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Cavitation Prevention for Submarine Propeller with Empirical Method

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Abstract

Submarines are a component that is taken into account in assessing the security of a country. Many countries have developed their own types of submarines according to technological developments in that country. To be able to move silently underwater, the most important requirement for submarine propellers is low noise generated by these propellers. So the first thing that must be avoided from the emergence of a noise on a submarine is the absence of cavitation when the propeller operates both on the surface and at depth. The cavitation value can be predicted based on the limits from the burril cavitation diagram. The diagram is obtained from cavitation experiments and recorded full-scale cavitation observations over many years. Simulation calculations will be varied by value of P/D, Ae/Ao, Number of blades (Z) and diameter (D). Other components such as advance velocity (Va) and rotation speed (n) of propeller are considered constant or ignored as in Keller's Formula. From the calculation, by adding the expanded area ratio and propeller diameter values can reduce cavitation in the propeller. While the opposite happens, when the propeller pitch value and the number of blades increase, the cavitation value will also increase. If submarine in dive condition the cavitation difficult to appears, because the pressure of the ship when diving conditions will be very high and the cavitation number will be very small.

1. Introduction

Submarines are a component that is taken into account in assessing the security of a country. Many countries have developed their own types of submarines according to technological developments in that country. How to operate a submarine that has two modes, namely surface mode and dive mode. However, in general the capabilities of submarines are tested or compared when the ship dives. A submarine is designed not to be slow in its movement underwater, but also to move silently underwater without being detected. To be able to move silently underwater, the most important requirement for submarine propellers is low noise generated by these propellers. So the first thing that must be avoided from the emergence of a noise on a submarine is the absence of cavitation when the propeller operates both on the surface and at depth. This is important because the pressure value on the water surface will be different from the pressure value when the ship dives.

The propeller has already been studied and experimentally tested for nearly 80 years and there are many causes that lead to noise formation, including machinery vibration, auxiliary machinery and propeller rotation. Many factors are needed in designing or determining a propeller to be used, especially for submarine propellers. The design procedure of the propeller should ideally include feedback on the design of the submarine hull and its control surfaces [1]. Therefore, the spiral design method will be very helpful in determining how the design process takes place as shown in Figure 1. Spiral design describes design as a process that has the goal of fulfilling certain parameters. So that this is felt to be appropriate for submarines that have special parameters to determine which propeller to use.

Cavitation is a complex phenomenon to measure, depending on site conditions in specific regions of the Earth, where there is water with various physical properties like cavitation occurring more aggressively at higher water temperature than at lower temperature [2]. Since cavitation number reduces with increasing velocity, cavitation is most likely to occur towards the blade tips where the rotational component of velocity is highest. The maximum reduction in pressure occurs at a point between the mid-chord and the leading edge so bubbles are likely to form there first [3]. For the foil profile, the cavitation limit is assessed by the value of the angle of attack for cavitation bucket diagram (Figure 1). The greater angle of attack made the back propeller cavitate. However, if the angle of attack is too small or minus, cavitation may occur on the propeller face. There will be no cavitation as long as the design operates within the bucket. The wider the bucket, the greater the range of angle of attack or advance coefficient for cavitation free operation at a given cavitation number.

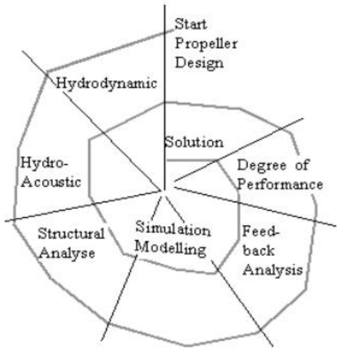


Figure 1. Design spiral for submarine propellers [1]

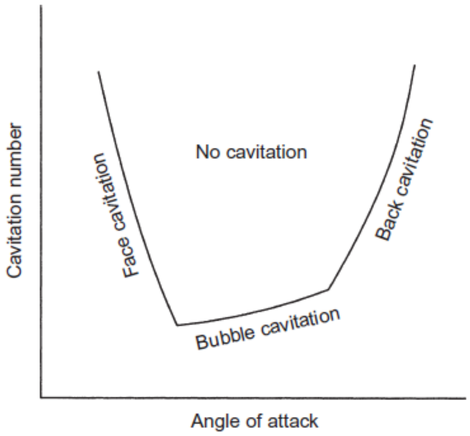


Figure 2. Cavitation bucket [3]

