Vertical Fin Interaction

Responsible Innovation of Deep-Sea Vehicles

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By
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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

The ocean is the final frontier that mankind has yet to truly explore with roughly 90% of the deep sea remaining unexplored (Helmenstine, 2019). Some argue that underwater exploration is more challenging and dangerous than space exploration but leaving the atmosphere and entering outer space may sound more exciting but reaching the deepest depths of our oceans could be even more intriguing (Etzioni, 2022). Underwater robotics will be crucial in this mission to explore the ocean and unlock its secrets. Thus, studying underwater creatures, like fish, will provide key insights into how they are able to do so every day (Berlinger, 2021).

Fish typically swim in schools to achieve benefits such as avoidance of predators, better reproductive opportunities, higher foraging efficiency, and better hydrodynamic efficiency (Weihs, 1973). Vertical fin interaction is studying vertical fish schooling at different distances between the fish fins and its benefits as opposed to horizontal schooling. This is done by running experiments with replica trout caudal fins and comparing the results to computational fluid dynamics (CFD) simulations. By creating a variety of vertically spaced fins and placing them in a water channel replicates how trout fish swim at a variety of different conditions such as speed, frequency, and Reynolds number. In theory, this should be an approximate match to the CFD simulations that were created by biological data. If not, then more experimentation is done to find the disconnect between the simulations and the previous experimentation.

Additionally, underwater exploration must be done safely and responsibly to ensure that everyone is protected. Currently, the main use of underwater vehicles is utilized by militaries, in the form of submarines (Venancio, 2023). However, times are changing, similarly to how space exploration went from just government organizations like NASA or JAXA to now having numerous companies like SpaceX or Blue Origin creating a space travel industry. Ocean Gate is doing the same thing with underwater exploration by creating underwater tourism (Asady, 2023). However, tragedy stuck first with underwater exploration but why? Are there less safety regulations governing human underwater exploration? Who or what organizations are making these rules and regulations in this new age of exploration? Who is in charge of enforcing these rules so that accidents can be prevented? I plan to answer these questions and more by performing a case study of the Titan Submarine accident of 2023. This is done to understand how scientists and entrepreneurs can be responsible innovators and so that tragedy does not strike twice.

Responsible innovation of deep-sea vehicles must be at the forefront of the creation and maturation of underwater vehicles, such as fish schooling robots. These topics of responsible innovation and vertical fin interaction are closely related and intertwined similarly to engineering ethics and engineering to ensure that all new ideas are created with everyone’s safety in mind. By researching both in sync, I will be able to provide a more complete and well-rounded perspective on underwater exploration. This will also include a case study on Ocean Gate’s Titan submarine accident and how that tragedy could have been prevented.

Vertical Fin Interaction

Fish school for a plethora of benefits including, rate of predation, social factors, and hydrodynamic effects (Weihs, 1973). Schooling can occur in planes: horizontal, vertical, or a combination of both. Horizontal fish schooling has been studied more extensively than the latter thus I chose to focus my research project on vertical fish school. Fin interaction is the effects that the vertically spaced fins have on each other and the forces. Understanding these benefits and effects will be crucial in increasing performance and efficiency in underwater robotics development (Berlinger, 2021).

Dr. Yu Pan, a previous researcher at Professor Haibo Dong's CFD lab, wrote his dissertation on CFD simulations of fish schooling. Firstly, Dr. Yu Pan completed CFD simulations for vertical schooling, which provided a basis for my experimental study into fish schooling. He modeled in-phase tip-to-tip vertical fish schooling meaning that the fins were directly on top of one another and move in synchronous motion as show in Figure 1. These simulations showed that in-phase tip-to-tip fish schooling at different distances apart (H) showed that thrust, lift, and power decrease with increasing separation (Pan, 2022).

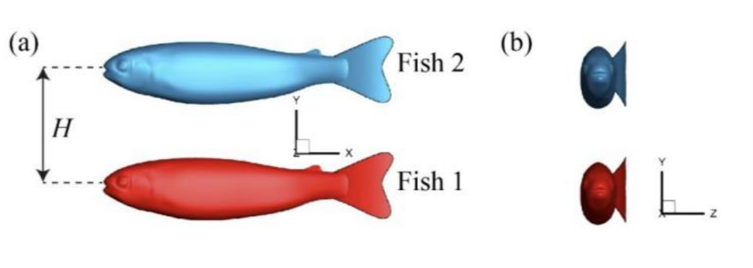

Figure 1: Schematic of a trout school arranged in the tip-to-tip configuration from Dr. Yu Pan

To recreate these simulations in an experiment, fish like fins had to be created so that they were similar to the simulations and able to fit in the water channel. Following the dimensions in Figure 2, fins were modeled to have a chord length (c) of 3 inches and bases of 2.7 and 3.3 inches. To replicate the motion of the simulations, the experiment would involve pitching (θ) and heaving (A_y) the fins in the water channel with flow speed (U'_∞). Lastly, the fins would be spaced apart via a distance (H') (Pan, 2022).

