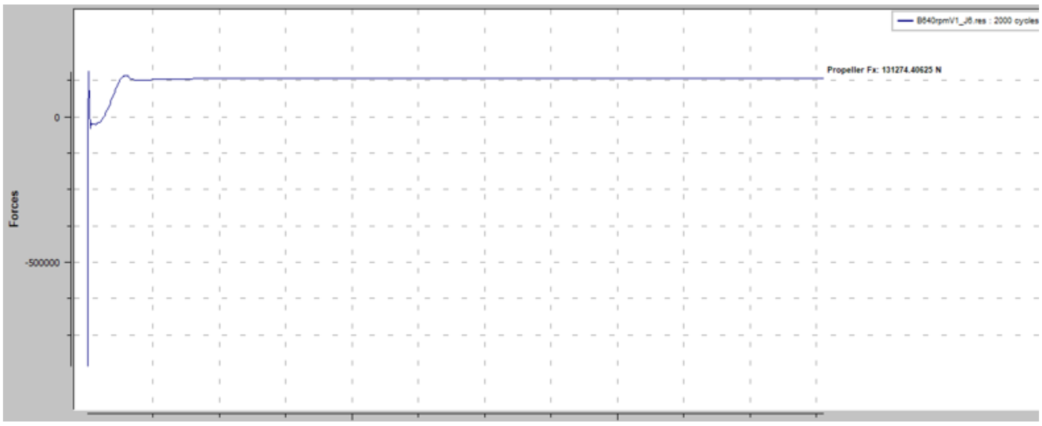


Figure 6. CFD simulation process for propeller

Table 6. CFD simulation software validation results of B6.40 standard propeller

No	J	Fx (N)	Mx (Nm)	K_T	K_Q	10 x KQ	η	Error-K_T (%)	Error-K_Q (%)	Error- η (%)
1	0.10	182377.500	44408.422	0.434	0.070	0.704	0.098	2.23	-2.17	4.32
2	0.20	175841.000	43048.219	0.418	0.068	0.683	0.195	1.99	-1.94	3.86
3	0.30	168102.203	41699.262	0.400	0.066	0.661	0.289	1.24	-2.14	3.31
4	0.40	157753.203	40020.039	0.375	0.063	0.635	0.377	0.80	-2.18	2.91
5	0.50	145446.094	37893.262	0.346	0.060	0.602	0.457	0.32	-2.17	2.44
6	0.60	131274.406	35534.160	0.312	0.056	0.564	0.529	-0.24	-2.21	1.93
7	0.70	115385.000	32599.000	0.275	0.052	0.517	0.592	-0.98	-2.34	2.33
8	0.80	97876.328	29130.020	0.233	0.046	0.462	0.642	-2.06	-2.72	0.64
9	0.90	78646.367	25026.410	0.187	0.040	0.397	0.676	-3.56	-3.42	-0.14
10	1.00	20247.090	20247.090	0.137	0.032	0.321	0.681	-6.04	-4.98	-1.02

CFD simulation of hull resistance and open water test whose validation has met the requirements, the next step is to simulate the open water test for the propeller that has been modified as shown in Figure 7 consist of: a) Standard, b) Modif 1, c) Modif 2, d) Modif 3, with the picth distribution pattern as shown in Figure 7. The purpose of this simulation is to obtain the characteristics of the tested propeller, namely the KT, KQ and J values of each propeller. These values will be used in the self propulsion test or as input data.

Table 7. Distribution of pitch propeller data

NO.	r/R	Value (mm)	B 6.40 Standard		B 6.40 Modification		B 6.40 Modification 2.		B 6.40 Modification 3.	
			Pitch (%)	Pitch (mm)	Pitch (%)	Pitch (mm)	Pitch (%)	Pitch (mm)	Pitch (%)	Pitch (mm)
1	0.200	150.00	100	1716	82.10	1408.83	94.00	1613.04	94.04	1545.00
2	0.300	225.00	100	1716	88.10	1511.79	100.20	1719.41	91.33	1567.27
3	0.400	300.00	100	1716	94.80	1626.76	102.40	1757.16	92.83	1593.00
4	0.500	375.00	100	1716	99.60	1709.13	102.89	1765.59	94.67	1624.48
5	0.600	450.00	100	1716	102.20	1753.73	102.22	1754.09	97.96	1681.00
6	0.700	525.00	100	1716	102.89	1765.59	99.60	1709.13	100.33	1721.71
7	0.800	600.00	100	1716	102.40	1757.16	94.80	1626.76	99.18	1701.99
8	0.900	675.00	100	1716	100.20	1719.41	88.10	1511.79	96.00	1647.36
9	0.950	712.50	100	1716	97.90	1679.94	85.10	1460.31	93.01	1596.00
10	0.975	731.25	100	1716	96.20	1650.77	83.60	1434.57	90.62	1555.00
11	0.987	740.62	100	1716	95.10	1631.91	82.85	1421.70	89.45	1535.00
12	1.000	750.00	100	1716	94.00	1613.04	82.10	1408.83	88.33	1515.79

