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PARAMETRIC OPTIMIZATION OF PROPELLER GUARDS FOR ENHANCED HYDRODYNAMIC PERFORMANCE AND ACOUSTIC PROFILE OF UNDERWATER VEHICLES

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ABSTRACT

Increasing prevalence of underwater vehicles, such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), for use across numerous applications necessitates engineering propulsion systems that maximize thrust while aiming to limit anthropogenic-sourced noise pollution. While propeller guards alter hydrodynamics and can impact thrust and noise, research on underwater vehicle propeller guard optimization remains limited. Existing studies primarily focus on surface vehicles and open propeller designs, leaving both a gap in understanding how guarded propellers influence underwater vehicle propulsion efficiency and an opportunity to make a positive environmental impact. This research employed parametric computational fluid dynamics (CFD) to analyze 75 propeller guard configurations for optimal design identification. To validate these results, six guard *configurations—selected from high and low points in the parametric study across three guard lengths—were fabricated and tested in a custom-built apparatus to measure thrust generated and noise produced. Experimental results aligned with CFD predictions for thrust measurement. Given validation of thrust results, all configurations from the parametric study that exceeded the open propeller's thrust level would yield higher thrust. Four of six experimental guards demonstrated noise reductions ranging from 0.01 dB to 10.29 dB less than the open propeller. The most efficient experimental propeller guard design increased thrust by 5.86% while reducing noise by 1.08 dB. This study demonstrates that propeller guards can be optimized to enhance underwater vehicle performance while simultaneously mitigating noise pollution. Future directions include exploring additional parameters to test, refinement of the testing apparatus, and evaluation of guarded propellers in real-world underwater vehicle applications.*

Keywords: Propeller Guards, Propeller Noise, Propeller Thrust, Underwater Vehicles

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1. INTRODUCTION

Oceanographic research has expanded significantly in recent years largely due to the development and increasing utilization of underwater vehicles, including autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs), which allow scientists to reach previously inaccessible parts of the ocean and collect data autonomously. These vehicles have become essential in diverse fields of marine research from environmental monitoring to infrastructure inspections as they provide safe, efficient, and detailed insights into underwater environments. Advances in AUV navigation, power management, and sensor capabilities have transformed these vehicles into critical tools for deep-sea exploration, enabling tasks such as mapping hydrothermal vents and collecting sediment samples in hazardous deep-sea environments with high precision—work too dangerous for human divers [1]. Advancements in dynamic positioning for ROVs through control algorithms, such as the linear quadratic regulator (LQR) and model predictive control (MPC), enable precise vehicle positioning even in challenging oceanic conditions [2]. Such positioning systems are critical for stability and accuracy in data collection. Innovations and technical advancements like these have allowed for the expansion of underwater research. AUVs contribute substantially to marine geoscience by supporting geological mapping and the study of seafloor processes, which is critical to understanding oceanic and tectonic activity [3]. Wynn et al. also emphasized the importance of benthic habitat mapping, a process that creates spatial representations of distinct seafloor areas associated with specific groups of fragile plants and animals. Similarly, Purser et al. discussed the use of high-resolution imaging and sonar-equipped AUVs for producing detailed maps of benthic ecosystems, aiding in habitat assessments and biodiversity monitoring [4]. These high-resolution imaging and sonar-equipped AUVs are also used for assessing geological structures, identifying mineral deposits, and monitoring biological communities within these benthic habitats. Collectively, advancements in underwater vehicle technology highlight their essential role in advancing oceanographic research.

Propeller guards are essential in underwater vehicle design, enhancing safety and reducing environmental impacts by limiting direct exposure to rotating propeller blades. Although propeller optimization has been studied, significant research gaps remain regarding optimal propeller guard design. While open propellers are widely used because they provide minimal water resistance, they expose marine life to potential harm and are vulnerable to impact damage [5]. Chapple & Renilson’s study found that ringed propeller guards reduce the thrust efficiency of a boat by about 30% compared to open propellers. In a study by Lee, computational fluid dynamics (CFD) analysis was used to explore how different guard designs—specifically variations in shape, size, and proximity to the propeller—affect the thrust efficiency and water resistance [6]. This study also revealed that, while larger and more protective guards increase coverage, they add considerable drag, reducing overall propulsion efficiency by about 20%. For instance, circular and octagonal guards perform well in terms of safety coverage but introduce drag, highlighting the trade-off between guard size and thrust efficiency. Findings from these studies underscore the need to optimize propeller guard designs to maximize thrust while maintaining effective protection. Lee noted that because this study was conducted solely with CFD analysis, further empirical testing is essential to validate the findings in real-world conditions [6]. Lee also discussed how there are numerous design parameters that have yet to be explored thoroughly. Koh et al. compared the thrust generated from open versus ducted (guarded) propellers on fishing vessels and found up to a 24% increase in thrust efficiency at low RPMs due to minimized flow separation within the nozzle [7].

