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Design and Hydrodynamic Model Test of Mini Submarine Propeller with High Efficiency and Low Cavitation

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Abstract

Design and development of propellers for submarines are in some ways different from propellers for surface vessels. The most important demand is low acoustic signature and propeller efficiency. The design for the propulsor for submarine is a specialist task of a later stage of design. The propulsive efficiency has essentially three parts in the traditional method of approach. The first and major part is the efficiency of the propeller itself as a device which may develop to overcome the resistance to motion the vessel. The aim of this research is to design a mini submarine propeller and obtain high efficiency and low cavitation. To reach this aim, model tests were performed both in Towing Tank and Cavitation Tunnel. From the propeller model tests, the result shows a good efficiency and low cavitation.

Keywords: Cavitation; efficiency; propeller; submarine

1. Introduction

In designing a mini-submarine propeller, there are some important things that need to be taken into consideration, namely the model results on a mini-submarine, whether obtained through model testing, as well as by means of numerical computation using CFD program.

In contrast to surface ships, in the propeller design process, submarine needs to consider the efficiency of the propeller as well as the cavitation [1]. Unlike surface ships, submarines, in addition to considering propeller efficiency, also need to pay attention to signature of acoustic aspects which may come from cavitation.

The thrust produced by the propeller is needed to move forward the submarine in certain speed. The relationship between propeller thurst resistance can be translated into the following equation:

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

where T is the thrust of propeller, R_T is the resistance of mini submarine and t is the thrust deduction factor of mini submarine [2]. Assuming the value of thrust deduction factor is 0:17 which refers to published studies on the relationship between the ship's hull with propeller submarine.

Basically, model testing to measure drag on mini-submarines can be performed in Towing Tank [3] or in Wind tunnel (Fig. 1). The following is an example of ship model testing performed in towing tank and Wind Tunnel.

The result is almost the same as the difference in the density of the fluid acting on each testing facility

$$R_T = \frac{1}{2}\rho V^2 A_{frontal} C_D \tag{2}$$

Figure 1. Model test of submarine in wind tunnel and towing tank (IHL)

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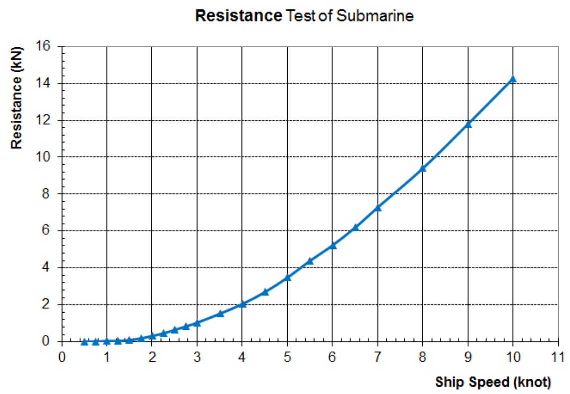


Figure 2. Resistance model test result of submarine model in towing tank [2]

where R_T is the resistance of mini submarine, ρ is the density of water, V is the velocity mini submarine, A is the frontal area of mini submarine and C_D is the coefficient drag [4].

In Indonesian Hydrodynamic Laboratory (IHL), a package of resistance model test of mini submarine has been performed in Towing Tank [3]. The model submarine is tested at submerge mode, submarine model was tested at depth of 2 m. The results from model test in Fig. 2 are as follows:

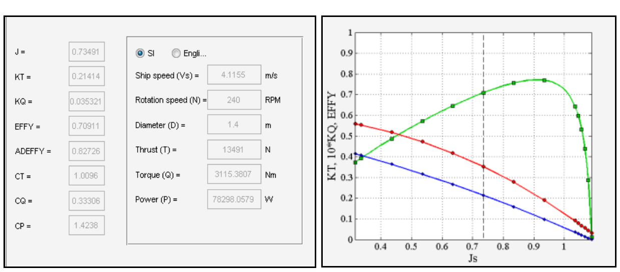
The data from resistance test is very useful in designing propeller to obtain an optimum efficiency according to its purpose during operational.

Propeller design with low cavitation levels is absolutely necessary for submarine. This propeller cavitation can cause noise. Propeller cavitation may occur in the propeller tip area, the root area of the propeller and the vortex on the hub propeller.

Based on literature studies, to reduce cavitation in the propeller tip area required a good skew form on the propeller blade.