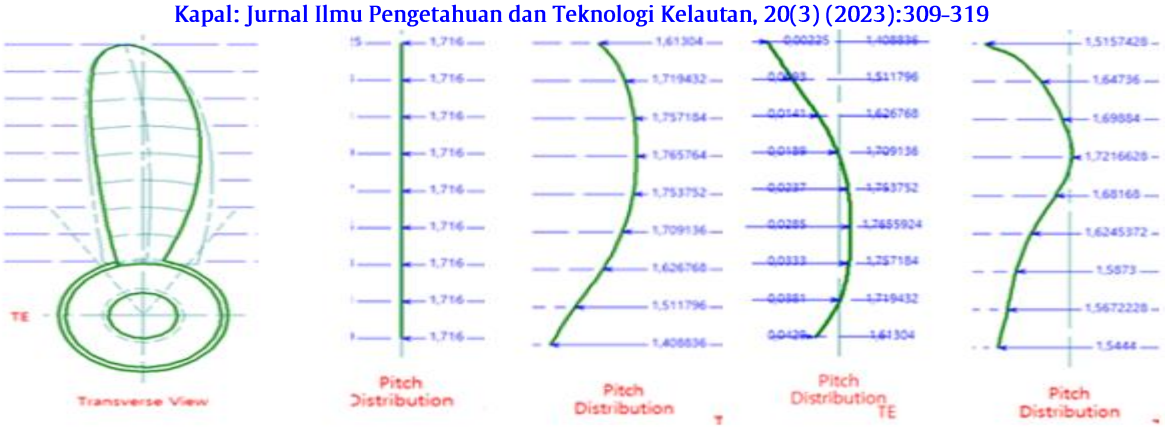


Figure 7. Distribution of pitch propeller B.6.40

The CFD simulation process for the self propulsion test was carried out for each propeller with the planned propeller rotation using Actuator Disc to represent the actual propeller conditions, the results of this simulation obtained K_T, K_Q and J values which were then used to obtain the final result, namely the Propulsion coefficient (PC) value of each propeller.

3. Result and Discussion

Figure 8 shows the results of open water test simulations of constant pitch and variable pitch propellers when viewed in the figure for propellers operating at Advance coefficients in general J = 0.5 to J = 0.8 it is found that the efficiency of propellers with variable pitch has a higher value when compared to constant pitch, the actual value as in Table 8. This is in accordance with the theory that the higher pitch, the thrust will increase because there is more water in each propeller rotation.

Calculation of the Open Water Efficiency (η_o)as resulted in K_T, K_Q, and J is shown in Equation 1.

$$\eta 0 = \frac{K_T J}{K_Q 2\pi} \quad (1)$$

where η_o : Propeller efficiency, K_T :Thrust coefficient, K_Q :Torque Coefficient, J : Advance Coefficient