However, they found that at speeds greater than 580 RPM, the efficiency drops, concluding that ducted propellers excel primarily at low speeds. These studies collectively indicate the need for optimized propeller guard designs to improve the thrust efficiency of underwater vehicles which operate at high RPMs. Though some of these studies were done with surface water vehicles such as boats, as opposed to underwater vehicles, they remain highly informative and further underscore the research gap in optimal underwater vehicle propeller guard designs.

Noise pollution in underwater environments disrupts behaviors in marine life, such as navigation, communication, and mating. Prolonged noise exposure induces physical stress and can alter migration routes and breeding grounds through disorientation. Human activities, such as shipping, underwater vehicle operations, and sonar usage, contribute significantly to this noise pollution, raising concerns about the impact on ecosystems [8]. Much of the noise produced by underwater vehicles is caused by their propulsion systems, specifically from propeller sheet cavitations and tip vortices. Sheet cavitation, an effect where vapor bubbles form and collapse due to pressure changes near the blade surface, produces a strong acoustic signature. Sheet cavitation not only diminishes propulsion efficiency but also generates low frequency noise that can disrupt marine ecosystems [9]. Tip vortices occur due to the pressure difference between the upper and lower surfaces of the blades, causing water to spiral around the tip. The collapse of vapor bubbles and swirling of water is a noise source.

Integrating guards around propellers has the potential to reduce sheet cavitation and tip vortex noise, but could also amplify propeller noise, although this effect remains under-researched. A study by Kaewkhiaw on long-tail boats examined the effects of surface water propeller guards on hydrodynamic performance using CFD to analyze how the guards influence thrust, torque, and wake turbulence. Findings revealed that, while guards provide substantial protection, they increase drag and disturb the wake flow, therefore generating noise due to increased pressure changes and water movement [10]. Although this study focused on surface water propeller guards for long-tail boats, it highlights the need to optimize underwater vehicle propeller guard designs to minimize hydrodynamic disturbances, which, in turn, could also help mitigate noise impact. This limited research on guard-related noise further emphasizes the gap in studies targeting underwater propeller guard designs optimized for noise reduction, underscoring a critical need for focused research in this area.

The literature reviewed for this study highlights the essential role of underwater vehicles in oceanographic research, detailing advancements that have made deep-sea exploration and data collection safer and more efficient. Increasing efficiency and reducing noise of these vehicles are critical areas open to improvement, particularly through advancements in propeller guard design. Studies show that while guards prevent damage to propellers and are more eco-friendly by safeguarding marine life and habitats, they introduce trade-offs in thrust efficiency and noise production. Guards can increase drag and change the water flow around the propellers, reducing propulsion. They may also create additional noise through wake turbulence, and this noise pollution can interfere with marine environments. The literature suggests that while some guard designs mitigate these effects in certain conditions, there is limited research focused on configurations optimized for underwater vehicles specifically, as much of the available data centers on surface water vehicles.

This study sought to address this gap by investigating how variations in three specific propeller guard parameters—inner diameter (d), angle of incline (Θ), and guard length (L)—affect thrust and noise production in underwater vehicles. By conducting a parametric CFD study followed by experimental validation, this research aimed to identify configurations that enhance thrust and minimize noise production. These findings can support the development of underwater vehicles that operate more efficiently and with less environmental impact, contributing to more sustainable marine exploration and research.

2. Materials and Methods

This research consisted of performing a parametric CFD analysis of a propeller guard, designing and fabricating a test setup for physical testing, and then testing six physical propeller guards to validate the thrust determined by the CFD analysis. Additionally, the noise produced by the propeller with the physical guards was measured. The configurations of the physical guards were based on the results of the CFD analysis.

