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PRIME HYDRODYNAMIC PERFORMANCE AND ACOUSTIC PROFILE IN UNDERWATER VEHICLES: OPTIMIZING PROPELLER GUARDS PARAMETERS

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ABSTRACT

The development of propulsion systems for underwater vehicles, including AUVs and ROVs, that optimize thrust while minimizing noise pollution caused by humans is becoming more important because to the wide range of uses for these vehicles. Little is known about how to optimize the propeller guards of underwater vehicles, despite the fact that these components change hydrodynamics and affect thrust and noise. There is a lack of research on the effects of guarded propellers on the propulsion efficiency of underwater vehicles and a missed chance to improve environmental outcomes since much of the existing literature focuses on surface vehicles and open propeller designs. In order to find the best design, this study used parametric computational fluid dynamics (CFD) to examine 75 different propeller guard designs. A custom-built equipment was used to measure thrust generated and noise created in order to confirm these findings. Six guard configurations were chosen at random from the parametric research spanning three guard lengths. When it came to measuring thrust, the experimental findings were in agreement with the model-based expectations. Assuming the thrust findings are correct, any parametric study configuration that produces more thrust than the open propeller would be even better. Out of the six experimental guards, four showed noise reductions below the open propeller of 0.01 dB to 10.29 dB. A 5.86% increase in thrust and a 1.08 dB reduction in noise were achieved by the experimental propeller guard design with the highest efficiency. Optimizing propeller guards may improve underwater vehicle performance and reduce noise pollution, according to this research. Research into other testable criteria, improvements to the testing equipment, and assessment of guarded propellers for use in actual underwater vehicles are all potential next steps.

Underwater Vehicles, Propeller Guards, Propeller Noise, and Propeller Thrust



1. INTRODUCTION

Thanks to the development and increasing use of underwater vehicles, such as autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs), oceanographic research has grown substantially in recent years. These vehicles enable scientists to autonomously gather data from previously inaccessible parts of the ocean. Because they provide safe, efficient, and thorough insights into underwater environments, these vehicles have become crucial in different disciplines of marine research, including environmental monitoring and infrastructure inspections. Improvements in autonomous underwater vehicles' navigation, power management, and sensor capabilities have made them indispensable for deep-sea exploration. Now, these vehicles can map hydrothermal vents and collect sediment samples in dangerous deep-sea environments with pinpoint accuracy, jobs that would be too risky for human divers to do [1]. Robotic underwater vehicles (ROVs) have come a long way in terms of dynamic positioning, thanks to advancements in control algorithms like model predictive control (MPC) and linear quadratic regulator (LQR) [2]. The reliability and precision of data collected depend on such positioning systems. The growth of undersea study has been made possible by innovations and technological developments such as these. AUVs play an important role in marine geoscience by facilitating the study of seabed processes and geological mapping, both of which are essential for comprehending oceanic and tectonic activity [3]. Additionally, Wynn et al. highlighted the significance of benthic habitat mapping, which involves creating maps of particular regions of the ocean bottom linked to vulnerable plant and animal species. The combination of sonar-equipped AUVs with high-resolution imagery to create comprehensive maps of benthic ecosystems was also addressed by Purser et al., who used this method to help in habitat evaluations and biodiversity monitoring [4]. Assessment of geological features, identification of mineral deposits, and monitoring of biological populations within these benthic environments are all tasks that modern AUVs equipped with high-resolution imagery and sonar can do. Improvements in underwater vehicle technology have brought attention to their crucial role in furthering oceanographic research. Underwater vehicles cannot function without propeller guards, which prevent harm to humans and the environment from coming into direct contact with the propeller blades as they spin. Optimal propeller guard design is an area where a lot of unanswered questions persist, despite the fact that propeller optimization is not new. Open propellers are popular because of their low water resistance, however they put marine life at risk and are easily damaged by impacts [5]. According to research by Chapple and Renilson, a boat's propulsion efficiency drops by about 30% when using ringed propeller guards instead than open propellers. Lee explored the effects of several guard designs on thrust efficiency and water resistance using computational fluid dynamics (CFD) research. The designs varied in form, size, and distance from the propeller [6]. While bigger and more protective shields do enhance coverage, the research also found that they reduce overall propulsion efficiency by about 20% due to the significant drag they introduce. As an example of the trade-off between guard size and thrust efficiency, consider how circular and octagonal guards provide good safety coverage but add drag. The research results highlight the need of designing propeller guards in a way that maximizes performance while yet providing adequate protection. Lee pointed out that more empirical testing is necessary to confirm the results in real-world scenarios, as this work relied entirely on CFD analysis [6]. Additionally, Lee brought out the fact that several design aspects have not been investigated in detail. At low RPMs, thrust efficiency may rise by as much as 24% owing to reduced flow separation inside the nozzle, according to a study by Koh et al. [7] that compared the thrust produced by open and ducted (guarded) propellers on fishing boats. But they discovered that efficiency diminishes at speeds beyond 580 RPM, therefore ducted propellers are best used at modest speeds. In order to increase the thrust efficiency of underwater vehicles that run at high RPMs, these studies suggest that improved designs for propeller guards are necessary. The study gap in ideal propeller guard designs for underwater vehicles is further