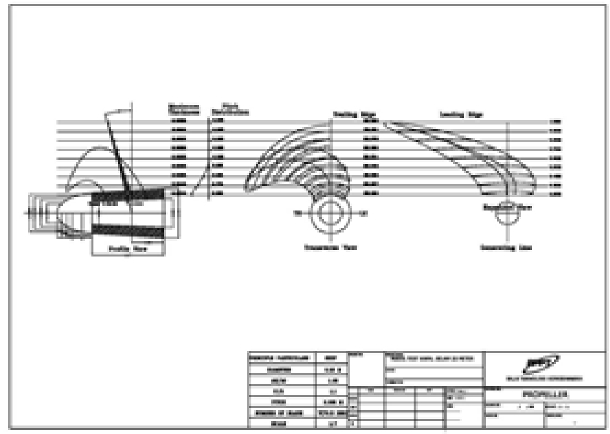
2. Theory and Methodology

The use of open-source programs such as *Open Prop V.2.4.6* that run with MATLAB, can be entered multiple input data such as vessel speed, rpm, diameter, and thrust to get initial design propeller. For planning Thrust price is determined using Eq. (1).

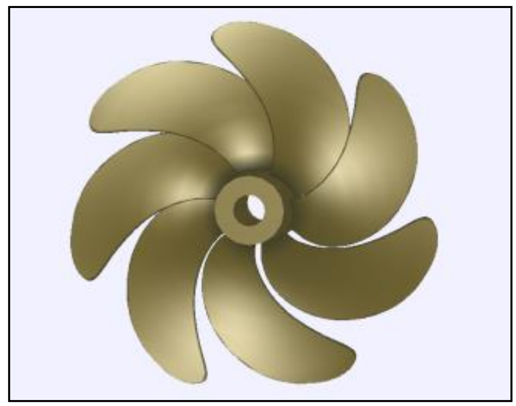


(a) (b)

Figure 3. Computational analysis using Matlab (a) Input, (b) Diagram K_T K_Q J



(a)



(b)

Figure 4. (a) 2D, (b) 3D propeller design with 7 blades

In this research a lifting line theory and Matlab program were used in designing submarine propeller in order to get the outline and thickness of the blade. By running Matlab program, some results are obtained as presented in Fig. 3. From the initial analysis, the design of blade is a type of blade symmetrical, so still need few changes with the addition of skew outline propeller on the propeller tip to reduce the level of cavitation that occurs at the end of the propeller blade. The final design result is shown in Figs. 4a (2D design propeller) and 4b (3D design propeller).

In Figure 4(a), is a design model submarine in the form of two-dimensional, used as working drawings in making a mini-submarine propeller model. Whereas in Fig. 4(b) is a three-dimensional visual in solid form, this image is used as a basic drawing for further numerical analysis program Computer Fluid Dynamic (CFD).

A few changes in outline of propeller drawing with the addition of a model propeller blade skew on the CFD analysis is required. This addition of skew at the blade propeller efficiency will decline and the rising value of the Coefficient Advance (J). But the effect is not too significant to the prediction of the initial design of the propeller. Besides being used for numerical analysis of a 3D image can serve as a visual tool. So, it can be used as a validation of the physical form in propeller model manufacture that will be carried out.

2.1. Propeller efficiency

The basic aim of this research is to determine how much the efficiency of the designed propeller. To determine the efficiency of the propeller can be done by open water test along with a test dummy models in cavitation tunnel facility. The open water test using an Open Water Propeller Apparatus which is available in IHL. Through this testing, the amount of thrust and torque propeller models can be measured by varying the speed of the propeller models when tested. so we get the values of thrust (T) and torque (Q) and can be calculated thrust coefficient and torque coefficient K_T K_Q based advanced coefficient (J). K_T, K_Q, by following equations

$$K_T = \frac{T_{prop}}{\rho n^2 D^2} \tag{3}$$

$$K_Q = \frac{Q_{prop}}{\rho n^2 D^3} \tag{4}$$

$$J = \frac{V_a}{nD} \tag{5}$$

Where K_T is the coefficient thrust of propeller, K_Q is the coefficient torque of propeller T_{prop} is the thrust of propeller, Q_{prop} is the torque of propeller, ρ is the density of water, n is the rotation of propeller, Va is the advance velocity of mini submarine, J *is* the advance coefficient of mini submarine and D is the Diameter propeller [2]. While the efficiency of propeller can be represented by the following equation:

$$\eta_0 = \frac{J}{2\tau}\frac{K_T}{K_Q} \tag{6}$$

where η is the efficiency of propeller [2].