First, a Jameco MS5N-1885-R 12V DC motor was waterproofed by wrapping it with electrical tape and encasing it in a wax-filled container, ensuring durability for underwater testing. Once waterproofed, measurements of the motor were taken to create an accurate model in the computer-aided design program, SolidWorks. Following this, SolidWorks was used to design a 50 mm propeller that replicated underwater vehicle propellers that are currently used in many small vehicle applications. The modeled propeller was used for both the CFD analysis and physical tests.

Next, a parametric propeller guard was modeled in SolidWorks and allowed systematic adjustments of the three parameters being studied: the guard diameter (d), angle of incline (Θ), and guard length (L). The inner diameter of the propeller guard ranged from 52 to 65 mm, the angle of incline from 1 to 25 degrees, and the guard length from 1 to 20 mm (Fig. 1). Each guard was identified by its diameter (mm), angle of incline (Θ), and guard length (mm). For example, if a guard had a 55 mm diameter, 10° angle of incline, and length of 15 mm, it would be identified as 55d 10Θ 15L.

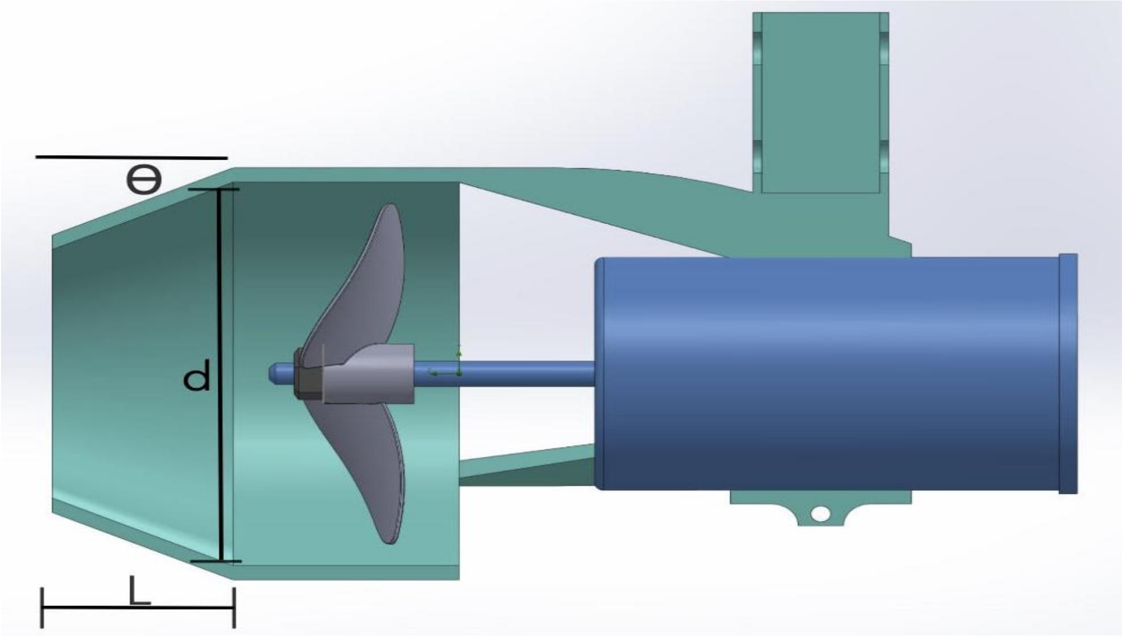


Figure 1 – Parameters studied in the propeller guard

Using Solidworks Flow Simulation software (Flow Wizard), a parametric design of experiments and optimization (DoE) analysis was done at a rotational speed of 8,500 RPM. Flow Wizard enabled standardization of parameters such as fluid properties, computational domain dimensions, and meshing for each test, providing consistency across simulations. Using the parametric guard model, 75 guard configurations were automatically generated and underwent (CFD) thrust analysis to assess performance. A computational domain of ±250 mm in the x direction, ±125 mm in the y direction, and +500/-325 mm in the z direction was used. For control comparison, a CFD thrust analysis was also conducted on an open (unguarded) propeller, providing a baseline to evaluate the guards' effects on thrust. A rotational region was defined around the propeller and matched the propeller's diameter and height.

