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Effect of Reynold Number and Angle of Attack on the Hydrodynamic Forces Generated from A Bionic Concave Pectoral Fins

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Abstract. The pectoral fin shape, diameter and speed are the three main parameters for our robotic fish design. The influence of geometrical shape of pectoral fin in labriform mode swimming mechanism is evaluated with the aid of CFD method which is considered as a first step before building the complete design prototype. Two concave shape fins were designed precisely, each of them was attached to a servo motor arm which is in turn connected to a servo motor that is sliding on pair of shafts to work as robot straighter. The two servo motors along with their pectoral fins are placed in 1m x 0.5m x 0.5m pool. Different number of angles of attack were tested and the results showed the optimum value is 50°. Further analysis based on Reynold number and its effect on the drag coefficient was investigated carefully. The hydrodynamic forces will be increases with the increasing of angle of attack for all Reynold numbers, which will in turn speed up the overall velocity of the body.

1. Introduction

Large number of applications in our daily life need the use of robotic fish such as aquatic life monitoring, military intervention, water pollution detection which all required the continuous development of underwater robots to use them instead of human beings [1]. The design of the fish robot to behave like a real fish in terms of movement and maneuvering require a deep knowledge of swimming mode mechanisms and behaviours. Different types of fishes use different types of fins as their locomotor. Generally, there are two types: Body and/or Caudal fin (BCF) and Median and/or Pectoral fin (MPF) and according to the type of fins that uses in locomotion they can be further classified into undulatory type and oscillatory type [2]. For BCF - undulatory type the motion is a wave of muscles that generated from the head of the fish to its tail such as anguliform, carangiform, subcarangiform locomotion. Whereas the oscillation motion involves turning of the body and caudal fin to propel the fish such as ostraciiform and thunniform locomotion. On the other hand, the MPF undulatory motion involves diodontiform, gymnotiform, amiform, and balistiform locomotion and oscillatory motion such as labriform and tetadntiform. Another type known as rajiform can be considered as a combination of undulatory and oscillatory locomotion [3]. When an object moves through a fluid, there should be a resistance to that movement. This a resistance generates a hydrodynamic force that can be classified into force due to the friction and force due to the pressure. These two forces may associate with the geometrical shape of the object, its speed in the fluid and also the characteristics of the fluid itself. Solving Navier Stokes equations by computational fluid dynamics



which is incredibly a powerful tool provided by SolidWorks software that can be utilized in identifying these hydrodynamic forces [4]. The researchers in [5] proposed an evolutionary multi-objective optimization (EMO) approach to the design and control of flexible fins for robotic fish where they investigated fins of different stiffness values and sizes. While in [6] the authors mentioned the unmanned underwater vehicles (UUVs) by studying the hydrodynamics of UUVs especially drag force since it is required to determine the total thrust. In [7] a perfect design of AUV of the marine propeller with the aid of both CFD simulation by SolidWorks and FEA method in order to get the optimum thrust from the propeller. In [8] the authors developed a dynamic model of the oscillating pectoral fin based on the quasi-steady blade element theory they investigated different motion parameters to show the performance of the oscillating pectoral fin. A 6-DOF of robotic fish is adopted by [9] by considering surge, sway, heave, roll, pitch, and yaw, they considered the swimming in the ocean with carangiform mode swimming mechanism. In labriform (rowing motion) mode swimming mechanism, the main component of the hydrodynamic force is due to the drag force [12-15]. Different attitude angles of rotation which are defined as roll, pitch, and yaw. Where roll (Φ) is the angle of rotation around the X-axis, pitch (α) is the rotation around Y axis, and yaw (ψ) is the angle of rotation around the Z-axis. Our proposed model is concerned with the variation of the angle of attack between the longitudinal axis of the pectoral fin with the main direction of the water flow, which in our case is α .

The main contribution of this work is to present a dynamic model for a concave fin actuated robotic fish based on the hydrodynamic forces of a rigid-body which in turn plays a significant role in picking up the body's rotation and translation motion of robotic fish. We enhanced the proposed model with simulation results by making use of CFD method which shows the effectiveness of such a model.

The following section is dedicated to modelling the proposed design of concave pectoral fins. Since our main target is to design a robotic fish with a paired of pectoral fins in labriform mode swimming mechanism, we ignored the effect of the body shape for the current prototype and directed our interest on the perfect design of the fins as they are the main propellers of the robot.

2. Mathematical model of the proposed design

Consider the body of the fish robot as in Figure 1, the pectoral fins placed in an angular position $\alpha(t)$ such that

$$\alpha(t) = \frac{A}{2} - \frac{A}{2} \cos(\omega t) \quad (1)$$

Where; $\alpha(t)$ represents the instantaneous angular position of the base of the fin, A is the amplitude of the wave generated by the fin, and ω is the angular frequency which can be given as $\omega = 2\pi f$ [10-11].

