Improving the Hydrodynamic Performances of an Underwater Snake Robot Using Computational Fluid Dynamics

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***Abstract*--The ocean contains biological resources, energy, and mineral resources. Therefore, underwater vehicles could extensively be used for inspections and installation of machinery in the underwater environment. Bio-inspired underwater snake robots are a key research area in underwater robotics. The ability to reach narrow spaces and their capability of being used as manipulators are significant attributes of snake robots. However, their limitations, such as slow speeds and low efficiency, hinder their widespread application. To overcome these limitations, a range of caudal fins are introduced to underwater snake robots. These fin geometries were selected based on the locomotion of fish. This study investigates truncate, rounded, forked and heterocercal fin geometries. Computational fluid dynamics (CFD) techniques are used to identify the most suitable types of caudal fin shapes that can maximize the thrust and neutralize the lift. According to the results, rounded caudal fin geometry was concluded to be the best candidate among the other proposed fin geometries for underwater snake robots.**

Keywords--Underwater snake robots, Caudal fin, anguilliform, computational fluid dynamics

I. INTRODUCTION

Considering the evolution of robotics there has been trend of using bio-inspired robot than traditional robots. The inspiration for the underwater snake robot comes from snakes that are living underwater such as ocean snake, eel etc. The ocean contains biological resources, energy, and mineral resources that are significant to the survival of the human race. Due to that, the demand for the underwater vehicles is increased since they can be used for installation of the machines [1] and inspections of underwater. Currently, remotely operated underwater vehicles (RUV) and autonomous underwater vehicles (AUV) are used for these purposes. Despite their common use in RUVs and AUVs, rotary propellers are known to exhibit limitations in terms of efficiency. As a solution researchers are trying to incorporate the field of biomimetic into RUV and AUV. Initially, researchers used fish-like robots. Fishlike robots can swim more efficiently compared to conventional underwater robots. Therefore, the study of bio-inspired robotics remains a critical area of research [1].

Snake Robots can be identified as an emerging field in underwater robotics. Underwater snake robots are much more significant, because of the narrow and flexible body that can access narrow spaces that cannot be reached by humans and conventional robots.

In 1972 Prof. Hirose developed the world's first snake robot at the Tokyo Institute of Technology.[2] In 1999 Swiss federal technology made amphiBot. This was not only made for swimming, but it also had the ability to walk on the beach.[3] NTNU has developed an underwater snake robot called Mamba. In 2017 the company called Eelume AS in Trondheim, Norway, and NTNU developed a robot called Eelume. This was introduced for the oil and gas industry because of the demand for subsea inspections, maintenance. For Eelume propellers were used to control the motion. [4]

At present, the main issue is how to increase efficiency and speed for underwater snake robots. Many researchers are trying to find out methods for increasing speed and efficiency. Such as fluid parameters study, motion pattern, tail fin, etc. Considering the underwater snake robot with different geometrical shapes of caudal fin not yet been discussed. This paper proposed four different geometrical shapes for underwater snake robot motion to find the performance of the snake robot.

Unlike land snakes, sea snakes have a tall body which enables them to swim effectively. On the other hand, sea snakes have soft fins (eel-like) for increasing the efficiency of underwater locomotion. Sea snakes have tall bodies, short oarlike tails, valvular nostrils on top of the snout, and elongated lungs that extend the entire length of the body. Also, when swimming, a keel is formed along part of the belly for increasing the surface area while aiding propulsion. Generally, sea snakes use lateral undulation and eel-like motion for maneuvering.

F. Aubret and R. Shine (2006) [5]experimented with sea snakes and found out that small paddle has the highest swimming performance and lowest crawling performance. The experiment was done with real sea snakes that have different types of paddles. This was conducted in two different experiments for crawling and swimming.

This experiment was done in three conditions such as no paddle, small paddle, and large paddle. The small and large paddle differed from the percentage of tail length covered. This paper showed that snakes with small paddles have an increased speed 25% higher than the snakes with no or large paddles (Fig 1).

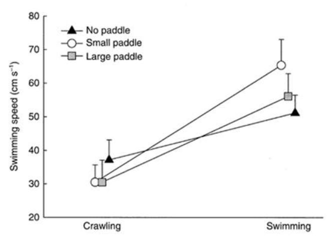

Fig. 1. Swimming speed results for crawling and swimming with a large paddle, small paddle, and no paddle. [5]

Their study was limited to the size of the paddles and it did not consider the geometry of the paddles. Also, the experiment is subjected to produce different results with any of the conditions the snake faced. For example, F. Aubret and R. Shine used sticks to move snakes, therefore an impulsive force could occur.

