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Performance Evaluation of Fixed Pitch Propellers: Flow Visualization of Cavitation in Unmanned Surface Vehicles

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ABSTRACT

This study was conducted to determine a suitable and appropriate propeller for use on unmanned surface vehicles. The tests involved varying the number of blades-2, 3, and 4 of fixed pitch propellers type to assess thrust, propeller performance during straight-line motion and maneuvering, as well as the flow patterns around the propeller that have the potential to cause cavitation. The experiments were carried out in both a reservoir and a test tank. The results showed that the average thrust produced by the 2-blade, 3-blade, and 4-blade propellers was 13.32 N, 17.13 N, and 12.78 N, respectively. In the straight-line test over a 20-meter distance, the average speeds achieved were 1.49 m/s (2 blades), 1.40 m/s (3 blades), and 1.21 m/s (4 blades). For maneuvering, the average speeds recorded were 0.80 m/s, 0.61 m/s, and 0.49 m/s, respectively. Flow pattern analysis around the propellers revealed that cavitation occurred in almost all conditions and blade number variations. The fewer the blades, the more clearly cavitation bubble formation was observed. Similarly, increasing the propeller rotational speed can lead to a higher rate of bubble formation. Overall, the 3-blade propeller yielded the best performance for unmanned surface vehicle, offering an optimal balance of thrust, speed, maneuverability, and more controlled cavitation potential.

KEYWORDS: *Cavitation, Flow Pattern, Propeller, Fluid Dynamic, Surface vehicle.*

NOMENCLATURE

δ_0	: Swirl angle	(°)
D_b	: Diameter Boss	(mm)
D_s	: Diameter Shaft	(mm)
L_b	: Panjang Boss	(mm)
A_E/A_0	: Expanded Area Ratio	(-)
P/D	: Pitch to diameter ratio	
η	: Efficiency	(%)
J	: Advance ratio of propeller	(-)

1.0 INTRODUCTION

This study is an effort to identify a suitable propeller for use on an unmanned surface vehicle. The work involves the design and testing of propellers in relatively slight wavy surface conditions by varying the number of blades. To determine the appropriate type of propeller for specific operating conditions of an unmanned surface vehicle, tests were conducted on fixed-pitch propellers with different blade.

The noise method is a practical approach to predicting cavitation on marine propellers. A comprehensive analysis of propeller issues involves using the lifting surface method, and blade noise prediction employs semi-empirical formulas for low frequencies. The propeller models used in the study are DTMB 4119, DTMB 4148, and Seiun-maru HSP. From a study concluded that analyzing propeller problems using this method is easy, practical, fast, low-cost, and useful during the pre-design phase [1]. Modifications to marine propellers are sometimes necessary in certain cases to achieve optimal results, with a sea margin reaching 15% and an efficiency of 0.537% [2].Based on a study by redesigned marine propellers to produce four models, each with diameters of 2760 mm, 2650 mm, 2600 mm, and 2550 mm. The highest thrust was achieved using the Ka4-70 series propeller with a rake angle of 60°, reaching a thrust of 337,206 N [3].

Efforts to determine the best propeller can also be conducted using Computational Fluid Dynamics (CFD) analysis on three 4-bladed propeller models [4]. They compared three propeller models for trimaran vessels and found the best result with the B-4 series model at 450 RPM, yielding a thrust of 28,213.92 N and a turbulent flow velocity of 17.95 m/s. Using Computational Fluid Dynamics, a 4-bladed fixed-pitch propeller with a diameter of 2.2 m, Ae/Ao = 0.7, and P/D = 0.67 under varying rake angles have been tested. Test results showed that the vessel could operate at up to 90% rated power and 90% rated speed [5].

Cavitation on propellers is a common phenomenon. It occurs due to a rapid pressure drop below atmospheric pressure, forming small vapor-filled bubbles. Since cavitation can damage propellers, various countermeasures have been explored [6]. A drastic reduction in cavitation can be achieved by removing gas from the liquid. From the result of the study concluded that the higher levels of gas removal can significantly reduce the likelihood of cavitation, even at propeller speeds above 2500 RPM [7].