The overall velocity of the fish robot is given by:

$$V_{pec} = -D \frac{d\alpha}{dt} \quad (2)$$

Where D is the diameter of the fin. This speed is used in determining the hydrodynamic forces acting on the fins as shown in Figure 2. Following [12-16] these hydrodynamic forces are given by:

$$F_D = \frac{1}{2} \rho V^2 S C_D \quad (3)$$

$$F_L = \frac{1}{2} \rho V^2 S C_L \quad (4)$$

$$F_B = \frac{1}{2} \rho V g \quad (5)$$

$$W = mg \quad (6)$$

Where F_D , F_L , F_B , and W are the body drag, lift, buoyancy and weight forces, respectively. ρ is the water density, C_D and C_L are the drag and lift coefficient, respectively whereas S denotes the projected surface area to the water, m is the mass of the body and g is the force due to the gravity.

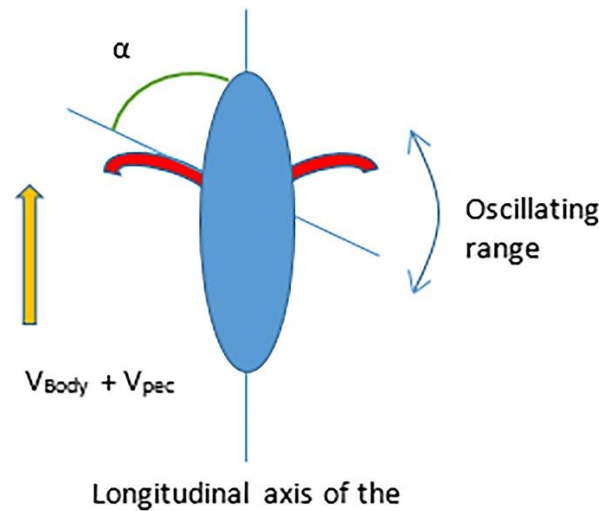


Figure 1. Fish robot showing the angular position of the fins.

From Figure 2 it is easy to notice that the drag is the same as the thrust force and buoyancy + lift balances the weight force in this state the robot fish is said to be neutrally buoyant. Since we are in labriform mode swimming mechanism, so the thrust force generated from the pectoral fins is equivalent to the force due to the drag and added mass [11]. The drag force is given in equation (3) while the added mass force can be calculated as follows:

$$F_A = v_{pec} \rho \frac{dV_{pec}}{dt} \quad (7)$$

$$\frac{dV_{pec}}{dt} = -D \frac{d^2 \alpha}{dt^2} \quad (8)$$

Where F_A denotes the added mass force of the fin, v_{pec} is the volume of the fin, V_{Body} stands for the velocity of body and V_{pec} is the velocity of the fins. Therefore, the sum of the drag force and the added mass force will give the thrust force as follows:

$$\begin{aligned} F_T &= F_D + F_A \\ &= 2 \left[0.5 \rho \mathcal{N}^2 S C_D + v_{pec} \rho \frac{dV_{pec}}{dt} \right] \end{aligned} \quad (9)$$

Where F_T is the thrust force and is multiplied by 2 to account for pair of pectoral fins. The total pressure on the fin surface is due to the static and dynamic pressure, such that:

$$P_t = P_s + P_d \quad (10)$$

$$P_s = \rho gh \quad (11)$$

$$P_d = 0.5 \rho \mathcal{N}_{pec}^2 \quad (12)$$

Where P_t , P_s , and P_d stands for total, static, dynamic pressure, respectively. h is the height of the water level.

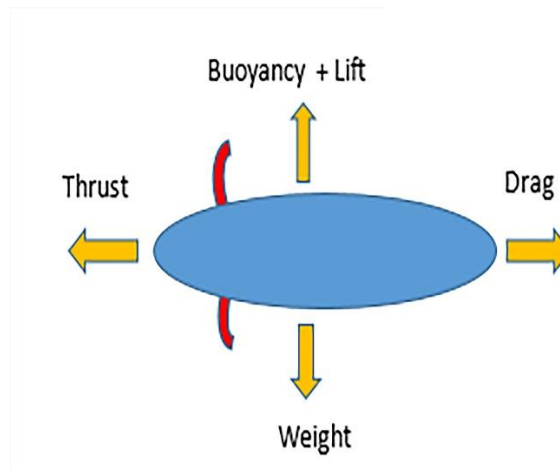


Figure 2. Hydrodynamic forces acting on a body in water.