highlighted by these studies, which were conducted with surface water vehicles like boats but are nonetheless very enlightening. Underwater noise pollution interferes with navigation, communication, and mating activities in marine life. Prolonged exposure to noise causes physical stress and, by confusing animals, may change their breeding grounds and migratory patterns. Environmentalists are worried about the effects of human-caused noise pollution on ecosystems due to activities including shipping, operating underwater vehicles, and using sonar [8]. A lot of the noise that you hear when you go underwater is really coming from the propellers and the cavitations and vortices in their sheets. Sheet cavitation is characterized by the formation and collapse of vapor bubbles caused by pressure fluctuations close to the surface of the blade, and it is audibly noticeable. Both the reduction in propulsion efficiency and the generation of low-frequency noise, which may disturb marine organisms, are consequences of sheet cavitation [9]. The pressure differential between the blades' top and bottom surfaces causes water to swirl around the tip, creating a vortex. A source of noise is the bursting of vapor bubbles and the churning of water. Propeller noise may be amplified or reduced by integrating guards around them; however, the impact on sheet cavitation and tip vortex noise is not well studied. Kaewkhiauw used computational fluid dynamics (CFD) to explore the impact of surface water propeller guards on hydrodynamic performance of long-tail boats. The guards were shown to affect thrust, torque, and wake turbulence. The results showed that guards do a good job of protecting the vessel, but they also make more noise because they increase drag and disrupt the wake flow, which causes more pressure fluctuations and water movement [10]. Despite the study's narrow emphasis on long-tail boats' propeller guards for surface water, it stresses the need of designing undersea vehicle guards to reduce hydrodynamic disturbances and, by extension, noise. There needs to be more targeted study on underwater propeller guard designs that minimize noise, as there is a lack of studies on guard-related noise. Underwater vehicles have been crucial in oceanographic research, with recent developments describing how they have improved the safety and efficiency of deep-sea exploration and data collecting. There is a lot of room for development in these vehicles when it comes to their efficiency and noise levels, and one promising area is propeller technology.

security plan. Research shows that guards protect marine life and ecosystems from harm and prevent propeller damage, although they reduce thrust efficiency and make more noise. A decrease in propulsion may occur if guards increase drag and alter the water flow around the propellers. Marine ecosystems may be negatively impacted by the noise pollution they produce, which can be amplified by wake turbulence. While there are guard designs that can help reduce these impacts in certain cases, much of the study has been on surface water vehicles, thus there hasn't been much investigation into configurations that work well for underwater vehicles. This research aimed to fill that void by exploring the effects on thrust and noise generation in underwater vehicles of changes in three particular propeller guard parameters—inner diameter (d), angle of inclination (Θ), and guard length (L)—. Finding combinations that maximize thrust while minimizing noise output was the goal of this research, which included a parametric computational fluid dynamics (CFD) analysis and experimental validation. More sustainable marine exploration and research may be achieved with the help of these results, which can encourage the creation of underwater vehicles that are both more efficient and less harmful to the environment.