Cavitation is a complex phenomenon to study. Its occurrence depends on water conditions and properties that change with temperature. To assess the effect of temperature changes on cavitation, a study conducted using Computational Fluid Dynamics analysis [8]. The Reynolds-averaged Navier-Stokes equation, Rayleigh-Plesset equation, k-ε turbulence model, and shear stress transport model were used to analyze cavitation under temperature variations from 0 to 50°C. The results showed that increased temperature raised the likelihood of cavitation. Cavitation can cause erosion and even accelerate corrosion on ship propellers [9]. They conducted an erosion demonstration test using seawater to measure mass loss caused by cavitation. The test revealed that at high rotation speeds, the propeller lost twice as much weight as at low speeds. Erosion pits formed in the region between 0.7 and 0.9 of the propeller radius.

This study aims to evaluate the performance and cavitation characteristics of propellers by varying the number of blades-two, three, and four blades. The study involves designing and fabricating from carbon fiber composite propellers and testing thrust, straight-line movement, and maneuverability, while observing cavitation through flow pattern visualization around the propeller. Direct testing was conducted to obtain essential information for future application on unmanned surface vehicles.

2.0 METHODS

This study used the design and testing methods for FPP (Fixed Pitch Propeller) types from the B4-40 series, B3-35 series, and B2-30 series as normal propeller in general [10,11]. A performance comparison of each propeller type is conducted to determine the best-performing one.

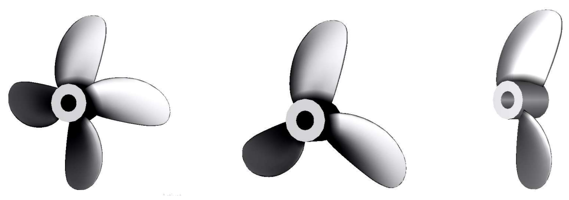
2.1 Design

The design process follows the principles and guidelines proposed by the experts [12,13,14,15], resulting in several parameters for two-blades, three-blades, and four-blades propellers. The designed parameters include propeller diameter, pitch, rake, expanded area ratio, scew, P/D ratio, 1/J, delta zero (δ_0), efficiency, hub diameter, shaft diameter, hub length, and cavitation risk. These parameters are presented in Table 1, with additional data obtained through calculations and standard design procedures.

The calculation results and design standards serve as input data for initiating the creation of 2D model designs or 3D offsets of the propeller using HydroComp PropCad software. The processed data produces the desired propeller shapes according to the specified variations, as shown in Figure 1.

Tabel 1: Results of Design

No	Number of Blade	Type of Propeller	Direction	Diameter (mm)	Pitch	Rake	Expanded area ratio	Scew	P/D	1/J	δ_0	η	D_b	D_s	L_b	Cavitation Risk
1	4	B4-40 FPP	*CW*	42.36	23.72	15^0	0.40	13.3	0.56	4.30	435.4	37.2 %	8.8	4	9.6	Cavitation
2	3	B3-35 FPP	*CW*	43.28	23.80	15^0	0.35	17.7	0.55	4.4	445.5	38.2 %	8.8	4	9.6	Cavitation
3	2	B2-30 FPP	*CW*	42.97	25.35	15^0	0.30	19.6	0.59	4.35	435.4	36.3 %	8.8	4	9.6	Cavitation



(a) (b) (c)

Figure 1: Fix pitch propeller type with various number of blades a). 4-blades, b) 3-blades, c) 2-blades

2.2 Materials

The selection of materials used to manufacture the propeller is based on the findings from previous study [16,17]. The propeller material chosen for this study is kevlar carbon fiber fabric plain 3K 200 gsm, combined with Yukalac 157 (BQTN) polyester resin and methyl ethyl ketone peroxide (MEKP) catalyst.

2.3 Evaluation

The equipment used in the testing includes: (a) digital scale for measuring thrust, (b) wattmeter for measuring electrical power, (c) tachometer for measuring rotational speed, (d) measuring tape for recording the distance traveled by the vehicle, and (e) representative water tank with high speed camera for capturing flow patterns during cavitation phenomena. The propeller testing method consists of several stages as follows:

1. Thrust

Thrust testing is carried out by positioning the vehicles on the water surface. The vehicle is then operated by gradually opening the remote throttle, maintaining a constant speed for each variation. The vehicle moves straight forward, pushing against the scale, which is held in place by a wall. The thrust testing setup is illustrated in Figure 2. Testing is conducted under stationary conditions by varying the number of blades--2, 3, and 4 blades, respectively. Each thrust test variation is repeated three times to obtain an average value.