Simulations were carried out using water with properties predefined in Flow Wizard. Tests were conducted at a static pressure of 101.325 Kpa (the average atmospheric pressure at sea level) and a temperature of 20°C. All CFD thrust data were recorded and graphed on a surface plot to identify trends and assess optimal guard configurations for enhancing thrust efficiency. An example of flow velocity from the CFD analysis is shown in Fig. 2.

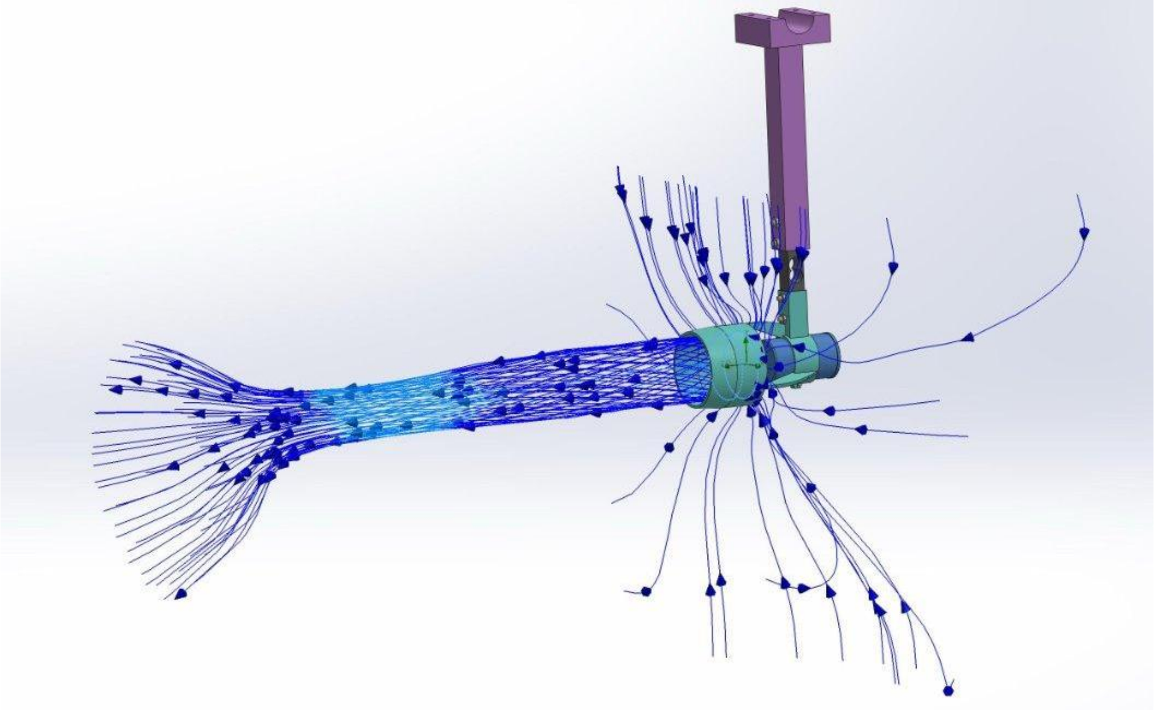


Figure 2 – CFD analysis example of 65d 2Θ 10.5L guard

With the propulsion assembly modeled and parametric CFD analysis complete, the next phase of this study involved constructing a physical testing apparatus and fabricating components to validate the computational results. As highlighted by Lee, physical testing is essential for confirming the accuracy of CFD simulations, as computational models could be affected by simplifications that might not fully capture real-world conditions, such as complex fluid interactions and material behavior [6].

First, the propeller was created using a resin 3D printer and Sunlu ABS-Like resin. Research has shown that resin printing produces thinner layer thickness and smoother surfaces compared to fused filament fabrication, which enhances accuracy and reduces surface roughness [11]. This also provides a realistic approximation of a commercial underwater propeller. Once printed, the propeller was cleaned for ten minutes in isopropyl alcohol and then cured under UV light for 15 minutes to ensure optimal hardening.

Based on the parametric CFD analysis, six guard configurations from high and low points across three lengths (3 mm, 10.5 mm, and 20 mm) on the surface plot were selected to physically test. They were printed with a fused filament 3D printer and PLA-CF (carbon fiber-infused polylactic acid filament), a material selected for its strength, durability, and water-resistant properties. These guards had the following configurations: 55d 25Θ 20L, 55d 2Θ 10.5L, 52d 8Θ 20L, 55d 10Θ 3L, 65d 2Θ 10.5L, and 65d 2Θ 20L.