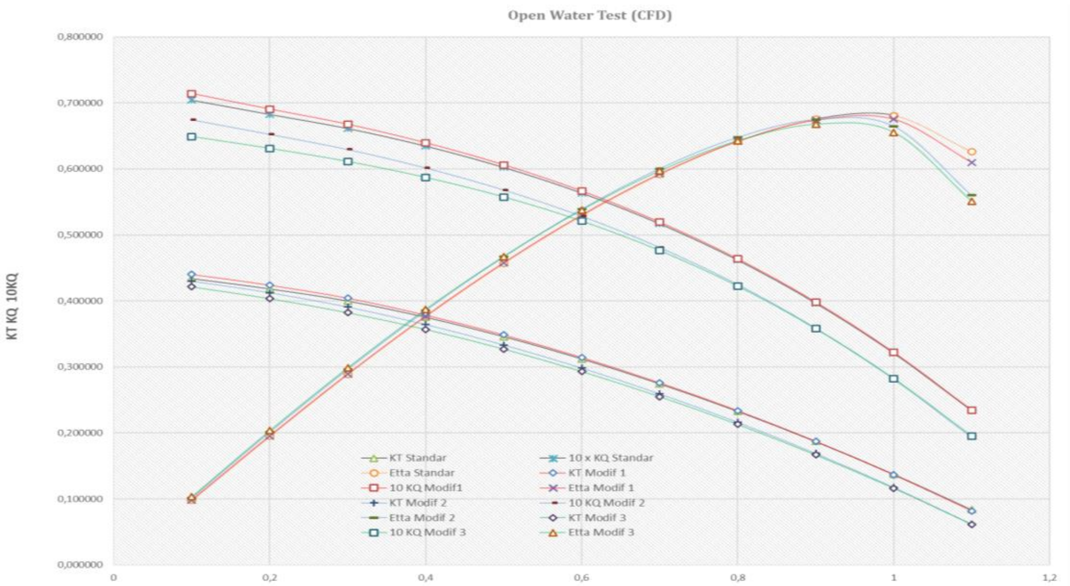


Figure 8. Propeller open water test results: B6.40 Standard, Modif 1, Modif 2, and Modif 3

Table 8. Determination of propeller efficiency at specified rps

Type Propeller	J	K_T	K_{QB}	n (rps)	η_o
Prop. Standard	0.650	0.2929	0.0540	4.6150	0.5626
Prop. Modif 1	0.650	0.2949	0.0543	4.6150	0.5632
Prop. Modif 2	0.650	0.2789	0.0505	4.6150	0.5718
Prop. Modif 3	0.650	0.2747	0.0499	4.6150	0.5679

With the obtained propeller rotation value (n) from the test of 4.615 rps. the advance speed (Va) is obtained by the following equation:

$$J = \frac{V_a}{n\,D} \tag{2}$$

Where V_a is Advanced velocity (m/s), n is Propeller rotation (rev/sec), D is Propeller diameter (m). With equations 3 and 4. the wake fractions (w) and thrust deduction (t) values can be obtained.

$$T = \frac{R_T}{(1-t)} \tag{3}$$

Where R_T is total resistance of the ship (kN), t is thrust deduction fraction.

$$V_a = V_s(1-w) \tag{4}$$

Where V_s is Service speed. This efficiency is the ratio between the torque in the propeller test or open water to the torque behind the operational ship.

$$\eta_R = \frac{Q_B}{Q_0} \tag{5}$$

where η_R is relative rotative efficiency, Q_0 is torque on open water test (N.m), Q_B is torque on self propulsion test (N.m). The propulsive coefficient (PC) value can be obtained by Equation 6:

$$\text{PC} = \eta H \text{ x } \eta R \text{ x } \eta O \tag{6}$$

Table 9. Calculation of w, t and ηR at the specified rps

Type Prop.	J	K_T	K_{QB}	n (rps)	Va(m/s)	w	T Total (N)	T-R (N)	Q Total (N.m)	t
Stand.	0.65	0.292	0.0540	4.615	4.5081	0.123	64749.30	14549.29	17.901.23	0.224
Mod1	0.65	0.294	0.0543	4.615	4.5053	0.124	65179.43	14979.43	17.990.09	0.229
Mod2	0.65	0.278	0.0505	4.615	4.5007	0.125	61644.63	11444.63	16.741.13	0.187
Mod3	0.65	0.274	0.0499	4.615	4.4871	0.127	60727.55	10527.55	16.555.13	0.173

Wake fraction (w) is a value that greatly affects the efficiency of the ship the greater the value of w the greater the resistance experienced by the ship from Table 9 obtained a good w owned by the performance of the propeller with constant pitch. With the same conditions for the value of thrust deduction also affects the same thing as the wake fraction in Table 9, from the existing value, the variable pitch propeller has better efficiency.

Table 10. PC Calculation at Specified rps (J = 0.65)

Type	J	n (rps)	ηo	ηH	ηR	PC	PD (Watt)
Prop. Standard	0.65	4.6150	0.5626	0.885	0.9997	0.4976	518817
Prop. Modif 1	0.65	4.6150	0.5632	0.879	0.9998	0.4952	521392
Prop. Modif 2	0.65	4.6150	0.5718	0.931	1.0002	0.5324	485194
Prop. Modif 3	0.65	4.6150	0.5679	0.948	1.0000	0.5382	479804

The simulation results of the open water test are depicted in Figure 8. It is found that J (Advance Coefficient) is taken as about 0.65. As for the operational conditions with Advance Coefficient 0.60 and 0.70 are obtained in Table 11 and Table 12. From Figure 8 for the operation of the ship around the J operational area of the ship (J = 0.6 to J = 07) with a linear curve shape so that the propeller type Modif-3 has the best efficiency. As in Figure 7. the type of propeller pitch distribution is divided into 3 positions. where in Propeller Modif-1 the high thrust position is located at the end to the middle of the r/R. for Propeller Modif-2 high thrust is located in the middle to the base of the propeller while Propeller Modif-3 is located in the middle of the r/R to the end of the propeller.