The best propeller design is a design that has a high-efficiency value and there is no cavitation when the propeller is operating, either when it is new or when the propeller bent and changes the skew or pitch. Cavitation can damage the propeller in addition to reducing thrust and torque. it can decrease the diameter and the performance of the propulsion system [4], [5]. The cavitation value can be identified based on the cavitation number value. Some researchers made a diagram of the cavitation limit on a propeller blade for each type of ship or propeller performance [6-8]. The higher cavitation number can decrease the cavitation value. The value of the cavitation number is influenced by the pressure on the propeller, the density of water, and the inflow into the propeller from the empirical equation. The higher local pressure around the propeller prevents cavitation. But on the other side, if the density and velocity are increased, the cavitation number will be smaller, and the cavitation will occur. For special cases such as in submarines, the possibility of cavitation is lower when the diving mode. Because the value of the propeller pressure changes drastically at every 10m. Therefore, the calculation of propeller cavitation for submarines should be carried out at a depth of 10 m or less with a pressure value of 1 atm. So the calculation of the possibility of cavitation only depends on the inflow and the design of the propeller used. This paper will discuss the elaboration of the empirical formula used to identify the occurrence of cavitation in new and used propeller designs, so that cavitation prevention can be carried out and recommendations for existing propellers to reduce cavitation.

2. Methods

The cavitation value can be predicted based on the limits from the burril cavitation diagram. The diagram is obtained from cavitation experiments and recorded full-scale cavitation observations over many years. The data were converted into a design chart which is known as the Burrill cavitation chart [6], [7], [9]. The value of the thrust loading coefficient (τ) becomes one of the components as a function of the Y-axis and the cavitation number (σ) becomes the limit on the X-axis. Both values are defined as in Equation 1-2 [10]. The combination of them can predict the value of cavitation percentages on propeller surface. From design matrix method, there are several parameters that affect the appearance of cavitation on the propeller [1]. Circulation, pitch and chamber distribution have a strong impact on general cavitation. In addition, the orthogonal blade length and the number of blades have an impact on the appearance of cavitation on the propeller tip besides the three previous parameters.

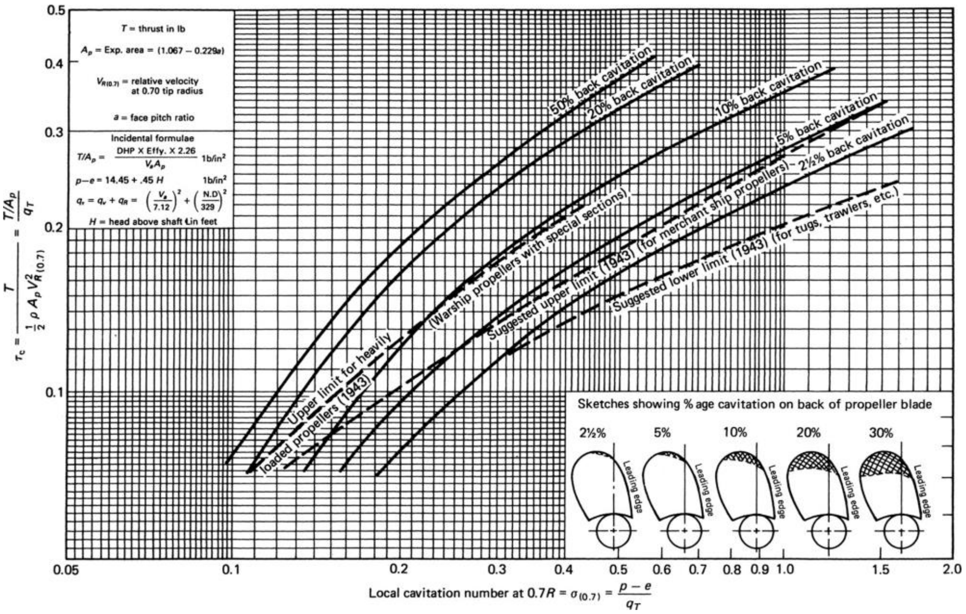


Figure 3. Burril cavitation diagram [8].