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 10 Θ 15L.

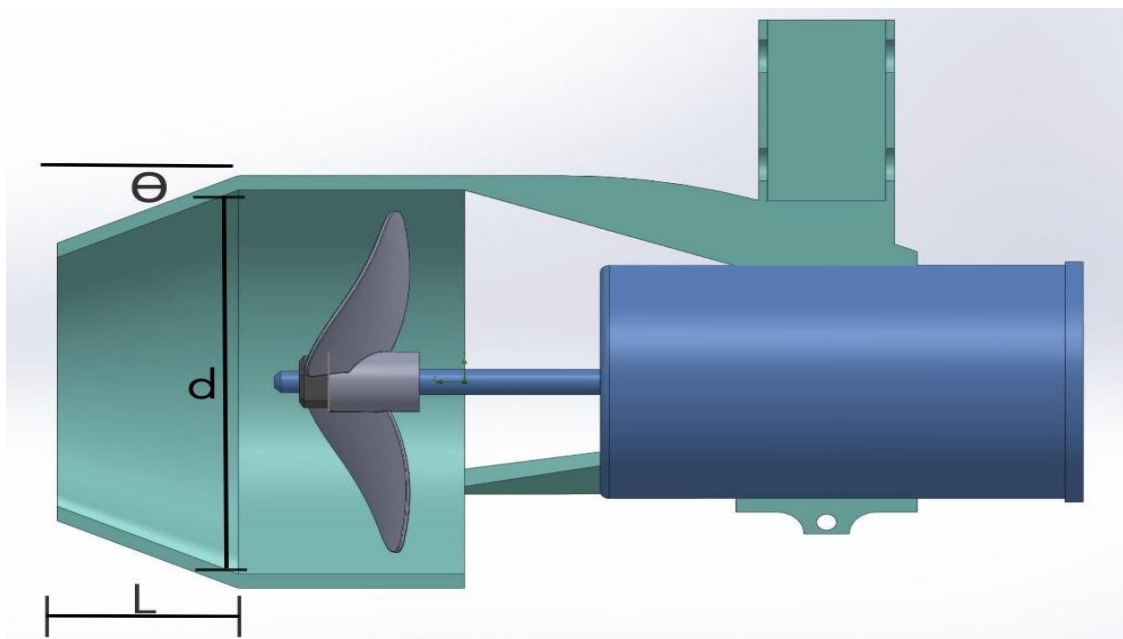


Figure 1 – Parameters studied in the propeller guard

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.