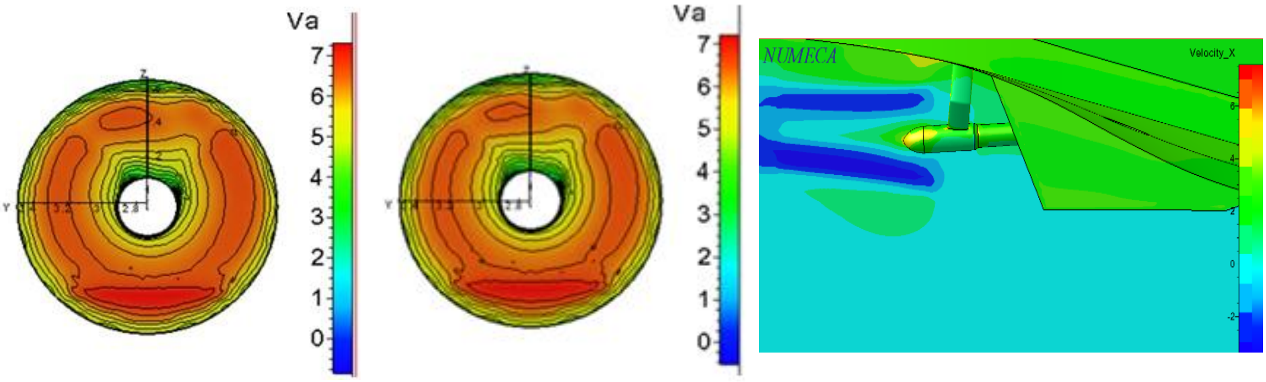
Table 11. PC calculation at specified rps (J = 0.60)

Type	J	n (rps)	η o	η H	η R	PC	PD (Watt)
Prop. standard	0.60	4.6150	0.5300	0.9007	1,0439	0,4983	540995
Prop. Modif 1	0.60	4.6150	0.5297	0.8947	1,0441	0,4949	544839
Prop. Modif 2	0.60	4.6150	0.5391	0.9424	1,0472	0,5320	508324
Prop. Modif 3	0.60	4.6150	0.5375	0.9597	1,0431	0,5380	500637

Table 12. PC calculation at specified rps (J = 0.70)

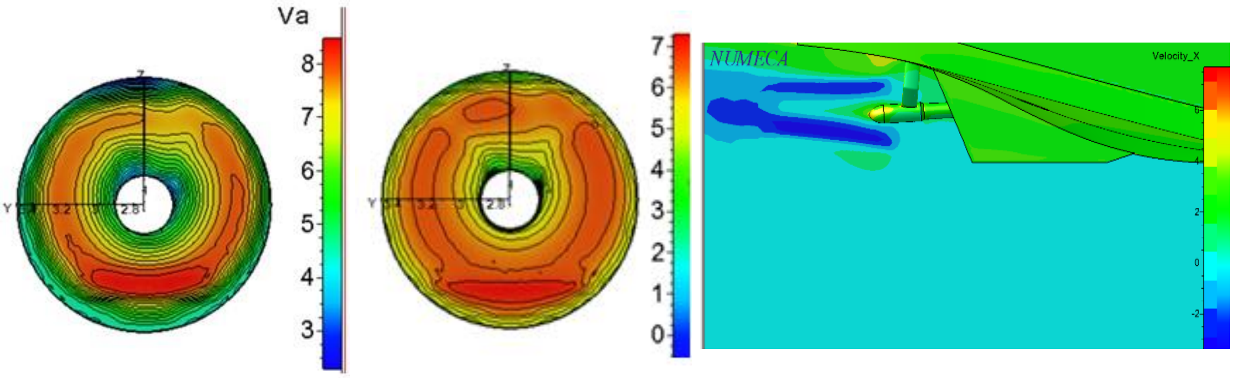
Type	J	n (rps)	η o	η H	η R	PC	PD (Watt)
Prop. Standard	0.70	4.6150	0.5918	0.878	0,9577	0,4978	496793
Prop. Modif 1	0.70	4.6150	0.5928	0.874	0,9571	0,4956	498714
Prop. Modif 2	0.70	4.6150	0.6011	0.930	0,9533	0,5326	462200
Prop. Modif 3	0.70	4.6150	0.5971	0.946	0,9537	0,5385	457395