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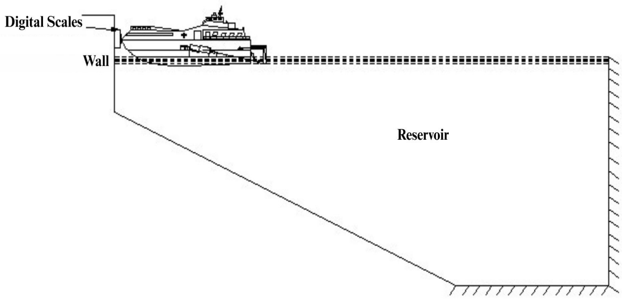

Figure 2: Thrust test scheme

2. Straight-line track
   Straight-line track testing is conducted over a distance of 20 meters, completed in three laps with repetitions. The track length is adjusted to suit the conditions of the testing location. The vehicles movement is remotely controlled and maintained at a constant speed. The testing setup for the straight-line track is shown in Figure 3.

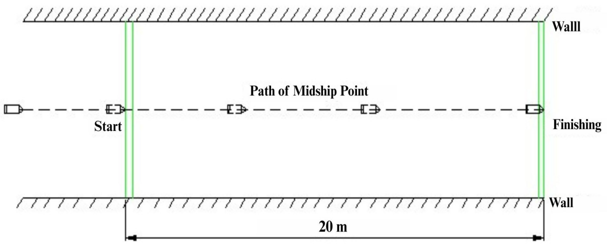

Figure 3: Straight track test scheme

3. Maneuver
   Maneuver testing is conducted to determine the vehicles movement characteristics when navigating a course, such as executing a 360° turn around a fixed marker with a radius of 1.5 meters. The testing setup is illustrated in Figure 4.

4. Flow pattern around the propeller
   The flow pattern testing around the propeller aims to observe bubble formations that indicate the occurrence of cavitation. The test is conducted by operating the vehicle's propulsion system in a transparent water tank, allowing visual observation of the phenomenon. The main dimensions of the water tank are 120 cm in length, 25 cm in width, and 30 cm in height. Testing is carried out for three blade variations and a range of rotational speeds from 120 RPM to 15,000 RPM. Video and photo captures of the propeller in operation are required for analysis. The schematic design of the test setup is shown in Figure 5.

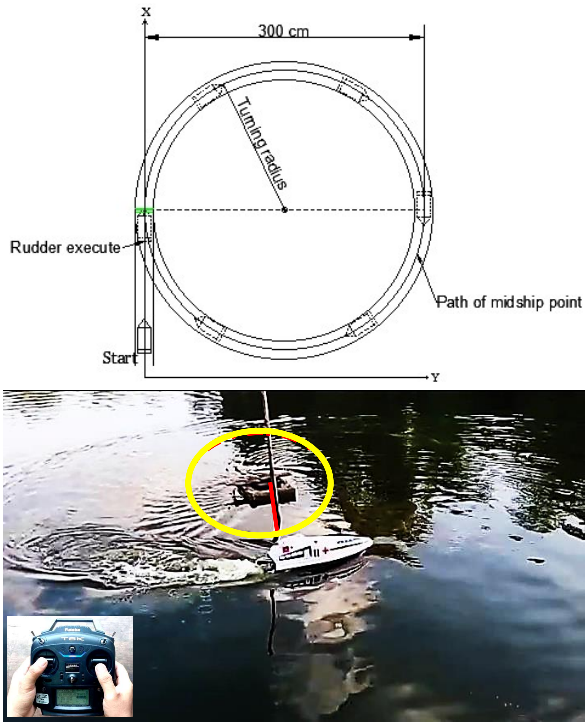

Figure 4: Schematic of maneuver testing

3.0 RESULT AND DISCUSSION

3.1 Thrust

From Figure 6, it can be observed that an increase in the number of blades leads to a decrease in thrust performance. The highest thrust is achieved with a 2-blade propeller, while the lowest is with a 4-blade propeller. The thrust generated for each blade variation is 17.32 N, 17.13 N, and 12.78 N, respectively. Meanwhile, the power required for each blade configuration is 540.67 Watts, 544.67 Watts, and 573.33 Watts, respectively. The increase in power consumption is due to the greater amount of work required as the number of blades increases. The reduction in thrust is caused by the decreased volume of water displaced, as the increased blade surface area disrupts the flow over the same period and under the same conditions. The more mass of water that can be effectively moved, the greater the thrust that can be produced. These results indicate that, to achieve higher thrust, the use of a 2-blade propeller is more effective than the others.