In 2019, Huang et al[7] published a study of an underwater snake robot consisting eight modules. The flexible tail was connected to the last module. The Authors experimented with different gait patterns with forked and un-forked caudal fins. Considered gait patterns were Sinusoidal, single tail swing, and Anguilliform.

The experiment was set up as a robot that could move naturally in the water tunnel. [7] The apparatus only generated a forward limit for the robot. Therefore using the apparatus, forward thrust was measured. Swimming gait, maximum amplitude (A), Angular frequency, and tail shape were used as controllable parameters (Fig 02, Fig 03, and Fig 04).

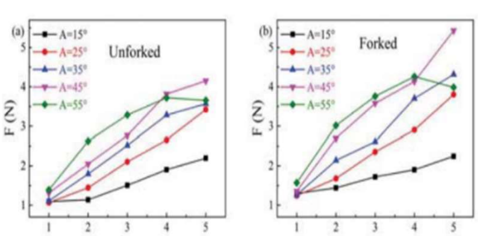

Fig. 2. Effect of angular frequency on thrust force of different amplitudes under sinusoidal gait [7].

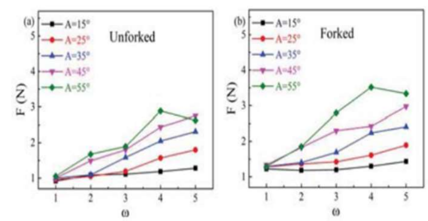

Fig. 3. Effect of angular frequency on thrust force of different amplitudes under angular gait [7].

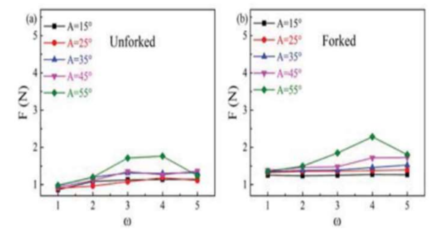

Fig. 4. Effect of angular frequency (ω) on the output thrust of different maximum amplitude (A) under STS gait. [7].

The results of the experiment showed that the frequency, amplitude, and tail shape have a significant effect on generating forward thrust. Sinusoidal gait pattern with forked tail fin has the highest thrust force for a particular amplitude (Figure 02). The geometry of the caudal fin has an effect on the forward thrust force. This research was limited to forked and un-forked geometry. The research could be implemented with different geometrical shapes of the caudal fin.[7]

The research contains three objectives.

A. Identify the different locomotion methods and hydrodynamics of snake robots for thrust generation

B. Investigate different types of caudal fin geometries used for underwater locomotion by analyzing fish

C. Investigate and simulate using CFD to find the hydrodynamic efficiency of snake robot with different caudal fin geometries.

II METHODOLOGY

ANSYS Fluent CFD software was used to perform the calculations. Fluent uses the finite volume method to discretize and solve the Navier-Stokes equation, mass conservation, and energy equation. Generalized, conservative differential form of the continuity equation.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \quad (1)$$

In equation 1 from[5], the left term is the change, the second term is the convective term resolving mass flow across boundaries, and the right side term source term that is under the control of the user.

Conservation of momentum equation used in fluent can be written as,

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \quad (2)$$

in equation 2, from[5], p is the static pressure, $\rho \vec{g}$ is the gravitational body force, $\vec{F}$ is the sum of external body forces, and $\bar{\bar{\tau}}$ is the stress tensor. It is defined as,

$$\bar{\bar{\tau}} = \mu[(\nabla\vec{v} + \nabla\vec{v}^{T}) - \frac{2}{3}\nabla \cdot \vec{v}I] \quad (3)$$

First-term of (3) is the rate of increase of property Φ within the differential element, the second term is the net outflow rate of Φ from the element, the third term of the equation is the increase rate in Φ because of diffusion r. Consider the fourth term it represents the rate of increase due to sources. Equation (3) can be combined for an arbitrary control volume and discretized spatially and then can get[5],

$$\frac{\partial(\rho\phi)}{\partial t}V + \sum_{f}^{N_{faces}}(\rho_f \vec{v_f}\phi_f . \vec{A_f}) = \sum_{f}^{N_{faces}}(\Gamma_f \nabla\phi_f . \vec{A_f}) + S_{\phi}V \quad (4)$$