2.2. Cavitation

To observed the cavitation phenomenon on the propeller, a testing in the cavitation tunnel is important. The propeller noise consists of four components which is cavitation noise, blade singing noise, blade noise and turbulence noise rate. Cavitation noise is the largest component of the propeller noise, especially on ships moving at high speed. Singing noise caused by vibrations that arise as a result of the curvature blade propeller. The amount of noise frequency is dependent on the magnitude of vibration frequencies [5].

The tests carried out in the Towing Tank and Cavitation Tunnel in Indonesia Hydrodynamics Laboratory, which aims to determine the results of the performance of the design of a propeller that has been determined through CFD calculations. The research methodology can be presented as follows

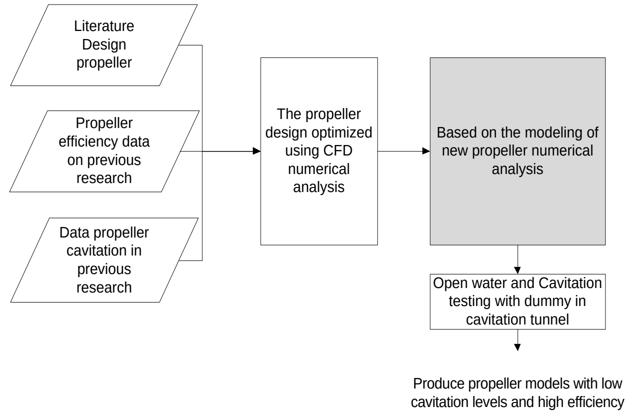


Figure 5. Research flow chart

Step of research as in Figure 5 can be explained as follows:

- Collecting data design, efficiency and propeller cavitation, both from the literature study and previous research
- Recalculating data using Matlab to obtain numerical simulation initial performance of the model propeller that we will create, which of the results obtained following the model as a primary measure
  - Propeller Diameter Model = 0.20 m
  - P/D = 0.816
  - Ae/Ao = 0.880
  - Total Blade = 7 blade
  - Scale = 1:7
- Performing numerical simulation (CFD) to create a 3D design in the form of solid propeller. This calculation should be done due to changing outline of design models by adding skew propeller on propeller blade about 54^o, as well as provide an overview of the characteristics of the propeller during design step.
- Making the model propeller according propeller drawings 4a. Based on these images can be created for table offset and table measurements that will be used to manufacture a model propeller with 7 blades.
- Testing the model propeller in Cavitation Tunnel by adding a dummy model of submarine as well as variations in pressure on the fluid to determine the cavitation occurs when the propeller operated at the specified depth.

Dynamometer measuring instrument consists of a motor, the holder of the measuring instrument, measuring instrument holder as well as a model propeller shaft. Where the measuring instrument function is to determine the amount of the value of thrust in units (*Newton*) and in units Torque (*Newton meter*). The output of this measure was to determine the efficiency of a propeller taking into account the magnitude of the coefficients and coefficients Torque Thrust. Cavitation Tunnel test performed at IHL.

3. Result and Discussion

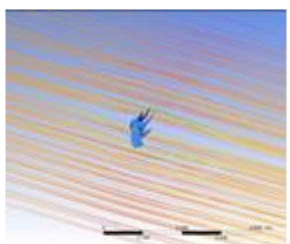
3.1. Numerical simulation results

The use of 3D solid program needed to obtain images in the form of 3-dimensional propeller, so it can be used on meshing as shown in Fig. 6(a). Meshing the propeller models aims to break the measuring object into an infinite element, making it easier for a computer to calculate the shape of the element finite. This is needed to get the results of numerical simulations in the form of Computer Fluid Dynamic (CFD) .

CFD simulation for this propeller using ANSYS. where in the previous study the comparison between the numerical method (CFD) and the test differed between 10% -20% [6]. After the meshing process both propeller and fluid models that operate around the propeller, CFD can be done running the program with steps that run the program as well as the time of testing the open water tests in Cavitation Tunnel.

From the results of numerical simulations using CFD then obtained value Thrust and torque at any speed propeller models. Equations (3) and (4) are used to obtain the propeller thrust and torque coefficients. Furthermore, in Eq. (6) is used to get the propeller efficiency. From the results of these calculations can be shown in Table 1, with maximum efficiency rates of 0689 where it is comparable with the price coefficients thrust and coefficients torque respectively are 0.257 and 0.436 [3].