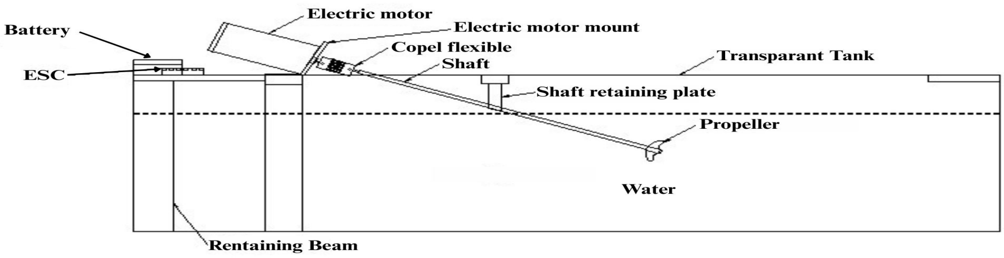

Figure 5: Testing scheme for cavitation phenomena on propellers

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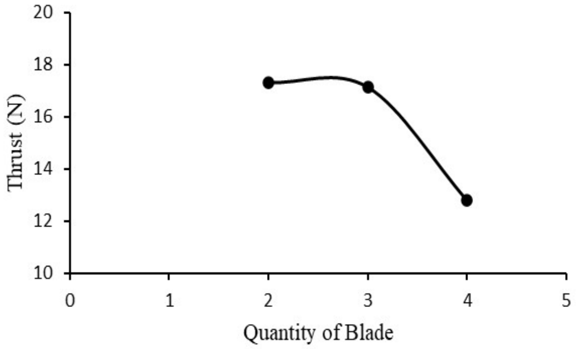

Figure 6: The effect of the number of propeller blades on thrust

3.2 Straight-line Track

As shown in Figure 7, the highest straight-line speed is achieved by the 2-blade propeller, reaching 1.5 m/s over a 20-meter track. Meanwhile, the 3-blade propeller reaches a speed of 1.4 m/s, and the 4-blade propeller records the lowest speed at 1.2 m/s. An increase in the number of blades results in a decrease in the speed achieved. This occurs because propellers with more blades have smaller curved blade surface areas, which reduces their efficiency in pushing water. The results of the straight-line speed test exhibit a similar pattern to the thrust test, where the 2-blade propeller consistently outperforms the others.

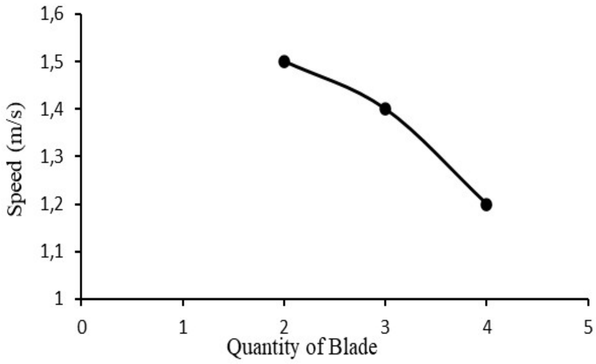

Figure 7: Effect of the number of propeller blades on straight-line speed.

3.3 Maneuver

Based on Figure 8, the highest maneuvering speed is achieved using the 2-blade propeller, reaching 0.8 m/s. The 3-blade propeller follows with a speed of 0.6 m/s, while the 4-blade propeller records the lowest speed at 0.5 m/s. As the number of blades increases, a decrease in maneuvering speed is observed. This reduction is influenced not only by the curved blade surface area but also by the rudder installed at the stern of the vessel, which appears to significantly affect speed during maneuvers. During the maneuver test, the rudder is positioned at a 45° angle, which increases drag and contributes to the turning motion along the hull. The results of the maneuver test exhibit the same characteristics as the thrust and straight-line speed tests, where the 2-blade propeller consistently achieves higher speeds than the others.

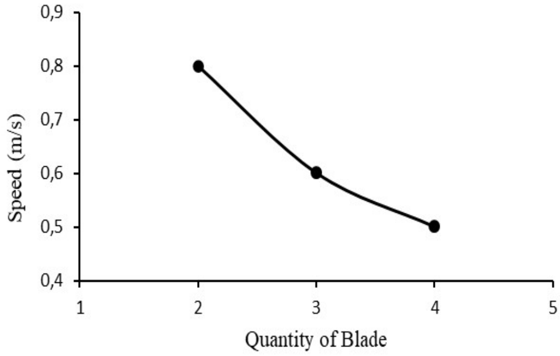

Figure 8: Effect of the number of propeller blades on achieved speed during maneuvering.