The transport property Φ I the equation (4) now found on the face. In this way, it must be solved not only for a single volume, the volumes that are bounded by that particular face. Extrapolating this out to many thousands of small cells may result in a large set of equations that must be solved simultaneously for the correct transport property. Equation (4) needs to be linearized to solve equations.[5]

To solve these sets of equations ANSYS Fluent consist of different methodologies. Each of the methods has pros and cons. There are four algorithms available for pressure-based solvers such as SIMPLE, SIMPLEC, PISO, and fractional Step.

A. Identifying the Angle of the Caudal fin

This research was aimed to simulate through CFD and analyzed the hydrodynamic efficiency of different types of caudal fin geometries. This simulation involves several steps.

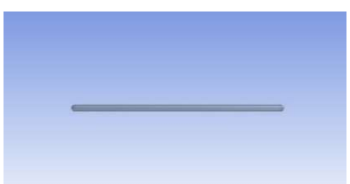

Fig. 5. Geometry of the snake

a). Create the Geometry of the model

The first step was to create the geometry. This was done in SolidWorks (Fig. 5). Model completion and all the other steps was done in the ANSYS environment.

b). Meshing

The creation of the mesh in the combined part of the solution. Mesh is the domain of the solution and discretized space that defines the volume for calculations. Considered domain divided into individual cells of varying shapes with nodes at the corners. This research simulation was conducted in 3D and these cells are tetrahedrons (Fig. 6).

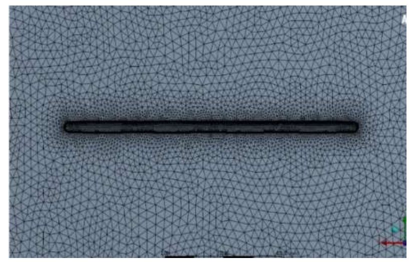

Fig. 6. Zoomed view of the mesh created around the snake

c). UDF Creation

The solver needs the desired movement of the snake to be specified as input. This is done by FLUENT by using User Defined Functions (UDF). In here the UDF has constructed the mesh according to the movement of the eel. UDFs are written in C programming language by using Visual Studio.

d). Solution setup and Dynamic Mesh

This step includes setting the cell boundary conditions, spatial discretization, solution initialization, and other flow models. Boundary conditions play a major role, consider the effect of the solution.

After the solution is obtained by numerically solving the model, postprocessing can be done to further analyze the results

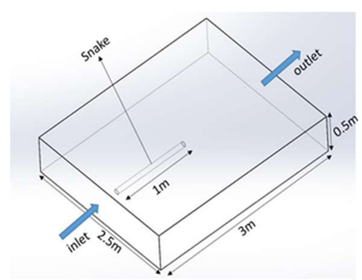

Fig. 7. Boundary setup

In this research inlet, wall condition, symmetric condition, and outlet as boundary conditions. The inlet boundary condition used velocity inlet, outlet boundary condition used pressure outlet, external walls used as moving walls, and the snake as a stationary wall. The inlet velocity of the flow is equal to the forward speed of the snake. The snake itself slip or no-slip condition is given as to whether the flow model is viscid or in-viscid.

A time step value of 0.001s was used. The boundary setup of the simulation has shown in Figure 08.

The setup of the dynamic mesh is an integral part of the solution. ANSYS Fluent consists of three main options to update interior volume meshes when there is a dynamic boundary. Those three are the smoothing method, layering, and remeshing method. Having the proper dynamic mesh methods help much to avoid negative cell volume error. In dynamic meshing, the snake should be set as user-defined motion and the wall surface should be set as a stationary wall.

B. Selection of Caudal Fin

This research has been considered four of caudal fin as forked, Heterocercal, Truncate, and rounded.

Fig. 8. Rounded

Fig. 9. Heterocercal

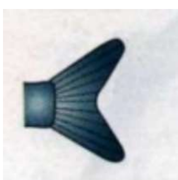

Fig. 10. Forked

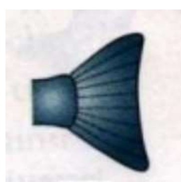

Fig.11. Truncate

This simulation also was done using ANSYS Fluent software. Transient simulation has to be done from the above selected four caudal fin geometries with that simulated results from the previous simulation.

a) Geometry design

The first step was to create the geometry was done in SolidWorks (Fig.12). Model completion and other steps will be done in the ANSYS environment.