The shape of the flow pattern at the back of the ship from each propeller type is depicted in Figure 9 to Figure 12 below. Figure b. shows the flow pattern in front of the propeller (back side of propeller), while Figure a. shows the flow pattern behind the propeller (face side of propeller). The flow pattern in front of the propeller for all propeller types has almost the same pattern, as well as the same flow pattern occurs at the back of the propeller in the standard type and Modification-2 propeller, while different flow patterns occur at the back of the Modification-1 and Modification-3 propeller types in Figure 10a and Figure 12a, this condition indicates a relatively larger wake fraction value. When the wake fraction is large and the thrust deduction value is equal or smaller, the hull efficiency value (η hull) will increase, this condition occurs in the Modification-3 propeller (Figure 12).



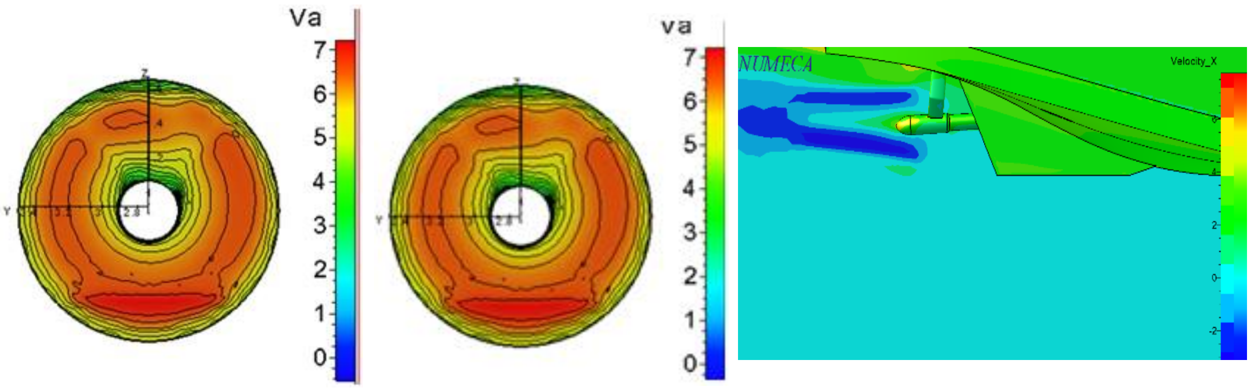
(a) (b) (c)

Figure 9. Flow pattern on propeller B6.40 standard constant-pitch shape at 4.615 rps



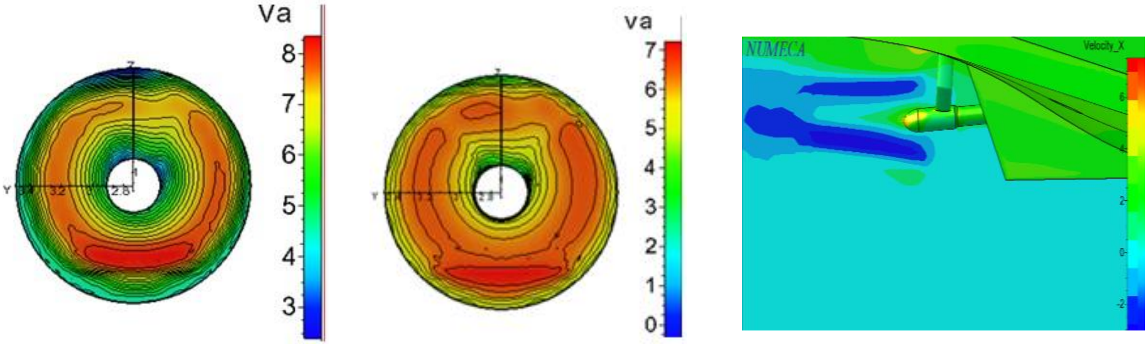
(a) (b) (c)

Figure 10. Flow pattern on propeller B6.40 Modif-1 variable-pitch shape at 4.615 rps



(a) (b) (c)