3.4 Cavitation and Flow Pattern Investigation

The flow pattern observation is intended to evaluate the potential occurrence of cavitation, following the principles outlined by Noosomton and Charoensuk [18]. In this test, the blades are designed to reach a maximum rotational speed of 26,640 RPM. Testing is conducted with throttle openings ranging from 0% to 50%, resulting in shaft rotational speeds from 0 RPM up to approximately 15,000 RPM. Quantitative observation of cavitation on the propeller has been carried out under the specified test conditions.

1. Flow investigation at 120 RPM

The flow pattern testing of propellers with different blade numbers includes: (a) 4-blades, (b) 3-blades, and (c) 2-blades configurations, each set to a rotational speed of approximately 120 RPM. The flow pattern results around the propellers are shown in Figure 9. As seen in Figure 9 (a), air bubbles near the area closest to the propeller have not yet been detected as marked circle line R1, although there is visible fluids movement toward the leading edge starting to appear in the circle line area R3.

As the number of blades decreases, air bubbles begin to appear slightly farther from the propeller, aligned along the shaft axis starting from area R4 to area R2. The air bubbles are like being drawn into the area closer to the propeller. In the case of the 2-blade propeller (Figure 9 (c)), these bubbles become more developed and move closer to the propeller path. These results indicate that the number of blades can influence the flow pattern. In general, the observed bubbles have not fully developed due to the low rotational speed. Cavitation is unlikely to occur at such low speeds.

2. Flow Investigation at 500 RPM

The flow pattern around the propeller at a rotational speed of up to 500 RPM is visually shown in Figure 10. Changes in the number of blades on the propeller appear to affect the number of bubbles in the area around the propeller. A significant change is observed as the number of blades decreases from 4 to 2. In this condition, vibrations and noise are noticeable, signaling the onset of cavitation. Additionally, the vibrations and increased noise could also might be caused by the propeller reaching its critical rotational speed. Generally, at 500 RPM, the propellers condition does not result in damage to the propulsion system. Based on identical rotational speeds across all propellers within the entire circular area, propellers with fewer than four blades are more prone to early cavitation occurrence.

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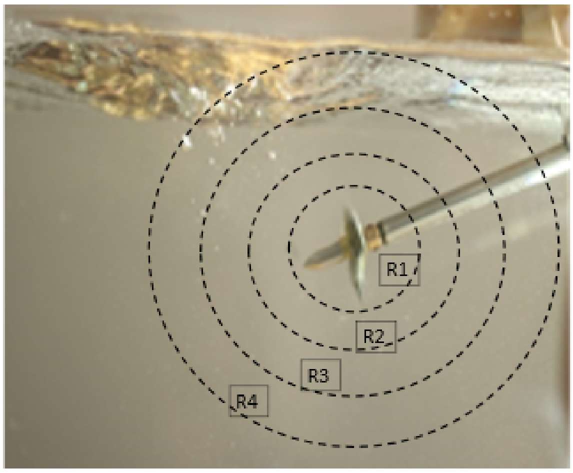

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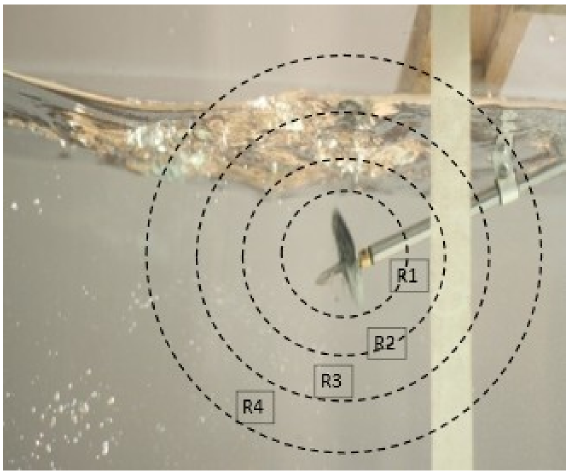