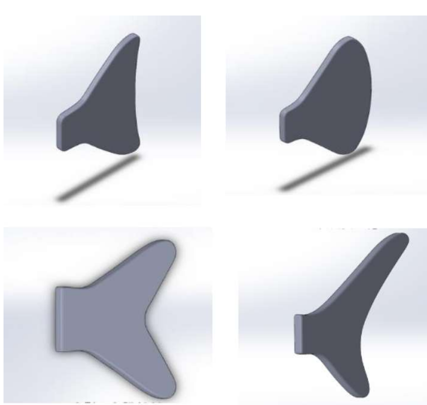

Figure 12. Caudal Fin Shapes

b) Mesh Creation

In this simulation, the selected caudal fin shapes are geometrically complex. Therefore, an unstructured mesh that consists of tetrahedrons was used.

One of the above selected caudal fin types is used to do a mesh independence analysis of the simulation. A rounded fin shape was selected and simulations were done for 100mm, 50mm, and 25mm mesh sizes.

c) Solution Setup

The simulation employed a velocity inlet boundary condition, specifying an inlet flow velocity of 0.5 m/s. Here inlet velocity was used as the forward speed of the sea snake. The caudal fin was designated as a stationary wall. The outlet boundary condition was defined as a pressure outlet, while the wall domain was treated as moving walls, synchronized with the forward speed of the snake robot. The simulation utilized a time step of 0.01 seconds.

III RESULTS AND DISCUSSION

According to existing literature on Underwater Snake Robots (USRs), the concept of a highly efficient motion will be selected. Underwater snakes primarily employ two locomotion methods: eel-like motion and lateral undulation.

These two methods by Strmsoyen (2015) [3] tested the caudal fin that tunas and sailfish for the first simulation amplitude, frequency, the phase between the joints are used as constant. The research was conducted for snake motion and eel-like motion with and without tail fin.

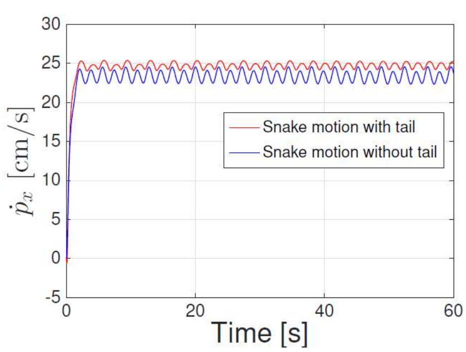

Fig. 13. velocity of the CM in the x – direction for lateral undulation

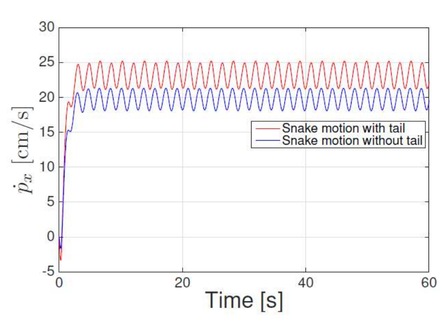

Fig.14. velocity of the CM in the x – direction for Eel-like motion

The results showed that snake motion speed was increased with the tail fin (Fig. 13). Considering the eel-like motion without the tail fin has a low speed but with the tail fin increased the considerable amount of speed (Fig. 14). Analysis [3] showed that the percentage of speed increased using caudal fin with Eels motion is greater than the lateral undulation. Therefore, in this research, Eel-like motion was considered.

TABLE I. EXPERIMENTAL INPUT

Length of the snake	1m
Forward speed	0.5m/s
Advance ratio	0.8
Displacement wave speed	0.625
Diameter	70mm

There are several inputs that are needed to calculate the motion of simulation. Such as length of the snake, forward speed of the snake, advanced ratio, displacement wave speed, diameter of the snake. Those inputs are shown in Table I. The values that were chosen were obtained from [8]. The main difference is the diameter of the snake.

User-Defined Function (UDF) achieved the expected results according to the requirement. As an initial step, a simulation was done for 0s, 0.125s, 0.25s, 0.375s, 0.5s, and 0.625s for pressure contour. Next, a simulation was done to find out the caudal fin angle where maximum thrust occurs.