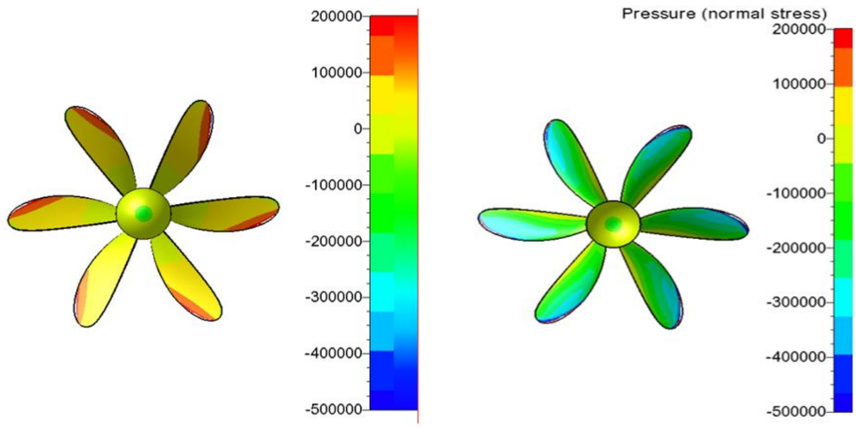
Figure 11. Flow pattern on propeller B6.40 Modif-2 variable-pitch shape at 4.615 rps.



(a) (b) (c)

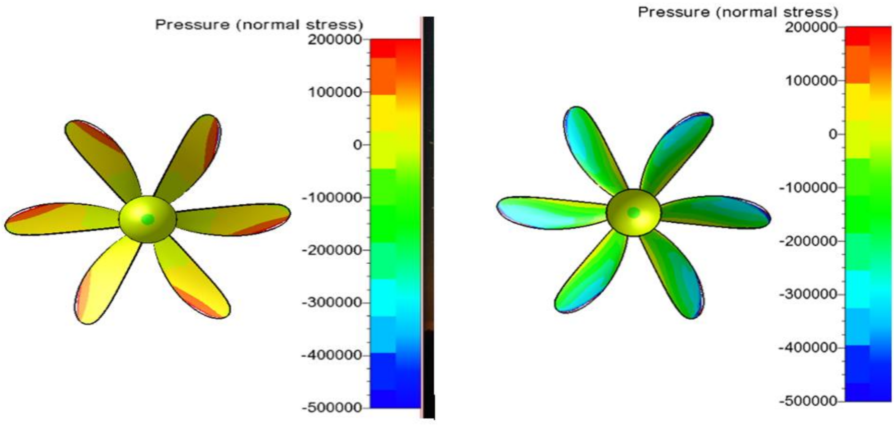
Figure 12. Flow pattern on propeller B6.40 Modif-3 variable-pitch shape at 4.615 rps.

Self-propulsion performance analysis was used to obtain the pressure distribution on the standard and modified B6.40 propeller at J = 0.6. The figures show the pressure distribution on each side, i.e. the front side of the propeller (a) and the back side of the propeller (b). On the back side the pressure is low, while on the front side the pressure is higher. The pressure difference between these two sides will cause the propeller performance to be better because the value of thrust deduction (t) becomes small, see the contrast between Figure a and Figure b for each type of propeller. In Figure 13 to Figure 16, the pressure difference between the back and face propeller is caused by Va flowing into the back propeller which is absorbed by the rotating back propeller side and channelled to the face propeller side. This causes the pressure on the face propeller side to be greater. Because the difference in propeller thrust between each type is not too significant, it results in a colour gardien on the pressure side of all propeller type variations having a maximum pressure value that is almost the same at approximately 2x10^5 Pascal.



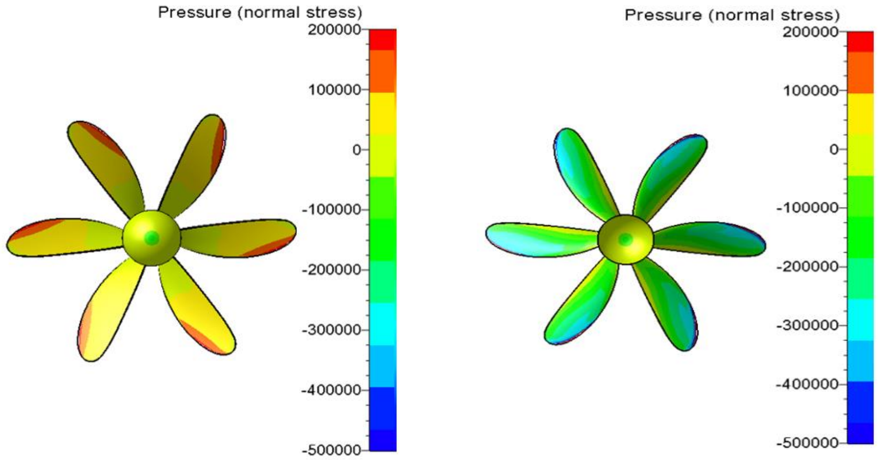
(a) (b)