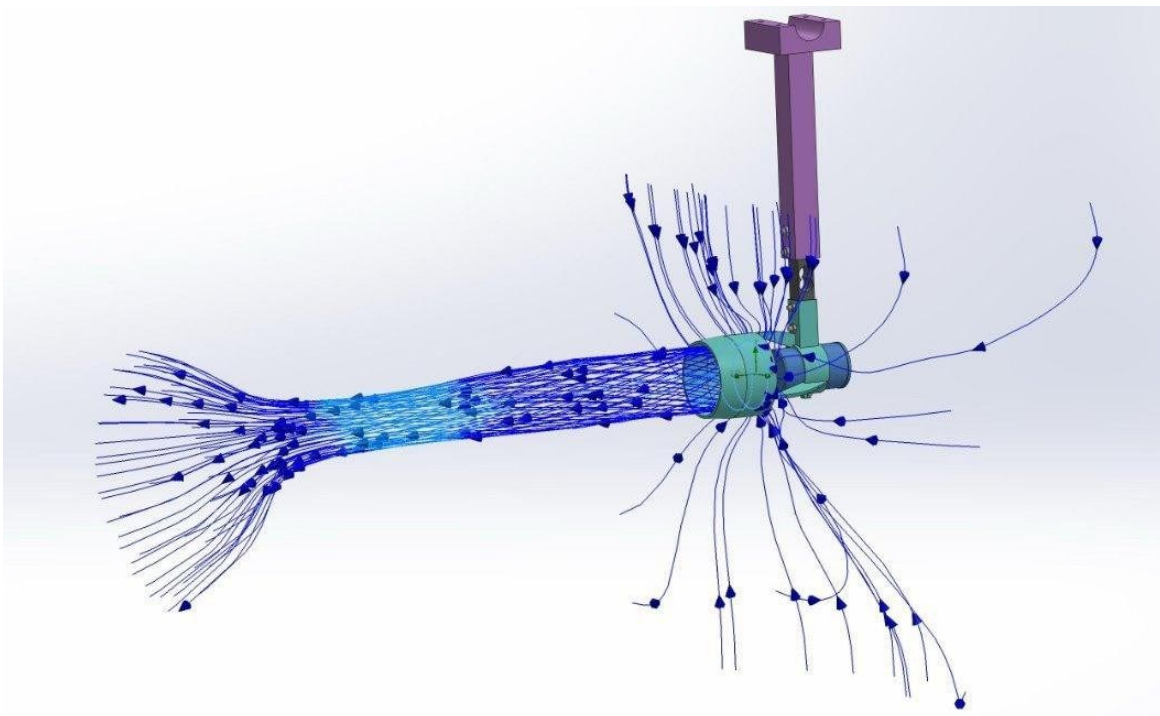


Figure 2 – CFD analysis example of 65d 2θ 10.5L guard

Building a physical testing equipment and producing components to confirm the computational findings followed the completion of the propulsion assembly model and parametric CFD analysis.

Lee rightly points out that computational fluid dynamics (CFD) models may be impacted by simplifications that fail to adequately represent real-world situations, including complicated fluid interactions and material behavior [6]. Consequently, physical testing is crucial for validating the correctness of CFD simulations.

An ABS-like resin from Sunlu was first used to construct the propeller in a resin 3D printer. When compared to fused filament production, resin printing results in thinner layers and smoother surfaces, which improves accuracy and decreases surface roughness [11]. Also, this gives you a good idea of what a commercial underwater propeller looks like. After printing, the propeller was soaked in isopropyl alcohol for 10 minutes for cleaning, and then cured for 15 minutes under UV light for the best possible hardness. The parametric CFD study informed the selection of six guard designs to be physically tested, spanning three lengths on the surface plot (3 mm, 10.5 mm, and 20 mm) and high and low points. its strength, longevity, and water resistance were factors in the material selection process that led to its printing using PLA-CF, a fused filament 3D printer filament. The configurations of these guards were as follows: 55d 25 Θ 20L, 55d 2 Θ 10.5L, 52d 8 Θ 20L, 55d 10 Θ 3L, 65d 2 Θ 10.5L, and 65d 2 Θ 20L.

An HX711 24-bit digital load cell amplifier was used to measure thrust using a 1 kg strain gauge load cell. Attached to the load cell was an arm that supported it underwater, and the propeller guard was fastened to the other side (Fig. 3). Calibration weights were used to set the load cell on a bench prior to testing.

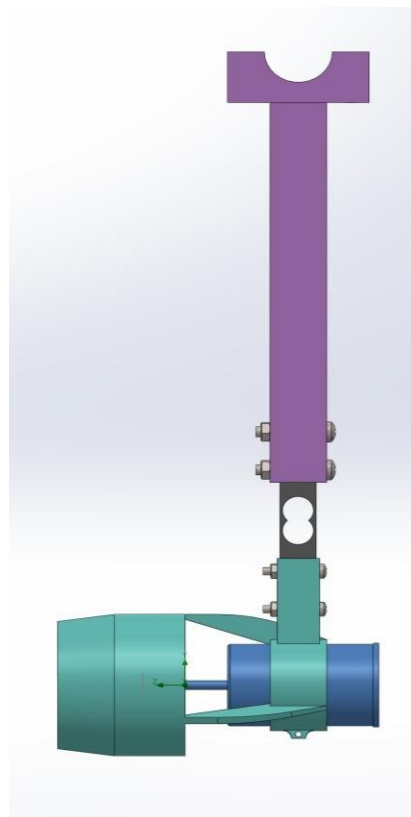


Figure 3 – Guard, motor, load cell, and mounting arm

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.