$$\tau_C\ Propeller = \frac{T}{0.5\rho A_E\left(1.067 - 0.229 \times \frac{P}{D}\right)(V_a^2 + (0.7\pi n D)^2)} \tag{1}$$

$$\sigma = \frac{(\rho g h + P_{AT} - P_V)}{0.5\rho V_R^2} \tag{2}$$

To simplify the calculation of the cavitation limit, from Molland, Turnock, and Hudson [11] used Equation 3 - 5 for the value of C Propeller and C limit. The value of C limit is divided into 3 limits. The lower limit which is used for heavily loaded propellers such as tugboats, trawlers etc. The second is upper limit (2-5%) which has a back cavitation value of 2%-5% and is usually used on merchant vessels etc. While the last one is upper limit (10-15%) which has a back cavitation value of 10%-15% for naval vessels, fast craft, etc. From another perspective regression equation, Lothar Birk [10] presesnt to used Equation 6-13 to get the limit value of thrust loading coefficient. From another reference, Auf’ M Keller [12] produce the formula to get estimation of the minimum expanded area (Equation 14) ratio to avoid cavitation, but the formula does not calculate the effect of the rotational speed and advance velocity of the propeller.

$$\tau_C\ lower\ limit = 0.21(\sigma - 0.04)^{0.46} \tag{3}$$

$$\tau_C\ upper\ limit\ (2\% - 5\%) = 0.28(\sigma - 0.03)^{0.57} \tag{4}$$

$$\tau_C\ upper\ limit\ (10\% - 15\%) = 0.43(\sigma - 0.02)^{0.71} \tag{5}$$

$$30\%\ Back\ Cavitation\ \tau_C = 0.910\sigma^{0.335} - 0.346 \tag{6}$$

$$20\%\ Back\ Cavitation\ \tau_C = 1.147\sigma^{0.195} - 0.672 \tag{7}$$

$$10\%\ Back\ Cavitation\ \tau_C = 1.267\sigma^{0.126} - 0.912 \tag{8}$$

$$5\%\ Back\ Cavitation\ \tau_C = 0.715\sigma^{0.184} - 0.437 \tag{9}$$

$$2.5\%\ Back\ Cavitation\ \tau_C = 0.611\sigma^{0.189} - 0.372 \tag{10}$$

$$\text{suggested lower limit for tugs, trawlers, etc. } \tau_C = 0.527\sigma^{0.155} - 0.324 \tag{11}$$

$$\text{suggested upper limit for merchant vessels } \tau_C = 0.304\sigma^{0.497} - 0.034 \tag{12}$$

$$\text{suggested upper limit for naval vessels } \tau_C = 0.464\sigma^{0.479} - 0.089 \tag{13}$$

$$\frac{A_E}{A_0} = \frac{(1.3 + 0.3Z)T}{(P_0 - P_v)D^2} + K \tag{14}$$

The empirical calculation conditions are carried out as in Table 1. Simulation calculations will be varied by value of P/D, Ae/Ao, Number of blades (Z) and diameter (D). Other components such as advance velocity (Va) and rotation speed (n) of propeller are considered constant or ignored as in Keller's Formula. So that the results obtained, the cavitation value limit used is the recommended upper limit for merchant ship (2-5%). For calculation of rotational speed propeller, it predicted with engine-propeller matching method that used polinomial of B-Series propeller [13].

Table 1. Propeller condition

Name	Value	
Propeller Series	B-Series	
Ship Resistance	44.766	kN
Advance Velocity	3.637	m/s
Fluid Density	1026	kg/m^3
Fluid / Propeller Pressure	101325	Pa
Vapor Pressure	2300	Pa
Shaft Depth	2	m
Thrust Propeller	36.673	kN

3. Results and Discussion

From the data used for the calculation, it is obtained several special parameters such as rotation and propeller thrust which have different values for each variation. This value becomes input for the calculation of the cavitation number and cavitation limit. So that it get several tables of calculation results as in Table 2-5.