Thrust was measured using a 1 kg strain gauge load cell connected to an HX711 24-bit digital load cell amplifier. The propeller guard was mounted on one side of the load cell and the load cell was mounted to an arm that held it underwater (Fig. 3). Before testing, the load cell was calibrated on a bench using calibration weights.

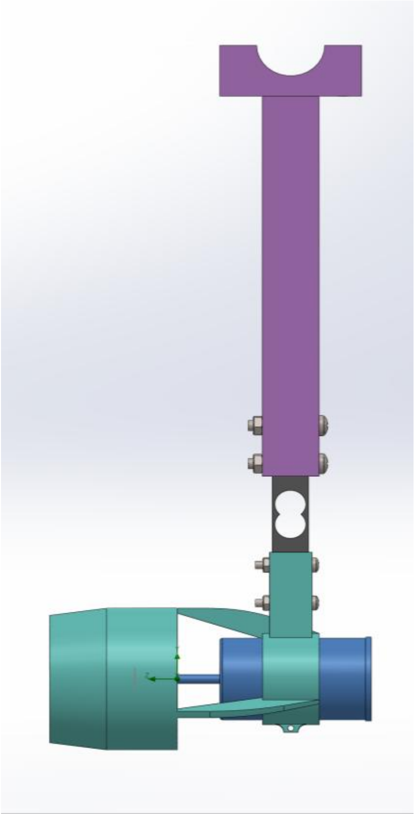


Figure 3 – Guard, motor, load cell, and mounting arm

An Aquarian H1a hydrophone connected to a Zoom AMS-22 amplifier was also mounted on the end of an arm that held it in place at a fixed distance and position from the motor. The apparatus frame was constructed out of PVC pipes and 3D-printed components that held the test components in a bathtub. The custom frame parts were modeled using SolidWorks and 3D printed using a fused filament printer and PLA-CF filament. Standard schedule 40, half-inch PVC pipe was used for the rest of the frame components. Motor power was provided by a 12-volt 7Ah F2 battery. Before each test, the voltage of the battery was checked to ensure consistency between tests. To ensure the physical test matched the CFD analysis, propeller RPM was measured underwater using a Neiko 20713A Digital Noncontact laser tachometer. The test setup is shown in Fig. 4.