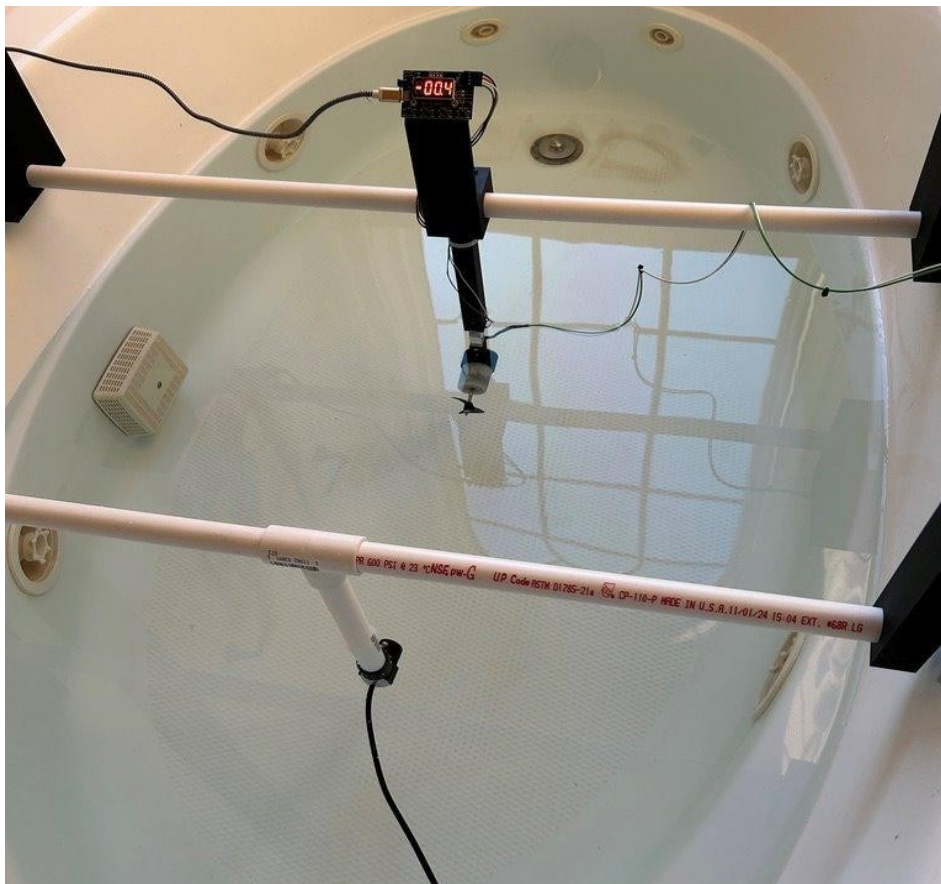


Figure 4 – Fully assembled test setup.

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 20 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:

$$\frac{(\text{Measured Value} - \text{Calculated Value})}{(\text{Calculated Value})} * 100.$$