Table 2. Cavitation on different P/D

Prop. Spec.	P/D	n	tC	Cav. Num.	tC limit	Result
Z = 4 AE/AO = 0.4 D = 1.75	0.6	5.5076	0.1259	0.4772	0.1770	No cavitation
	0.8	4.5103	0.1947	0.7017	0.2232	No cavitation
	1	3.8922	0.2718	0.9288	0.2635	Cavitation
	1.2	3.4763	0.3554	1.1481	0.2984	Cavitation

Based on the calculation data that has been obtained from changing the P/D value by adjusting the propeller rotation value using the Engine Propeller Matching calculation or the Propulsion calculation, it is explained that increasing the P/D value can cause cavitation. At each increase in the P/D value, it will be followed by a decrease in the propeller rotation value, resulting in an increase in tC that is not in line with the addition of the tC limit. One possibility that causes cavitation to changes in the P/D value is when the P/D value increases, the angle of attack or pitch angle in each section of the foil will also increase. This can result in excessive pressure on the propeller foil causing a pressure difference which results in the appearance of cavitation. This is in line with research conducted by Abdou and Al-Obaidi [14].

Table 3. Cavitation on different AE/AO

Prop. Spec.	AE/AO	n	tC	Cav. Num.	tC limit	Result
Z = 4 P/D = 1 D = 1.75	0.4	3.9242	0.3680	0.9145	0.2611	Cavitation
	0.55	3.8922	0.2718	0.9288	0.2635	Cavitation
	0.7	3.8700	0.2159	0.9389	0.2652	No cavitation
	0.85	3.8561	0.1790	0.9453	0.2662	No cavitation

When viewed from the change in the value of Ae/Ao, increasing the surface area of the propeller can reduce the cavitation that appears. This is due to the influence of the calculation of the tC value and does not affect the calculation of the limit tC value. So the tC limit value will be relatively the same but the propeller tC value will decrease with the addition of Ae/Ao. There is no significant change in the tC limit value because the Cavitation Number value does not change. This value is relatively constant or changes insignificantly because the propeller rotation value does not change significantly. In research from Lindgren [15] and Törnros et al. [16] conducted experienced the same change. As the propeller area increases, the cavitation area decreases.

Table 4. Cavitation on different number of blade

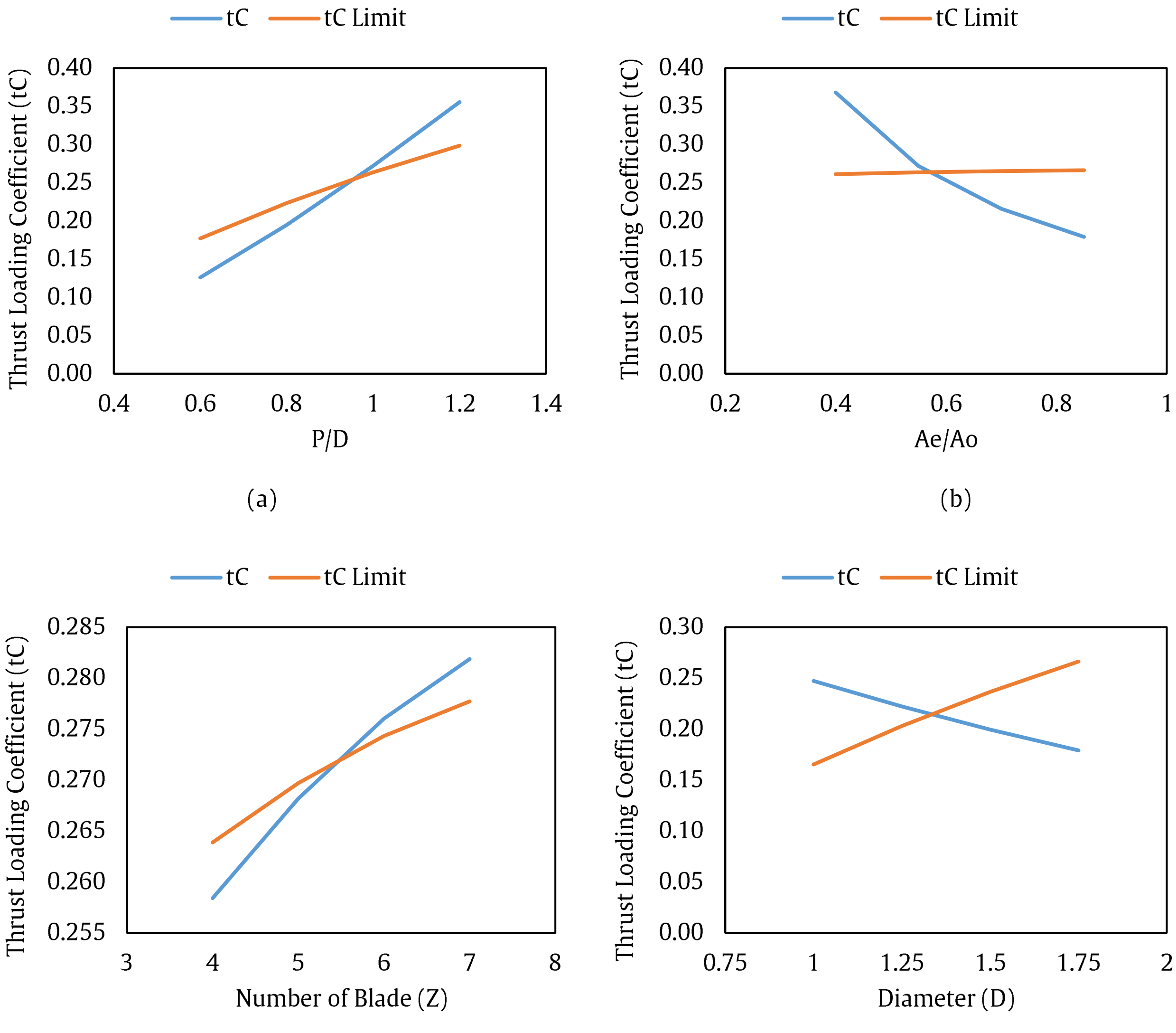
Prop. Spec.	Z	n	tC	Cav. Num.	tC limit	Result
AE/AO = 0.58 P/D = 1 D = 1.75	4	3.8870	0.2584	0.9311	0.2639	No cavitation
	5	3.8113	0.2682	0.9663	0.2697	No cavitation
	6	3.7533	0.2760	0.9946	0.2743	Cavitation
	7	3.7117	0.2819	1.0157	0.2777	Cavitation