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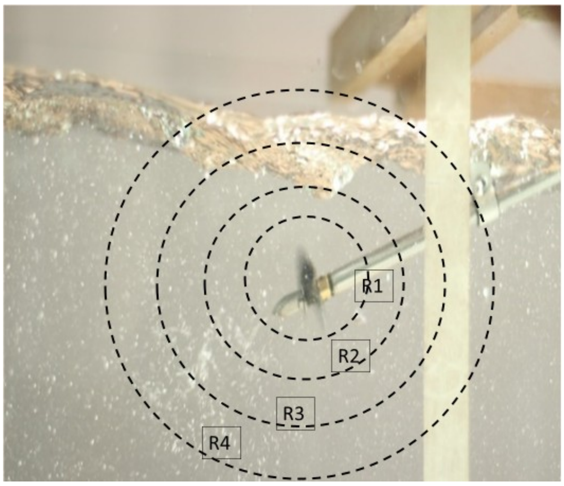
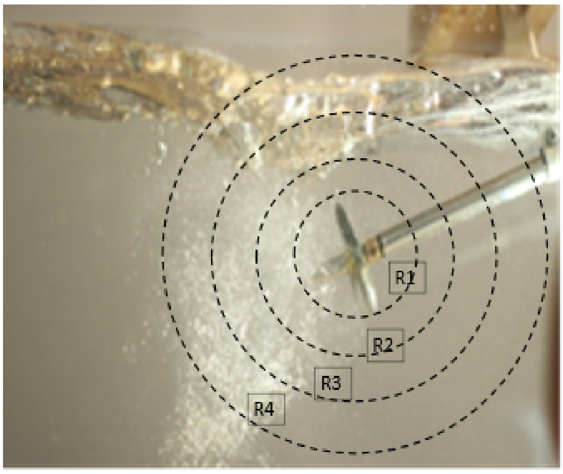


(c)

Figure 9: Fluid bubble movement patterns around the propeller at 120 RPM, (a). 4-blades, (b). 3-blades, (c). 2-blades



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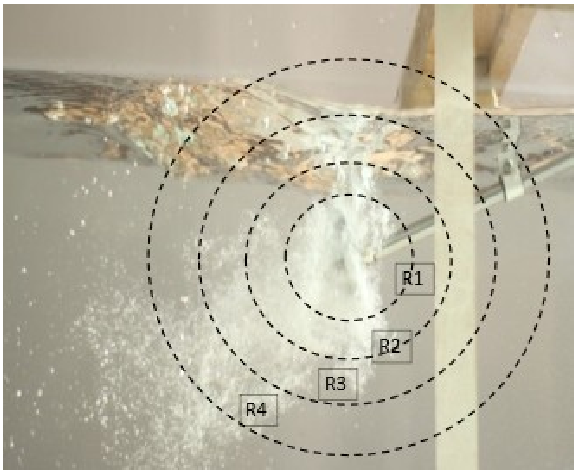

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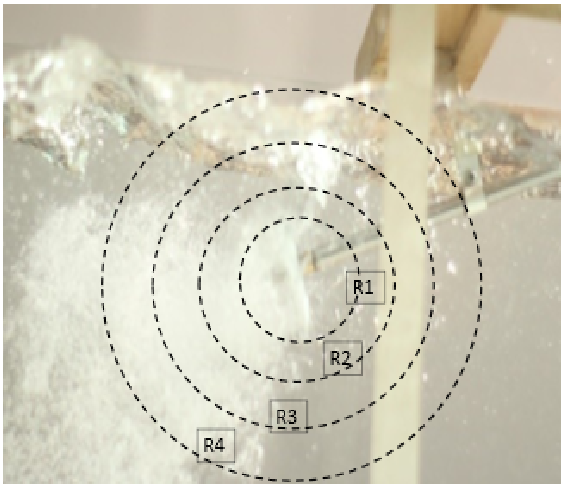

(c)

Figure 10: Fluid bubble movement patterns around the propeller at 500 RPM, (a). 4-blades, (b). 3-blades, (c). 2-blades

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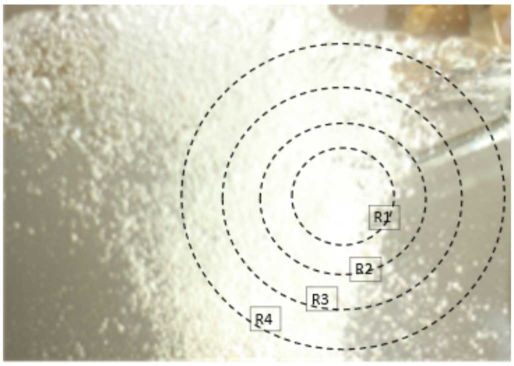
-Science and Engineering-
30th July 2025. Vol.69 No.2