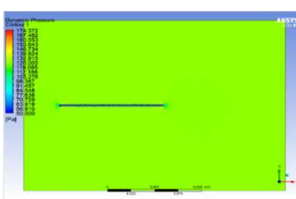

Fig. 15. Pressure contour at t = 0s

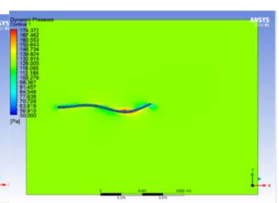

Fig. 16 Pressure contour at t = 0.125s

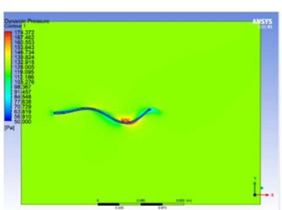

Fig. 17. Pressure contour at t = 0.25s

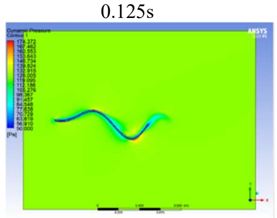

Fig. 18. Pressure contour at t = 0.375s

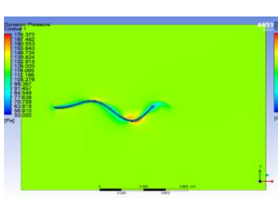

Fig. 19. Pressure contour at t = 0.5s

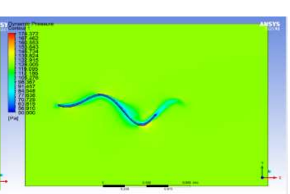

Fig. 20: Pressure contour at t = 0.625s

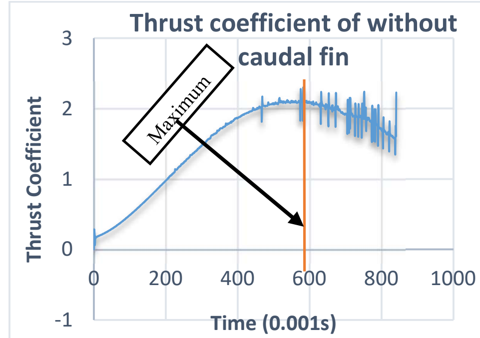

Fig. 21. Thrust coefficient changes with time for eel-like motion

According to the results of the simulation, maximum thrust coefficient is at t = 0.58s. Therefore, the body shape of the snake at t = 0.58s was selected. Then the angle of the tail was used as the angle of the caudal fin shape. The value of the angle is 48° .

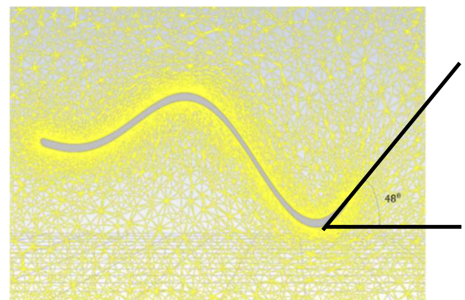

Fig. 22. Caudal fin shape angle when maximum thrust occurs

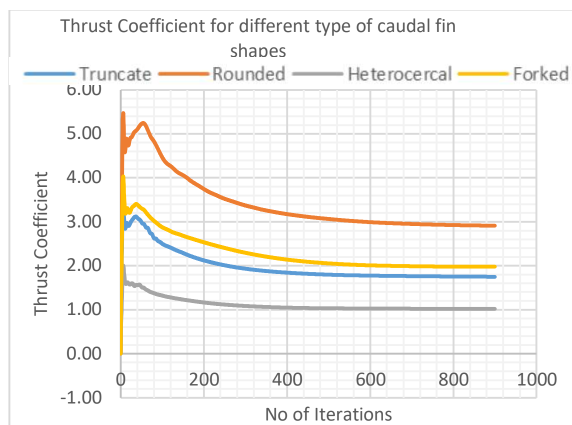

Fig. 23. Thrust coefficient changes with caudal fin shape

Considering Fig. 23 rounded fin shape gives highest thrust coefficient compared with forked, truncate, and heterocercal. Rounded fin thrust is almost thrice compared with heterocercal caudal fin and 1.5 times compared with forked and truncate fin shapes. Therefore, accordingly, a rounded caudal fin shape was selected as the best caudal fin for the underwater snake.