(a) Meshing



(b) Running Propeller

Figure 6. Meshing and numerical analysis

Table 1. Result of numeric simulation

J	Thrust (n)	Torque (Nm)	KT	10KQ	η
0.184	71.602	2.194	0.400	0.612	0.191
0.276	69.707	2.142	0.389	0.598	0.286
0.367	65.888	2.062	0.368	0.575	0.374
0.459	60.065	1.942	0.335	0.542	0.453
0.551	55.148	1.841	0.308	0.514	0.526
0.643	50.692	1.684	0.283	0.470	0.616
0.735	46.020	1.563	0.257	0.436	0.689
0.827	36.086	1.510	0.201	0.421	0.629
0.919	26.771	1.456	0.149	0.406	0.538
1.011	20.751	1.345	0.116	0.375	0.497
1.102	15.828	1.235	0.088	0.345	0.450

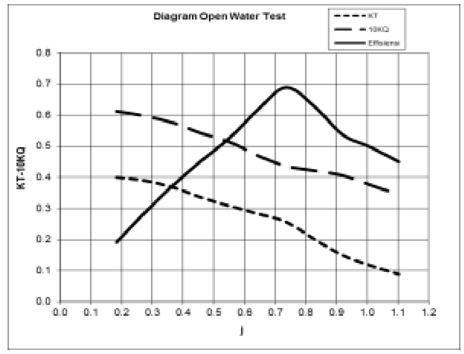


Figure 7. Result numerical simulation

So that the results of this testing are known that the propeller can work efficient on value J 0.735. Based on data from Table 1, the characteristics of the propeller can be known, but it cannot make the excuse that the propeller numerical simulation represents the actual condition of the propeller.

Tests carried out on propeller revolution per second (Rps) remain with the provision of carriage speed variation between 0.194 m/s to 1.750 m/s, where the model speed used by the scale factor 1:7.

Based on the results in Table 1 it can be presented in diagrams of propeller performance, whereas in Fig. 7 the results of numerical simulation of propeller design.

3.2. Model test results

The phenomenon of cavitation to consider in designing a submarine propeller after propeller models known characteristics of the test results open water test. Because cavitation generated from a submarine propeller can cause noise on the submarine. Noise that is too large will result in easily detectable presence of submarines by the enemy. Therefore, propeller submarine good are those that have a low cavitation.

On testing in cavitation tunnel remeasured performance mini-submarine propeller models at each pressure, the pressure variation at 1 bar and 1.5 bar. Where the provision of the pressure on the propeller models assuming real condition mini submarine at a depth of operational areas.

Table 2. Test results in Cavitation Tunnel at the pressure of 1.0 bar

J	Thrust (n)	Torque (Nm)	KT	10KQ	η	Cavitation
0.167	66.6	1.93	0.374	0.542	0.183	Lc
0.347	59.4	1.79	0.33	0.502	0.363	Lc
0.402	56.4	1.71	0.315	0.483	0.416	Lc
0.475	53.3	1.69	0.297	0.477	0.470	Lc
0.562	47.8	1.56	0.267	0.44	0.542	Lc
0.626	43.7	1.44	0.244	0.406	0.598	Lc
0.736	37.8	1.31	0.210	0.370	0.665	Lc
0.841	32.5	1.23	0.181	0.347	0.697	Lc
0.908	28.2	1.13	0.155	0.319	0.705	Lc
0.998	22.4	1.01	0.124	0.287	0.685	Lc
1.101	14.1	0.85	0.077	0.240	0.559	Lc

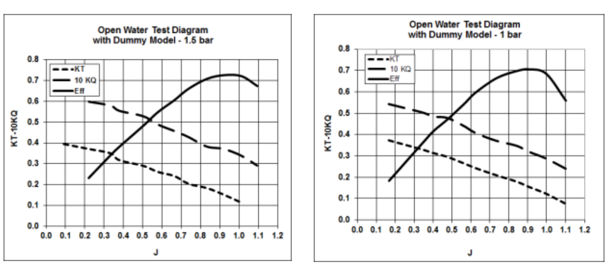
*Lc = Low Cavitation

Based on the Table 2, testing by giving pressure 1.0 bar can be seen that maximum efficiency occurs at a value 0.705. When compared with the value of the maximum efficiency of numerical simulations, the asset is increased both the value of the advance coefficient (*J*) and the efficiency of the propeller itself. due to the dummy models installed in front of the model propeller causing propeller flow into *Va* (advance velocity) is increasingly directed towards the propeller, that increase the efficiency and value of the advance coefficient (J), along with the rising value of *Va*, is directly proportional to the value of *J*, while the value of *J* is directly proportional to the efficiency of the propeller.