The same thing also happens when the number of propeller blades increases, because the surface area on each blade becomes smaller when the number of propeller blades is increased with a fixed Ae/Ao value. Its different from Hsieh et al. [17] and Felli et al. [18] researches. The lower the propeller rotation value makes cavitation appear on a larger number of blades. Changes in tC values do not move significantly compared to when changes in Ae/Ao are calculated. This can be interpreted that when the change in the number of propeller blades increases, the reduction in the area of the propeller on each blade does not decrease significantly. These results are also in line with research conducted by Mohammad Daniel Arifin et al. [19].

Table 5. Cavitation on different diameter

Prop. Spec.	D	n	tC	Cav. Num.	tC limit	Result
Z = 4 AE/AO = 0.85 P/D = 1	1	10.2141	0.2472	0.4262	0.1652	Cavitation
	1.25	6.8578	0.2222	0.5987	0.2030	Cavitation
	1.5	4.9992	0.1995	0.7739	0.2365	No cavitation
	1.75	3.8561	0.1790	0.9453	0.2662	No cavitation

The last variation is done on the change in propeller diameter. What is clear is that when the diameter increases, the propeller rotation value will decrease significantly compared to other calculation variations. Judging from the cavitation, the larger the diameter of the propeller, the cavitation on the propeller will decrease. This is because the τc value decreases and the limit tC value increases, so that the changes that occur between the limit and the cavitation become very dynamic. A similar thing happens when the scale changes to the model size and the actual size [20].



(a) (b)

(c) (d)

Figure 4. (a) Thrust loading coefficient chart P/D, (b) Ae/Ao, (c)number of blade, (d) and diameter.

Of the four variations in the calculations that have been carried out, changes in the diameter and Ae/Ao of the propeller can reduce cavitation on the propeller, whereas when the P/D value and the number of propeller blades increase cavitation will appear. When viewed from the tC limit and tC values (Figure 4), the P/D variations and the number of propellers have increased in both. However, this still causes cavitation to appear along with the addition of the P/D value and the number of blades. Meanwhile, when the diameter changes tC and tC the limit changes inversely, where the tC value increases and the tC limit value decreases. For changes in the Ae/Ao value, the cavitation limit value does not change significantly so that when the propeller blade area is widened, the tC value decreases which has an impact on reducing cavitation.