Figure 13. Pressure distribution on the face

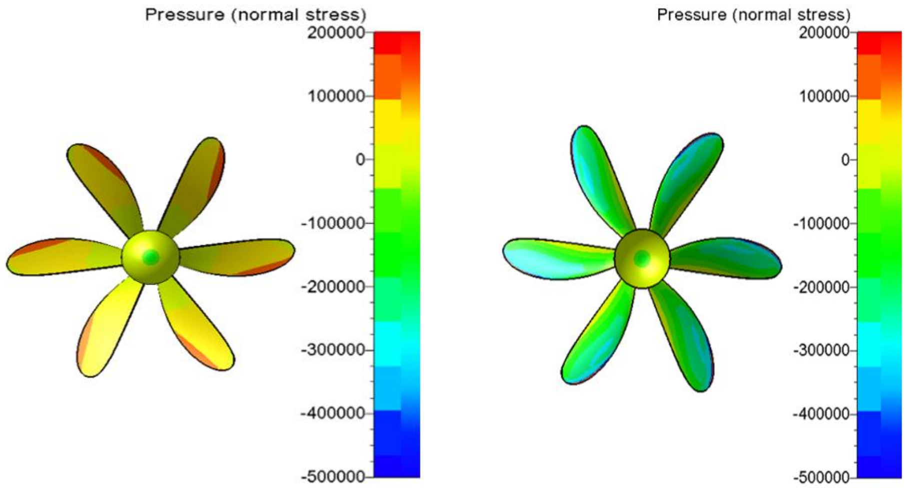


(a) (b)

Figure 14. Pressure distribution on the face



(a) (b)
Figure 15. Pressure distribution on the face



(a) (b)
Figure 16. Pressure distribution on the face

4. Conclusion

From the phenomena of pressure distribution when the propeller operates, the pressure on the face of the propeller is higher so that thrust occurs while at the back has a low pressure, in both conditions the type of pitch distribution pressure distribution that occurs has a large enough degradation that it is rather difficult to conclude it but for conditions on the pattern occurs otherwise with the nature of the pressure that occurs, on the face will have a low flow pattern or low speed while at the back has a high flow this condition produces better thrust. This condition occurs in Modification 1 and 3 propellers, namely variable pitch propellers.

Propulsion coefficient has a value directly proportional to propeller efficiency, hull efficiency and rotative efficiency. The propeller efficiency of the variable pitch type has a better efficiency than the constant pitch type, while the hull efficiency is influenced by the wake fraction (w) which is related to the shape of the ship and thrust deduction (t) which has a relationship with the efficiency of the propulsion system. From the best w value on the constant type while the best t value on the variable pitch propeller type. For the rotative efficiency value there is no significant difference, but overall the best PC value is owned by the propeller.

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References

[1] M. Ridwan and Sulaiman, " Parameter Design Propeller Kapal," *Kapal : Jurnal Ilmu Pengetahuan dan Teknologi Kelautan*, vol. 5, no. 3, pp. 206– 211, 2012, https://ejournal.undip.ac.id/index.php/kapal/article/view/3217/0

[2] Johannes. Hüffmeier and Mathias Johanson, " State-of-the-Art Methods to Improve Energy Efficiency of Ships," Journal Marine Science, vol. 9, no. 4, p. 447, Apr. 2021, doi: 10.3390/jmse9040447.

[3] I Ketut Aria Pria Utama, " Potential for Improvement of Future Ship Efficiency: Overview of Ship Design And Operational Aspects," *Archipelago Engineering (ALE) Proceeding*, vol. 1, pp. 1– 15, 2018.

[4] Maria Polakis, Panos Zachariadis, and Jan Otto de Kat, " The Energy Efficiency Design Index (EEDI)," in Sustainable Shipping, Cham: Springer International Publishing, 2019, pp. 93– 135. doi: 10.1007/978-3-030-04330-8_3.

[5] Kurt Mizzi, Yigit Kemal Demirel, Charlotte Banks, Osman Turan, Panagiotis Kaklis, and Mehmet Atlar, " Design optimisation of Propeller Boss Cap Fins for Enhanced Propeller Performance," *Applied Ocean Research*, vol. 62, pp. 210– 222, Jan. 2017, doi: 10.1016/j.apor.2016.12.006

[6] I Made Ariana, Riyan Bagus Prihandanu, Dhimas Widhi Handani, and AAB Dinariyana, " Investigation of The Effects of The Pre-Duct in a Ship on Propeller– Hull Interactions Using The CFD Method," *CFD Letters*, vol. 15, no. 4, pp. 17– 30, Feb. 2023, doi: 10.37934/cfdl.15.4.1730..