It can be concluded that the propeller has been designed based numerical approach and validated by hydrodynamic phisical model testing. In the present study propeller suitable for use in the form of mini-submarine hull model of 22 m. That applies to the testing of propeller models with the addition of 1.5 bar pressure, in which the additional pressure also affects its advance velocity (V_a), because the pressure acting on the larger propeller at a depth of operational, resulting in a small value of V_a in line with Euler equations. A number of results from testing in Cavitation Tunnel at a pressure of 1.5 bar shown in Table 3.

Table 3. Test results in cavitation tunnel at the pressure of 1.5 bar

J	Thrust (N)	Torque (Nm)	KT	10KQ	η	Cavitation
0.220	70.525	2.138	0.395	0.559	0.231	Lc
0.334	66.821	2.064	0.372	0.58	0.341	Lc
0.379	63.027	1.975	0.351	0.555	0.381	Lc
0.504	57.213	1.881	0.318	0.529	0.482	Lc
0.579	52.256	1.738	0.29	0.489	0.547	Lc
0.666	47.160	1.628	0.261	0.457	0.606	Lc
0.738	43.460	1.525	0.241	0.429	0.660	Lc
0.833	36.894	1.360	0.204	0.382	0.707	Lc
0.922	33.169	1.317	0.183	0.371	0.726	Lc
1.013	27.510	1.204	0.151	0.338	0.721	Lc
1.095	20.613	1.035	0.112	0.291	0.673	Lc



(a) Test 1 bar (b) Test 1.5 bar

Figure 8. Test results in cavitation tunnel with a pressure of 1 bar and 1.5 bar

Testing in Cavitation Tunnel at a pressure of 1.0 bar and 1.5 bar pressure increases both the efficiency and value of the value of the advance coefficient (*J*). But the increase is not significant, this can be seen from the value *J* in 0.922 with efficiency 0.726 at 1.5 bar. In other words, if the mini-submarine propeller 22 meters operated at a depth of approximately 100 meters then the propeller efficiency will be slightly increased thus saving consumption battery use on submarines that are connected to an electric motor. So that the propeller on a comparison of the characteristics of the test with a pressure of 1 bar and 1.5 bar can be seen in Fig. 8.

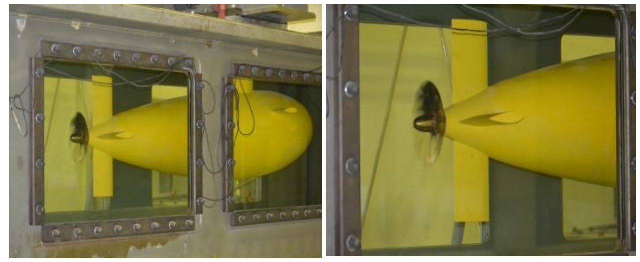


Figure 9. Photos in cavitation tunnel testing

In terms of the characteristics of the cavitation test results in both diagrams are relatively similar and both have a low cavitation levels, so the noise that is expected to arise as a result of propeller cavitation occurs is very low.

Giving difference of pressure on testing in cavitation tunnel is aimed to know propeller characteristic if operated at surface condition and when operational in water depth based on test results in cavitation tunnels. The efficiency of propellers produced a good result 0.7, but seen from the propeller thrust is still less when compared with the curve of the test results of miniature submarine resistance at 8 knots.

Therefore, for further research can change the pitch propeller to get a suitable thrust at a speed of 8 knots

4. Conclusion

Maximum Efficiency in the range of 0.6 numerical, while addition of a dummy model of the cavitation tunnel testing is able to add to the efficiency of the range 0.7, difference 0.1 at maximum efficiency. Little cavitation occurs on the propeller, this is evidenced by cavitation test at a pressure of 1 bar and 1.5 bar at the operational round, so this propeller is very suitable for use in models of mini-submarines 22 m , due to an increase after testing efficiency by using dummy models. This propeller is suitable for submerge mode operational, due to a slight increase in efficiency.

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