July 30, 2025

3. Flow Investigation at 700 RPM

The same test condition was conducted on the propeller with four blades, three blades, and two blades, nevertheless rotational speeds reaching approximately 700 RPM are shown in Figure 11. Increasing the rotational speed revealed more distinct indications of cavitation behavior on the propeller. A similar finding was also observed in previous studies [9]. The visual signs observed included a significant number of air bubbles surrounding the blades, followed by increasing vibrations and noise, caused by the stronger bursts of cavitation occurring on the propeller. These phenomena further clarified that at this speed, cavitation is present. The cavitation that occurs is likely to have varying impacts on each propeller. This is indicated by the differing bubble area. Propellers with fewer blades exhibit a wider and denser distribution of cavitation bubbles.



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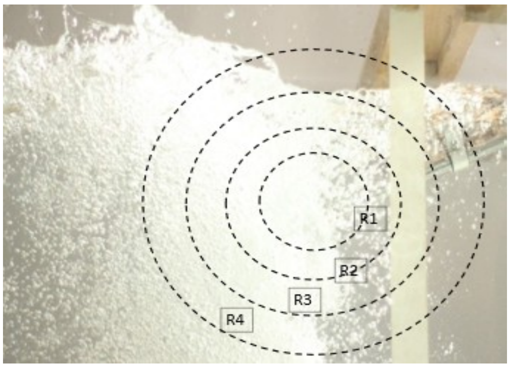

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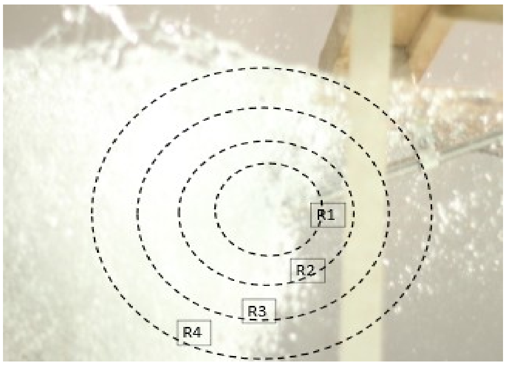
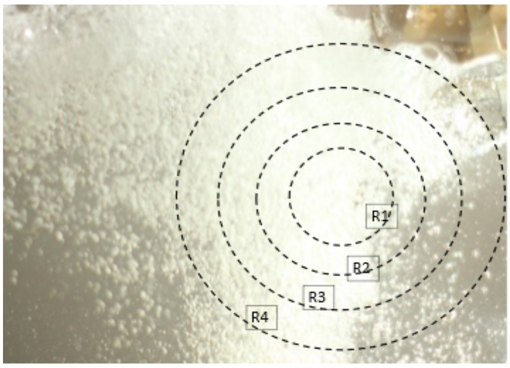


(c)

Figure 11: Fluid bubble movement patterns around the propeller at 700 RPM, a) 4-blades, b) 3-blades, c) 2-blades

4. Flow Investigation at 10,000 RPM

Cavitation testing was performed at a rotational speed of around 10,000 RPM. As shown in Figure 12, the pattern of air bubble formation resembles that observed in tests conducted at lower rotational speeds. However, the bubble density appears to increase as the number of blades decreases. Increasing the rotational speed showed worsening indications of cavitation behavior on the propeller. This can potentially damage the blade root area and the fillet region of the propeller. The visual signs observed included a substantial number of air bubbles enveloping the blades, followed by increasing vibrations and noise, caused by the stronger bursts of cavitation generated by the propeller. The phenomena observed in the results of this test have been previously reported in earlier studies [6]. This further clarified that at a rotational speed of 10,000 RPM, cavitation is occurring.



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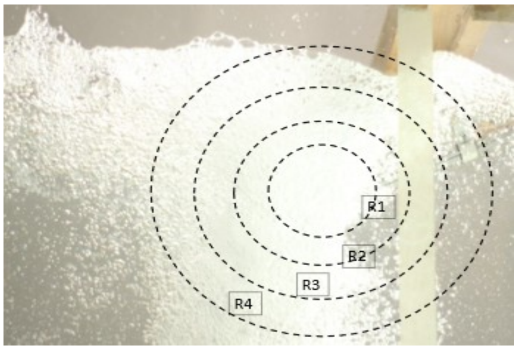