In order to enhance the performance of the system, we evaluate our model with different Reynold numbers, which is a dimensionless number that can determine whether the flow is laminar or turbulent where the flow is considered as

- Laminar when $Re \leq 2300$
- Transitional when $2300 \leq Re \leq 4000$
- Turbulent when $Re \geq 4000$

Where

$$Re = \text{Inertial forces} / \text{Viscous forces} = \frac{\rho V_{avg} L}{\mu}$$

Re is Reynolds number, V_{avg} is the average flow velocity (m/s), L = length (m) and μ is dynamic viscosity of the fluid (Pa.s) [17].

3. Design and simulation results

A pair of pectoral fins designed with plastic PVC rigid material of density of 1300 kg/m^3 was used in our simulation. A novel design of these fins was precisely build in an octal hollow spherical shape such that the outer radius is 5 cm and the inner radius is 4.6 cm producing a concave shape of a thickness of 2mm. The arm of the servo motor is connected to a well-designed joint attached to each pectoral fin to reduce the sharpness of the edges that may affect the water flow streamlines.

The pair of pectoral fins was attached to the two servo motors which in turns positioned to slide on two parallel shafts (weight and buoyancy forces are beyond the scope of this study) of length 1m and the whole design placed in a pool of 1m X 0.5 m X 0.5 in length, width and depth, respectively. The exact position of the shaft is in the middle of the pool.

The fins were tested for different angles of attack between the longitudinal axis of the body and a rotated pitch angle around Y-axis. Each fin is designed to move forth and back to produce the maximum thrust force in the forward direction and minimum drag in the reverse direction utilizing the concave shape in forwarding (power stroke) and the convex shape in reversing (recovery stroke).

To meet this goal concave pectoral fin design, the servo motor arm is designed to satisfy the motion dictated by the servo motor such that the pectoral fin maintains the highest speed at power stroke and lowest speed during the recovery stroke. The robot body is shown in Figure 3, while Figure 4 shows different design stages.