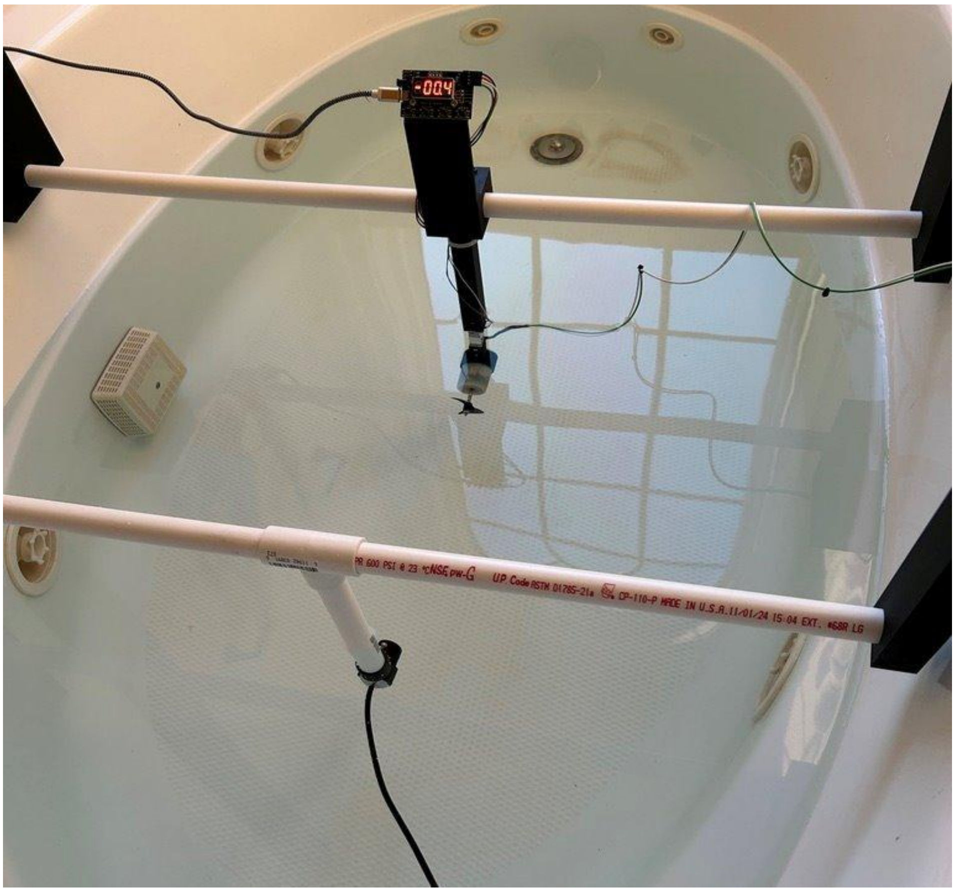


Figure 4 – Fully assembled test setup.

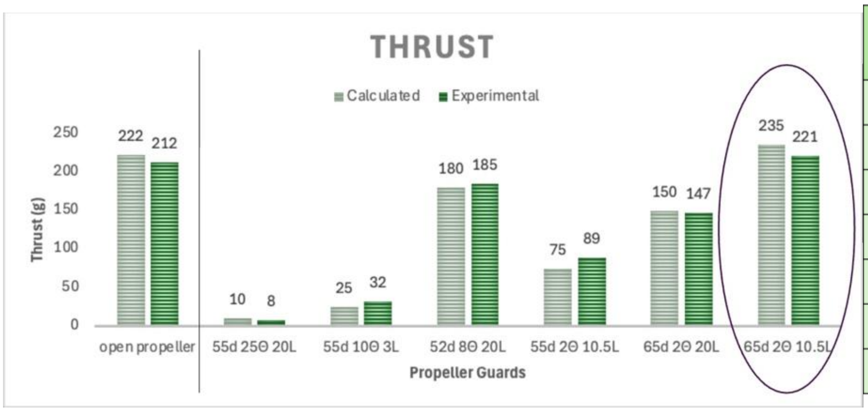
To ensure the safety of the experimental process, all potential risks associated with the project were carefully evaluated and comprehensive precautions were implemented. Hazardous materials, such as resin, isopropyl alcohol, and UV lights were used in the resin 3D printing process. A fused filament 3D printer and a soldering iron posed additional risks, including burns and fume exposure. Personal protective equipment (PPE), including gloves, long pants, long-sleeved shirts, safety glasses, closed-toed shoes, and masks, was worn during all handling of hazardous materials. UV-blocking shields and glasses protected users from exposure to curing lights. Gloves were used to remove cooled parts from the 3D printer, and soldering safety included wearing PPE and using lead-free solder. All hazardous waste, such as used resin, alcohol-soaked towels, and gloves, was disposed of according to safety regulations and taken to a local hazmat facility. These measures ensured a safe working environment throughout the design, fabrication, and testing processes.

With the testing apparatus fully assembled and all safety protocols in place, the final phase of this project involved testing the propeller guards and analyzing the results. The testing process began by measuring the performance of the open propeller as a control. This control established baseline values for thrust and noise, serving as a reference to evaluate the effects of adding a propeller guard. For each test, the motor was activated by connecting it to a battery, and thrust was measured with the force sensor and the values were displayed on the load cell. Noise levels were recorded using the hydrophone with data displayed and collected on the computer through the app Garageband. Data from these sensors were logged in real time, ensuring accurate and consistent measurements for each configuration. Once the control data were collected, each printed guard configuration underwent identical testing. Thrust and noise data were collected for each experimental guard design.

Following data collection, mp3 files of each noise recording were analyzed in the app Audacity to obtain the average decibel level. Next, the recorded thrust and noise measurements were organized into a dataset for analysis.