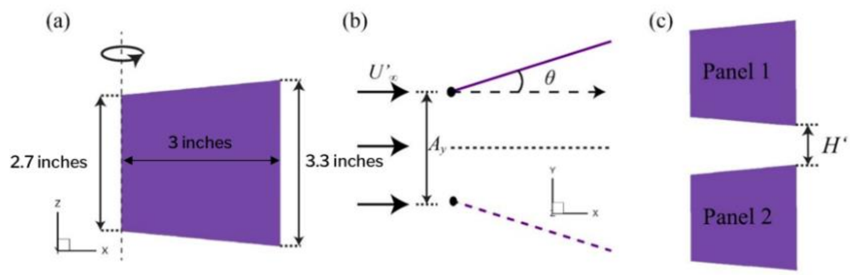

Figure 2: a) Geometry of trapezoidal panel model, (b) top view of the pitching-heaving motion and definitions of heaving motion and pitching motion, and (c) schematic of panels in a tip-to-tip configuration from Dr. Yu Pan

There are also several simulation parameters that must be calculated to be either approximately the same of have the ratios to each other that were prescribed. The main difference between the simulations and the experiment is the Reynolds number. The simulations had a Re = 600 while the experimental Re = 30,000, this is because it would be too challenging to implement the corresponding speed (U) and frequency (f) of the lower Reynolds number in the water channel. At Re = 30,000, the corresponding parameters are: f = 3.68 Hz, U = 394 $\frac{mm}{s}$, $\theta_0 = 15°$, $A_y = 0.4c = 1.2\ inches$, A = 0.05 m, and Strouhal number (St) = 0.467. These represented chosen and calculated variables utilizing these equations: $Re = \frac{u*c}{8.9*10^{-7}\frac{m^2}{s}}$, $St = \frac{f*A}{u}$, $y(t) = \frac{A_y}{2}\cos(2\pi t + \varphi)$, $\theta(t) = \theta_0 \sin(2\pi t + \varphi)$.

The fins were 3D printed and epoxied onto 12-inch shafts then were sanded and painted until smooth. Six different fin models (12 in total) were created to match different H' distances apart, shown in **Error! Reference source not found.**. They were then mounted into the water channel, with one being in the air and the other immersed in the water, shown in Figure 4. The fin in the air measures the inertial force and is subtracted from the fin in the water. The fins were designed to have a small shaft diameter to chord length ratio to be less susceptible to surface effects (King, 2018). They are trapezoidal because of the similarities between the shape and a trout's caudal fin (Pan, 2022).

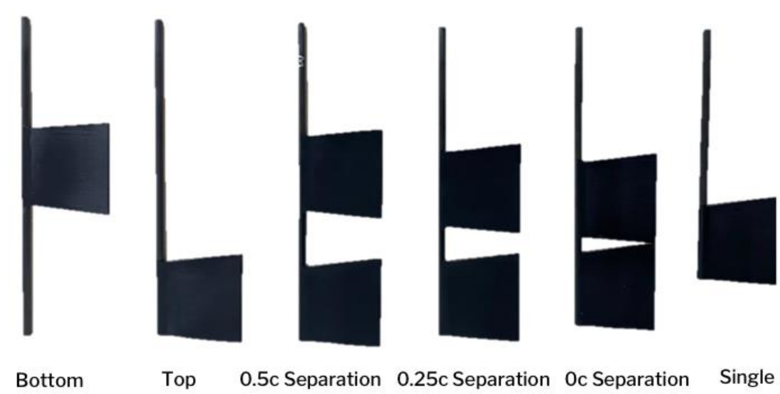

Figure 3: All the fins with their distances apart (H'). Their separation ranges from 0 to 1.5 inches.

Figure 4: 0c separation fin in the water and the air.