The reason for this result could be due to the surface area of the caudal fin shape. The rounded caudal fin shape has the highest surface area compared to the other three shapes. Heterocercal fin shapes, that have the lowest surface area results in the lowest drag. Naturally, this fin shape might not only depend on the surface area, it would depend on the motion pattern as well.

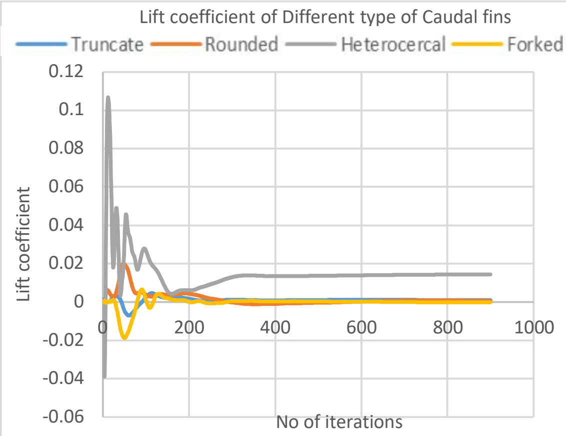

Fig. 24. Lift coefficient changes with caudal fin shape

Considering the lift coefficient of the selected caudal fin shapes, heterocercal gives the highest lift coefficient compared to the other three. Truncate, rounded, and forked fin shapes have lift coefficient of approximately zero (Table II). According to the results, heterocercal has a 0.012 lift coefficient. The only unsymmetric fin was the heterocercal fin shape. This asymmetricity of the shape could be the reason for the non-zero lift force.

TABLE II. THRUST COEFFICIENT AND LIFT COEFFICIENT FOR DIFFERENT TYPES OF CAUDAL FIN SHAPES

Caudal fin shape	Number of nodes	Thrust coefficient	Lift coefficient
Rounded	424089	2.91	0
Forked	415911	1.97	0
Heterocercal	368082	1.02	0.012
Truncate	370498	1.74	0

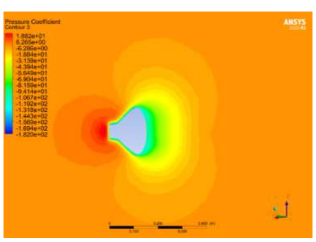

Fig. 25. Pressure coefficient contour of rounded fin

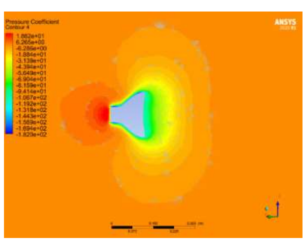

Fig. 26. Pressure coefficient contour of forked fin

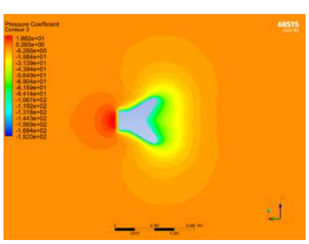

Fig. 27. Pressure coefficient contour of heterocercal fin

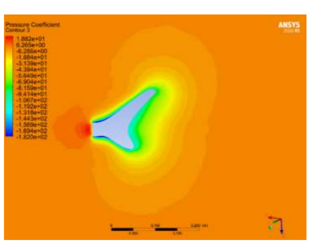

Fig. 28. Pressure coefficient contour of truncate fin

IV. CONCLUSION AND FUTURE WORK

The results of the research showed that eel-like motion pattern is more efficient with caudal fins. Four different types of caudal fin geometries were selected and simulation was done without caudal fin. Then using the simulation results the time that gives the maximum thrust coefficient was obtained. Then the body shape of the snake at that time was obtained and the angle of the tail end was measured. Then comparisons were done according to the results generated through ANSYS Fluent CFD simulation. According to the results, rounded caudal fin shape gives the highest thrust compared with forked, heterocercal, and truncate. Therefore, rounded caudal fin was selected as a caudal fin for underwater sea snake.

The validation of these simulations using experimental results would be done as future work. Improvements can be made to the results by using a finer mesh. Dynamic simulations by attaching different types of caudal fin geometries to the snake in the future can also be done to refine the results further.

Also research was conducted for only four types of caudal fin geometries. Research could be improved by introducing other types of fin shapes such as dorsal fins, pectoral fins, and anal fins to the sea snake. This will increase the controllability of the snake robot and other hydrodynamic parameters.

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