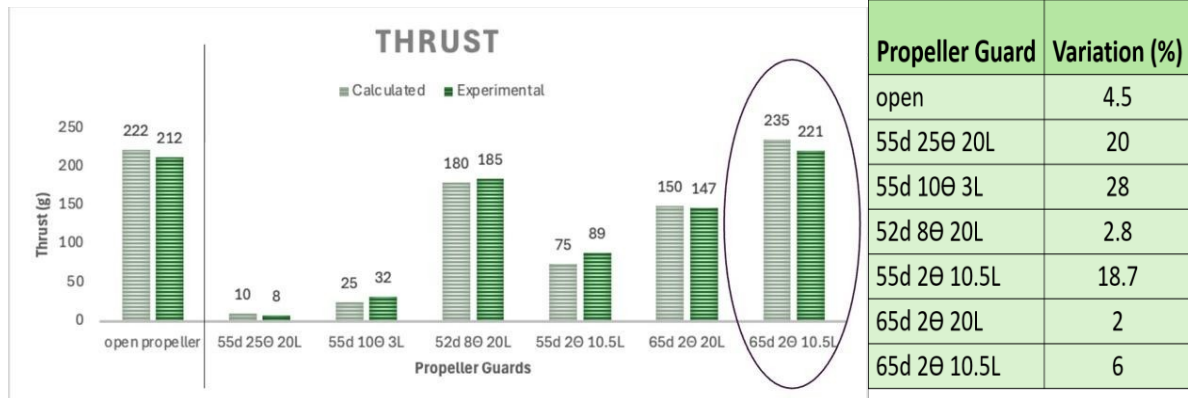


Figure 5 – Comparison between CFD and physical testing results

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 10Ø 20L guard configuration yields approximately 400 g of thrust, representing a substantial 44.5% improvement over the open propeller.

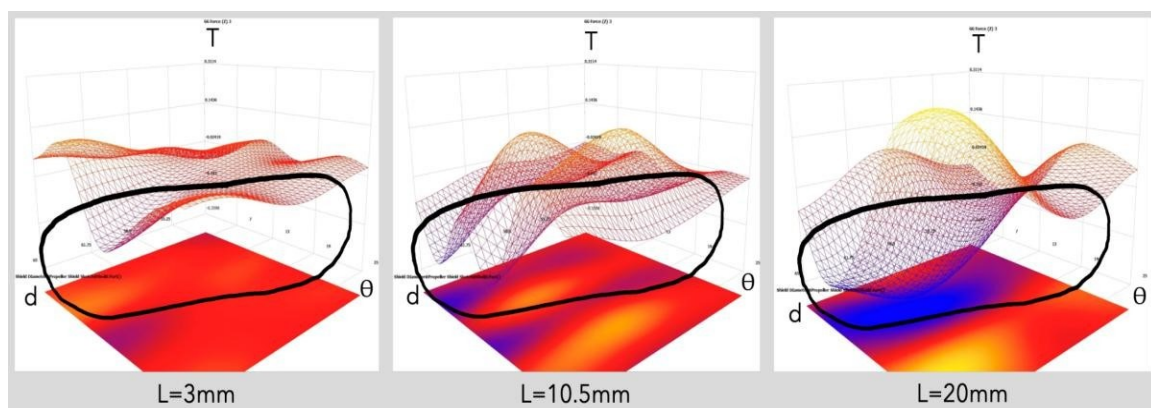


Figure 6 – Surface plot with range of guard configurations producing more thrust than the open propeller circled

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 2Ø 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.