Going forward, I plan to take and present data gathered from the force sensors attached to the fins in the water channel as well as taking PIV. This data will include thrust, lift, power, and efficiency measurements. I aim to make meaningful connections between the simulations and the experiment including showing that thrust, lift, and power decrease with increasing separation. I aim to show that one fin is less efficient than two fins, at any separable distance.

Responsible Innovation of Deep-Sea Vehicles

Underwater exploration may be more than intriguing to tourists, it could provide solutions to our world's energy, food, or environmental problems. Finding solutions in our oceans is far more likely than in our solar system which is why underwater vehicles are experiencing a "surge" (Etzioni, 2022).

With the advancement of underwater exploration and robotics, more consideration needs to be given to the rules and regulations that govern safety (Asady, 2023). What rules and regulations currently exist for deep sea vehicles? Who created and enforces the rules and regulations to ensure compliance? These research questions will be analyzed through a case study of OneGate's Titan Submarine tragedy in coordination with a complete explanation of what could have been done to prevent this.

Deep sea human exploration has been active since the 1500's when Ferdinand Magellan unsuccessfully attempted to measure the depth of the Pacific Ocean. When in 2012, James Cameron completed the first solo dive to the bottom of the Challenger Deep, it had been previously considered an impossible feat. More modern deep-sea exploration utilizes remotely operated vehicles (ROVs) or autonomous underwater vehicles (AUVs) (Helmenstine, 2019).

There is a severe lack of rules and regulations regarding deep sea exploration, there is even a well-known loophole under the United Nations Convention on the Law of the Sea (UNCLOS). Under UNCLOS, a submersible may be considered a ship or vessel, equipment, or device. By exploiting this ambiguity, stakeholders have been deploying underwater vehicles (UVs) without any regulatory constraints. The International Maritime Organization (IMO) has developed regulatory framework for maritime autonomous surface ships, but neglects UVs. Even the United States Government does not require inspections for submersibles with six or fewer passengers. Also, different countries rules for UVs can be avoided as well by launching in different nationalities (one where the rules and regulations are lacking) waters, a different nationalities ship, or by considering the UV as cargo until deployed (Venancio, 2023).

Collected evidence includes professional opinions of the safety standards subcommittee membership detailing that more safety standards need to be established for human occupied underwater vehicles (Safety standards for human occupied vehicles, 2009). As well as testimonies from the hearing before the subcommittee on investigations and oversight committee on science, space, and technology for the house of representatives stating that oceanic exploration is critical for the United States and how to best oversee this program (GovInfo, 2019). This evidence will be interpreted as defining those rules and regulations and who is making these and enforcing these rules and regulations to ensure compliance.

Lastly, my evidence will include a case study of the Titan submarine detailing the lack of safety regulations and common rules that were not followed. This includes how former passengers of the Titan had spoken about safety concerns including loss of communication with the host ship and how the CEO, Stockton Rush, felt that "… At some point safety just is pure waste …" (Shah, 2023). Industry experts were also concerned for the design choices made when the submarine was in development but nothing was changed. A former Ocean Gate director of marine operations and experienced submarine pilot, David Lochridge, was also fired for raising safety concerns, which were ignored, to executive management (Treisman, 2023). This evidence will be analyzed by detailing all of the safety concerns and how they were ignored by Ocean Gate.

Responsible innovation of deep-sea vehicles is crucial going forward as the industry turns away from militarization and toward commercialization. With all of the legal loopholes that are well known, it is no wonder how the Titan Submarine was able to be deployed. By analyzing governmental, professional experts, and personal experience testimonials, I will show that this tragedy could have been prevented as well as showing that future tragedies can be prevented as well.

Conclusion

The responsible innovation of deep-sea vehicles is crucial as we enter into a new era of underwater exploration accessibility. Ensuring that all parties are protected and as safe as possible will be the key with maturation of the underwater vehicles a robotics. Without advancement and maintained of these rules and regulations, more tragedies like the Titan Submarine will happen thus deterring further underwater tourism and more importantly, exploration. The results of my research paper will show that vertical fin interaction in relation to fish schooling yields hydrodynamic benefits and that their varying vertical separation plays a factor in thrust, lift, power, and efficiency of the fins. This paper will also show that responsible innovation of deep-sea vehicles is critical going forward on this new frontier not only for tourism but for scientific exploration of the deepest depths of our oceans. Together this research will provide a way forward for ethical and safe underwater robotics maturation.

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