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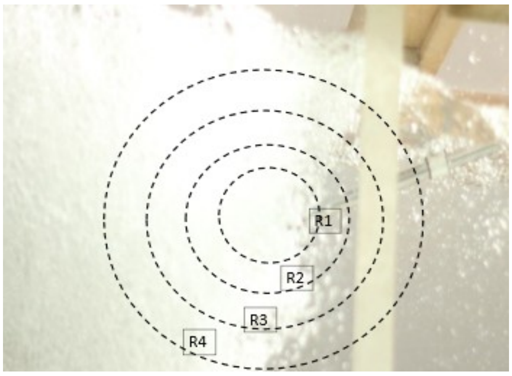

(c)

Figure 12: Fluid bubble movement patterns around the propeller at 10,000 RPM, a) 4-blades, b) 3-blades, c) 2-blades

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5. Flow Investigation at 15,000 RPM

Increasing the rotational speed from previous tests showed increasingly clear and worsening cavitation behavior on the propeller. As shown in Figure 13, the air bubbles appear increasingly concentrated near the area closest to the propeller. As the number of blades is reduced within the same circular area, the bubble density tends to increase. This increase in bubble density is accompanied by a decrease in bubble size. Such conditions are highly conducive to bubble collapse, leading to the occurrence of cavitation. This can potentially damage the blade root area and the fillet region of the propeller, leading to a loss of power due to the air mixture when the propeller operates [6]. The behavior observed clearly included a significant number of air bubbles enveloping the blades, followed by increasing vibrations and noise caused by the stronger bursts of cavitation. These signs further confirmed that cavitation was occurring on the tested propeller at 15,000 RPM.

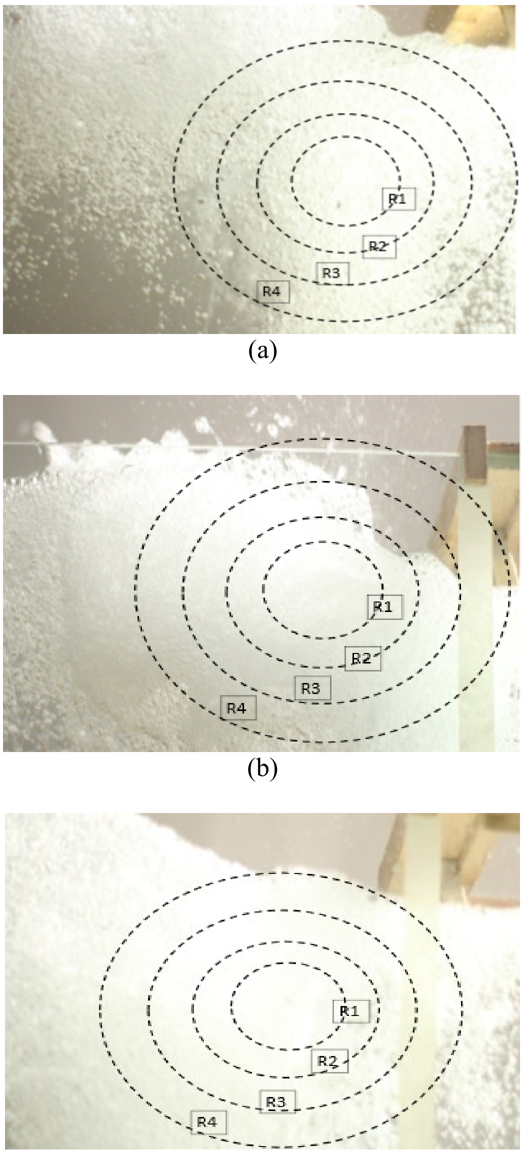

Figure 13: Fluid bubble movement patterns around the propeller at 15,000 RPM, a) 4-blades, b) 3-blades, c) 2-blades

5.0 CONCLUSION

Based on this current study, several important findings were obtained that can serve as guidelines for the operation of unmanned surface vehicles. The thrust force is influenced by the number of blades, and the achievement of speed on straight paths and during maneuvers is generally determined by the number of blades, with one optimal configuration being a fixed-pitch propeller with two blades. The growth of fluid bubbles indicating cavitation was found in all variations in the area around the propeller. Vibrations and noise increased along with the increase in rotational speed. The resulting vibrations and noise further confirmed the occurrence of cavitation. The growth of bubbles also increased with higher rotational speed. On the other hand, it was found that increasing the number of blades reduced the bubble formation area. Therefore, due to the effects of cavitation, the use of minimize number of blade propellers requires careful consideration for long-term use.

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