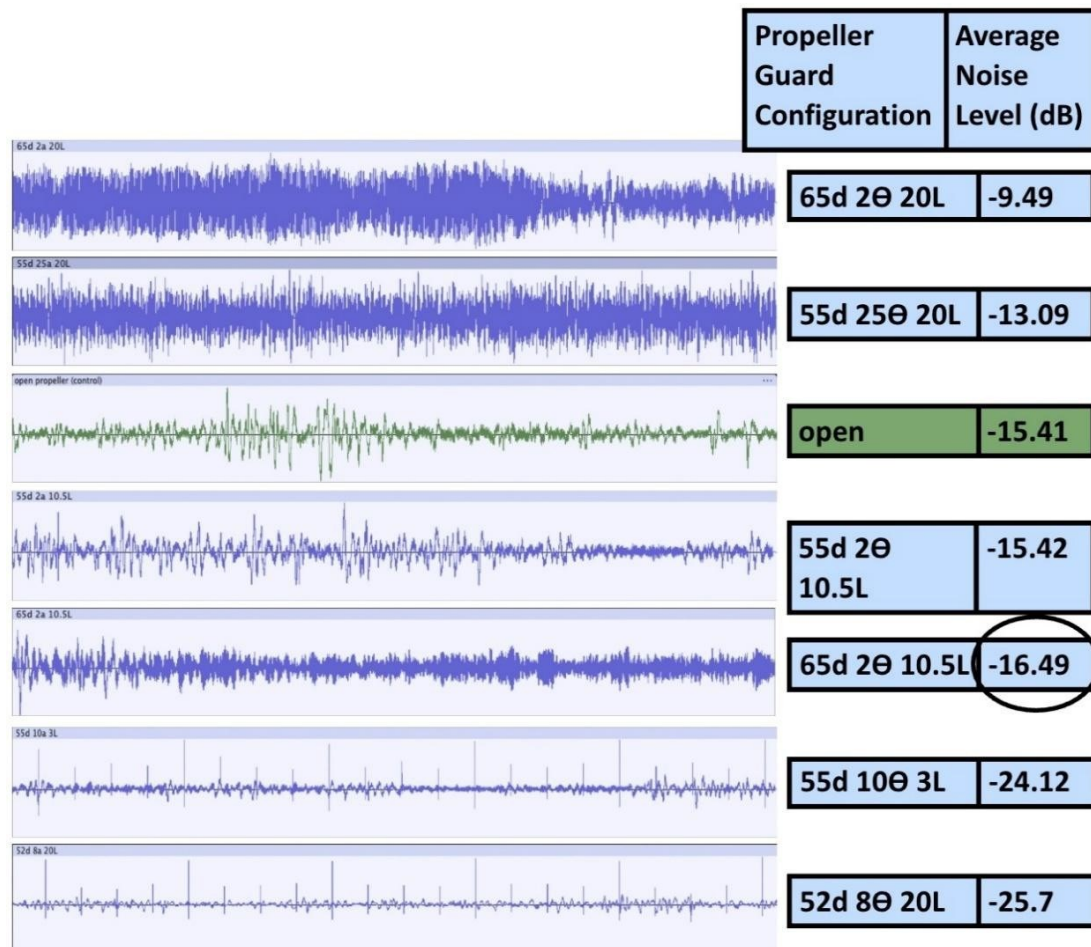


Figure 7 – Noise measurement results

4. Discussion and Conclusion

Propeller guards are an essential component of underwater vehicles for protecting marine life and their habitats from harm and ensuring the continued operation of the propulsion systems. This research shows that by optimizing the designs of propeller guards, vehicle thrust may be improved and noise pollution can be reduced. Modifying critical dimensions like inner diameter, inclination angle, and length allowed for the preservation or improvement of thrust in comparison to an open propeller in certain guard configurations. It is probable that the Venturi effect helped the guards whose thrust was more than that of the open propeller, according to Bernoulli's principle. Water experiences a decrease in pressure and an increase in velocity as it speeds past the guard's restricted region. Furthermore, improved guards have the potential to control tip vortices, which in turn decreases energy losses. On the flip side, guards that produced less thrust probably recirculated water, which in turn induced eddy currents and turbulent flow over the guard surface, interfering with the smooth propulsion. Select guard showed a decrease in noise.



designs, most likely as a result of less cavitation and more efficient flow management. These decreases signify a significant quieting of the environment, since the decibel scale is logarithmic. Since most studies have concentrated on changing the blade geometry instead of the guard geometry, this study fills a big need in the design of propellers for underwater vehicles. Both thrust generation and noise output are significantly impacted by the design of the propeller guard, according to the results. Because it was a parametric analysis, this research lays down the groundwork for choosing guard designs according to operational requirements. There will be new and unusual noises in formerly peaceful areas as the use of underwater vehicles grows. This study's results show that underwater vehicles may reduce their noise emissions by installing propeller guards, which simultaneously increase thrust. Since noise pollution has such a harmful impact on marine ecosystems, we need to be proactive in developing underwater vehicles that can satisfy the demands of scientists and businesses without endangering them. Further testing to collect further noise data, confirming these findings in real-world underwater vehicle applications, and assessing propeller guard efficacy using other parameters are all parts of the future plan for study.

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