[7] Niki Veranda Agil Permadi and Erik Sugianto, " CFD Simulation Model for Optimum Design of B-Series Propeller using Multiple Reference Frame (MRF)," *CFD Letters*, vol. 14, no. 11, pp. 22– 39, Nov. 2022, doi: 10.37934/cfdl.14.11.2239.

[8] J Jianhua Xu, W. Song, X. Yang, and H. Nie, " Aerodynamic Performance of Variable-Pitch Propellers for High-Altitude UAVs," *IOP Conference Series : Materials Science and Engineering*, vol. 686, no. 1, pp. 12019, 2019, doi: 10.1088/1757-899X/686/1/012019.

[9] Andi Trimulyono, Parlindungan Manik, and Nurul Huda, " Pengaruh Penggunaan Energy Saving Device Pada Propeller B4 55 Dengan Metode CFD," *Kapal: Jurnal Ilmu Pengetahuan dan Teknologi Kelautan*, vol. 10, no. 3, pp. 147– 153, 2013, https://ejournal.undip.ac.id/index.php/kapal/article/view/3217/02013.

[10] Bayu Agastiya, I. Made Ariana, and Achmad Baidowi, " Analysis of Self-propulsion Test for Propeller KP-505 with and without Pre-Swirl Stator," *IOP Conference Series: Earth Environmental Science*, vol. 1081, no. 1, p. 12055, Sep. 2022, doi: 10.1088/1755-1315/1081/1/012055

[11] C. Ma, H. Cai, Z. Qian, and K. Chen, " The design of propeller and propeller boss cap fins (PBCF) by an integrative method," *Journal of Hydrodynamics*, vol. 26, no. 4, pp. 586– 593, Aug. 2014, doi: 10.1016/S1001-6058(14)60066-4.

[12] Tuswan, Deddy Chrismianto, and Parlindungan Manik, " Analisa Effective Wake Friction Akibat Penambahan Stern Tunnels Pada Kapal Tropical Princess Cruises Menggunakan Metode CFD (Computational Fluid Dynamic)," *Kapal : Jurnal Ilmu Pengetahuan dan Teknologi Kelautan*, Vol. 13, no. 2 2016.

[13] M. I. Hariyadi, " No TitleAnalisa Pengaruh Variasi Pitch Ratio Pada Controllable Pitch Propeller Kapal Mini Lng Carrier Terhadap Engine Propeller Matching Menggunakan Metode Computational Fluid Dynamics," *ITS Repository.*, 2022.

[14] I. E. Sandjaja, I. M. Ariana, Erwandi, and M. Indiaryanto, " Propeller selection optimization on mini LNG ship based on engine propeller matching approach," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1081, no. 1, p. 012037, 2022, doi: 10.1088/1755-1315/1081/1/012037.

[15] *The Wageningen Propeller Series*. MARIN Publication, 1992.

[16] Adam Kaplan, " Propeller Pitch Distributions: (Part 1) Measurements," A Publication of The National Marine Propeller Association, Inside This Issue, 2020.

[17] Putra Bangkit Setyabudi, Deddy Chrismianto, and Good Rindo, " Analisa Nilai Thrust dan Torque Propeller Tipe B-Series Pada Kapal Selam Midget 150 m Dengan Variasi Skew Angle dan Blade Area Ratio (ae/ao) Menggunakan Metode CFD," *Kapal : Jurnal Ilmu Pengetahuan dan Teknologi Kelautan*, vol. 13, no. 3, pp. 109, 2016, doi: 10.14710/kpl.v13i3.12352.

[18] ITTC, " ITTC-Recommended Procedures and Guidelines Practical Guidelines for Ship Self-Pro-pulsion CFD ITTC Quality System Manual Recommended Procedures and Guidelines Guideline Practical Guidelines for Ship Self-Propulsion CFD."

[19] A. Purwana, I. M. Ariana, and W. Wardhana, " Numerical study on the cavitation noise of marine skew propellers," *Journal of Naval Architecture and Marine Engineering*, vol. 18, no. 2, pp. 97– 107, 2021, doi: 10.3329/jname.v18i2.38099.

[20] Niko Bayu Prasetyo, Untung Budiarto, Deddy Chrismianto " Analisa Perbandingan Engine Propeller Matching Antara Single Screw Propeller Dan Twin Screw Propeller Pada Kapal Tanker 6500 DWT," Jurnal Teknik Perkapalan, vol. 8, no. 3, pp. 368– 374, 2020.