3. Results

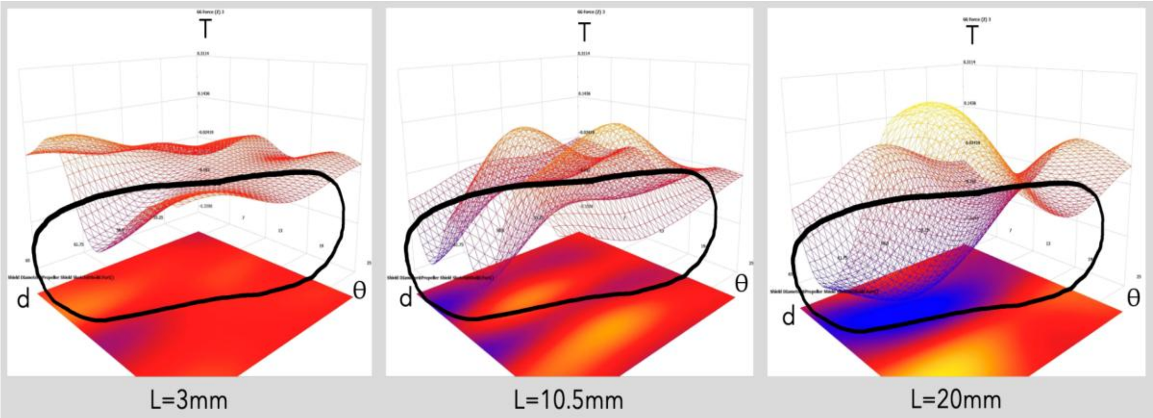
Results from each configuration were graphed and compared to the control (open propeller) and CFD results (Fig. 5). Among the experimental propeller guards tested, the 65d 2Θ 10.5L configuration demonstrated superior performance, producing 5.86% more thrust compared to the open propeller. CFD simulations and physical testing results correlated, although minor discrepancies were observed, likely due to surface imperfections inherent in the 3D-printed guards and propeller, as well as precision limitations of the testing equipment. To quantify these variations, the percent difference between CFD-calculated and physically measured thrust values was computed using the following formula: $\frac{(Measured\ Value - Calculated\ Value)}{(Calculated\ Value)} * 100$.



Propeller Guard	Variation (%)
open	4.5
55d 25Θ 20L	20
55d 10Θ 3L	28
52d 8Θ 20L	2.8
55d 2Θ 10.5L	18.7
65d 2Θ 20L	2
65d 2Θ 10.5L	6

Figure 5 – Comparison between CFD and physical testing results

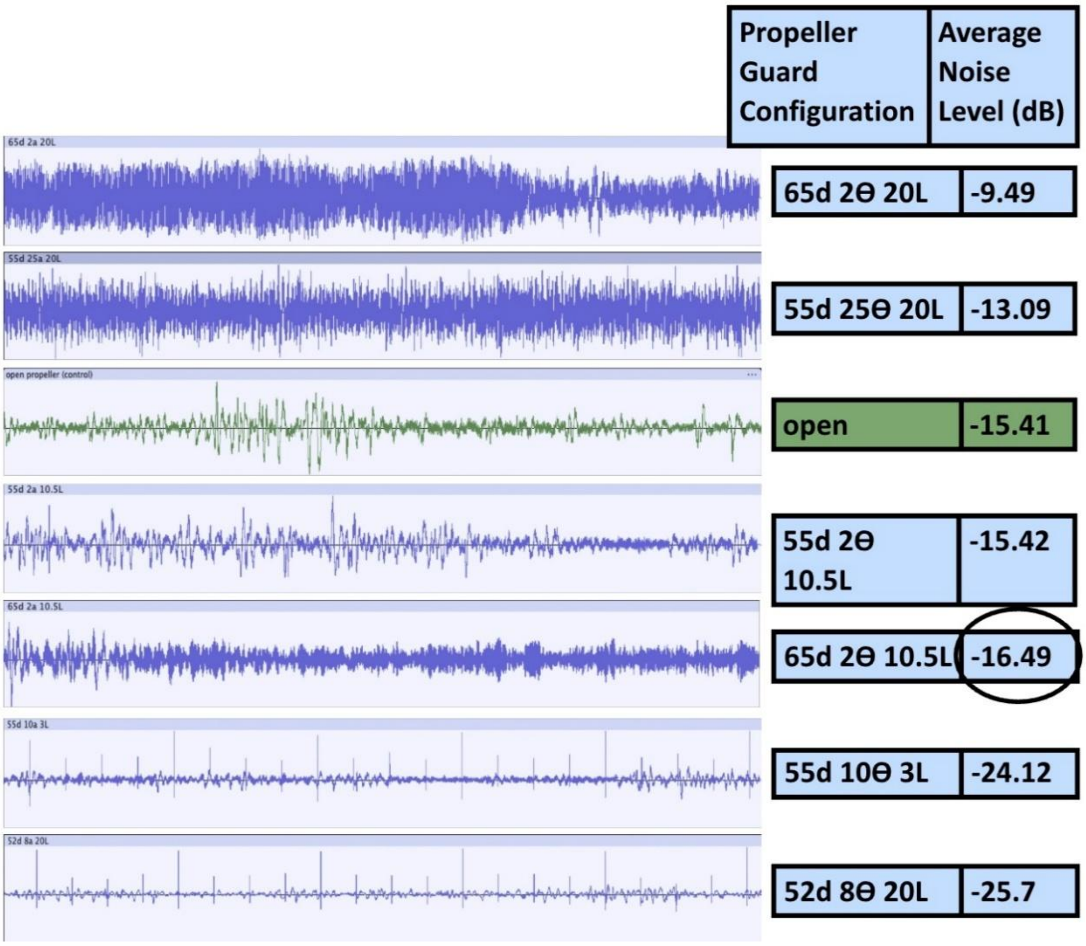
The average variation between the CFD and experimental results was 11.7%. The correlation between experimental and CFD results validates the parametric CFD analysis and indicates that a wide range of guard configurations exist that would outperform an open propeller (Fig. 6). For instance, according to the surface plot, the 60d 10Θ 20L guard configuration yields approximately 400 g of thrust, representing a substantial 44.5% improvement over the open propeller.