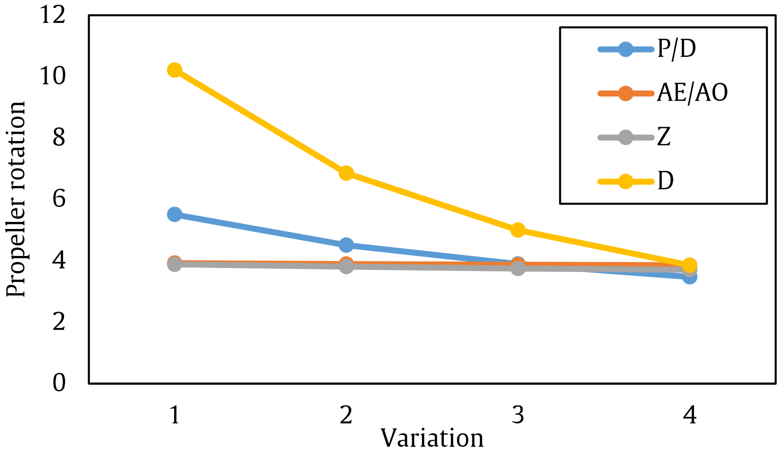


Figure 5. Propeller rotation on each variation

When viewed from the change in propeller speed (Figure 5), increasing the value of P/D, AE/AO, Number of Blades and Diameter has an impact on reducing the value of propeller rotation required for the same thrust force. However, decreasing propeller rotation does not always have an impact on reducing the estimated occurrence of cavitation in the propeller. As in research Mohammad Daniel Arifin et al. [19], [21], it is explained that cavitation occurs due to changes in propeller rotation, but in this study the value of the pitch angle also increases.

From the comparison of the data provided by the matrix design and burril cavitation calculations (Tables 6 and 7), it can be seen that changes in propeller pitch have a corresponding impact on the appearance of propeller cavitation from cavitation number gap. But in Ae/Ao, the number of blades and propeller diameter are different. This is possible because in this study the Keppel series Propellers were used, while Burril used the KCD series or was usually implemented for the B-Series. However, in general Ae/Ao does not have a significant impact on tip cavitation, while the number of blades does not have much impact on general cavitation margin.

Table 6. Design matrix. Influence: X little or none, XX moderate, XXX strong. [1]

Parameter	Cavit. Free range	
	Cavit. Margin, general	Cavit. Margin tip
Orthogonal blade length	xx	xxx
Section profile	xx	x
Circulation distribution	xxx	xxx
Pitch distribution	xxx	xxx
Camber distribution	xxx	xxx
Skew	xx	x
Area ratio	xx	x
Area distribution	xx	x
Diameter	xx	xx
Rpm	xx	xx
Blade number	x	xxx
Thickness ratio	xx	x
Trailing edge thickness	x	x
Anti-singing edge form	x	x
Material	x	x

Table 7. Changes in cavitation number and tC limit values

Name	Gap		
	tC	Cav.Num.	tC Limit
P/D	0.2295	0.6709	0.1214
AE/AO	-0.1890	0.0307	0.0051
Z	0.0235	0.0846	0.0138
D	-0.0682	0.5191	0.1010

Based on empirical calculations, adding the value of the pitch angle will also affect the addition of cavitation. In research on other parameters it is also explained that increasing the number of blades can reduce cavitation, but in this study the diameter of the more number of blades has a smaller value [22]. So from this it can be concluded that the emergence of cavitation should be investigated with identical propeller designs and only with a change of 1 variation. Increasing the propeller speed does not necessarily make cavitation appear, it still depends on the change in the propeller design used. Increasing the number of propeller blades also cannot be a full reference for cavitation, because the value of the propeller area is an important reference in the distribution of pressure on the surface of the propeller blades

4. Conclusion

Based on the calculation results, it can be concluded that by adding the expanded area ratio and propeller diameter values can reduce cavitation in the propeller. While the opposite happens, when the propeller pitch value and the number of blades increase, the cavitation value will also increase. From these calculation experiments it can be concluded that to meet the needs of submarine propellers,

1. If the submarine is in a diving condition or a scouting condition, it will be difficult for cavitation to appear. Because the pressure of the ship when diving conditions will be very high and the cavitation number will be very small. So the propeller cavitation limit will be very high or wide.
2. The design of a submarine propeller to avoid cavitation is to have a large value of the diameter and area of the propeller blades but with a small number of blades and pitch.
3. The cavitation prediction used may have different results if modifications occur to the propeller blades, such as adding cupping [23], winglets, kort nozzle [24] and other changes. Besides that, the difference in scale in the test also has an influence on how to predict cavitation in the future [25], [26].

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