L=3mm L=10.5mm L=20mm

Figure 6 – Surface plot with range of guard configurations producing more thrust than the open propeller circled

A reduction in noise production was also observed with the addition of propeller guards. Four out of six guard designs produced less noise than the open propeller, with reductions ranging from 0.01 dB to 10.29 dB (Fig. 7). The 65d 2Θ 10.5L guard not only produced more thrust than the open propeller but also reduced noise by 1.08 dB. This suggests that certain configurations can optimize both propulsion efficiency and acoustic performance.



Propeller Guard Configuration	Average Noise Level (dB)
65d 2Θ 20L	-9.49
55d 25Θ 20L	-13.09
open	-15.41
55d 2Θ 10.5L	-15.42
65d 2Θ 10.5L	-16.49
55d 10Θ 3L	-24.12
52d 8Θ 20L	-25.7

Figure 7 – Noise measurement results

4. Discussion and Conclusion

Underwater vehicles rely on propeller guards to prevent damage to their propulsion systems as well as safeguard marine life and habitats. This study demonstrates that optimized propeller guard designs can yield improvements in vehicle thrust while also mitigating noise pollution. By refining key parameters such as inner diameter, incline angle, and length, certain guard configurations maintained, or even enhanced thrust compared to an open propeller. Guards generating higher thrust than the open propeller likely benefited from the Venturi effect, based on Bernoulli's principle. As water moves through a constrained space created by the guard, it accelerates, reducing pressure and increasing velocity. Additionally, optimized guards may help contain tip vortices, reducing energy losses. Conversely, guards generating lower thrust likely caused water recirculation, leading to eddy currents and turbulent flow along the guard surface which disrupted smooth propulsion. Noise reduction was observed in select guard configurations, likely due to smoother flow regulation and reduced cavitation. Given that the decibel scale is logarithmic, these reductions represent a notable decrease in noise levels.

This research addresses a significant gap in underwater vehicle propeller design, as most studies have focused on blade modifications rather than guard geometry. The findings demonstrate that propeller guard design plays a critical role in both thrust generation and noise production. As this study was conducted as a parametric analysis, it provides a framework for selecting guard configurations based on specific operational needs.

As underwater vehicle operations continue to expand, once quiet environments will be exposed to noise and others subject to a new and unfamiliar noise. Findings of this research demonstrate that underwater vehicle noise reduction can be achieved with implementation of propeller guards that also improve thrust. Given the negative effects of noise pollution, proactive measures must be taken to ensure that underwater vehicles meet the needs of researchers and industry while minimizing risks to marine environments. Future research will include evaluating propeller guard performance using additional parameters, validating these results in real-world underwater vehicle applications, and further testing to gather additional noise data.

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