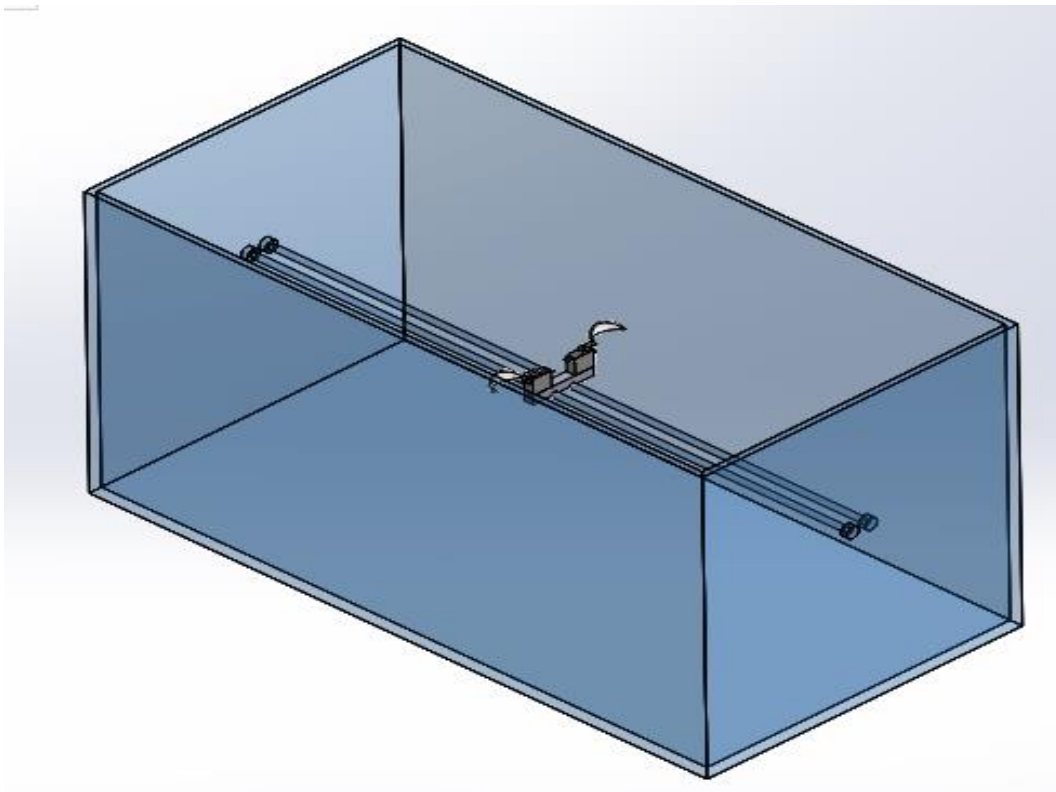


Figure 3. Complete design placed in a pool

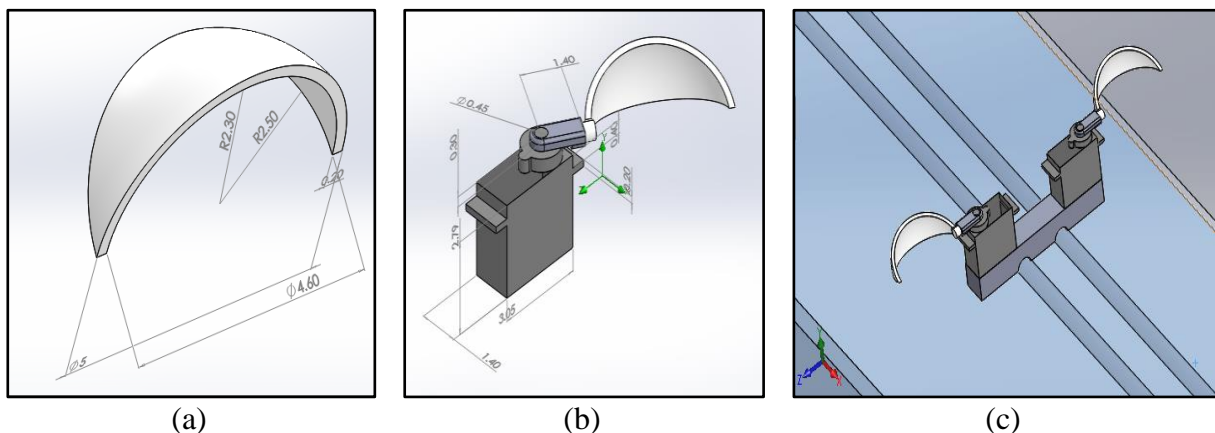


Figure 4. (a) pectoral fin design (b) servomotor with arm and pectoral fin (c) Two servomotors placed on parallel shafts.

Physically and geometrically, the movement of the body in a fluid may result in the displacement of a portion of the fluid with the moving body and results in moving that displaced fluid with the body producing an effect that should be taken into account on the body's dynamics this phenomenon known as added mass [18].

We assumed that the Body is neutrally buoyant where centre of mass and center of buoyancy coincides and have the same projection in the X-Y plane, therefore, the movement of the robot body is reduced to 3 DOF, so we have linear velocity components on the X and Y direction while having an angular velocity on Z-direction. Since we are concerned with only the pectoral fins at this stage, so the movement of the body is further reduced to 1 DOF which is represented by the linear velocity component along the X-axis. The following assumption has been used during the simulation:

- Air pressure is 101325 pas at 20°C (293 K).

- Gravity feature is considered where $g=9.81 \text{ m/s}^2$
- The roughness is 0 micrometres.
- No cavitation is in the simulation.
- The dynamic viscosity of water is $8.9 \times 10^{-4} \text{ (Pa.s)}$.
- The simulation tank (computational domain) is set to $1\text{m} \times 0.5\text{m} \times 0.5\text{m}$.
- The diameter of pectoral fin is 0.05 m.
- The water density is 1000 kg/m^3 .
- The projected surface area in power stroke is 0.0969 m^2 and 0.0822 m^2 in recovery stroke.
- A different angle of attack ($10^\circ, 20^\circ, 30^\circ, 40^\circ$ and 50°) has been investigated as shown in Figure 5 around y-axis.
- Water flow velocity at the power stroke is set to 0.05 m/s .
- Reynold number is tested at 2800,3800,4800,5800,6800,7800,8800,9800, and 10800.

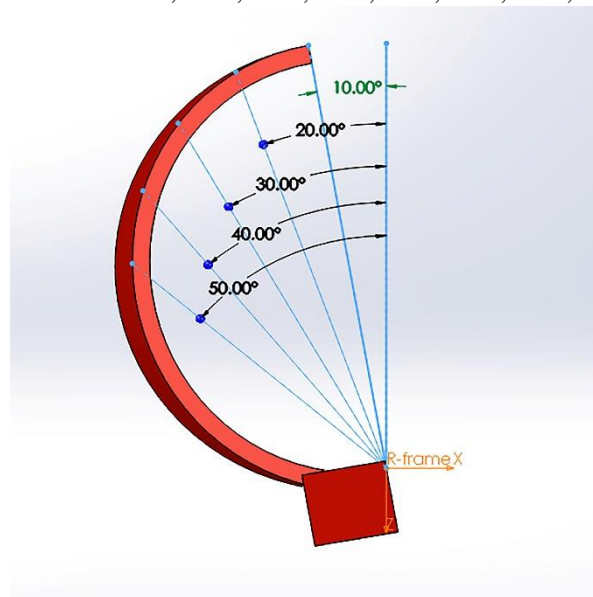


Figure 5. Rotation about y-axis

With the aid of CFD, we analyzed the distribution of water velocity around the robot body where the results showed that the maximum velocity reached up to 0.076 m/s as shown in Figure 6. Whereas Figure 7 explains the flow trajectories during the power stroke.

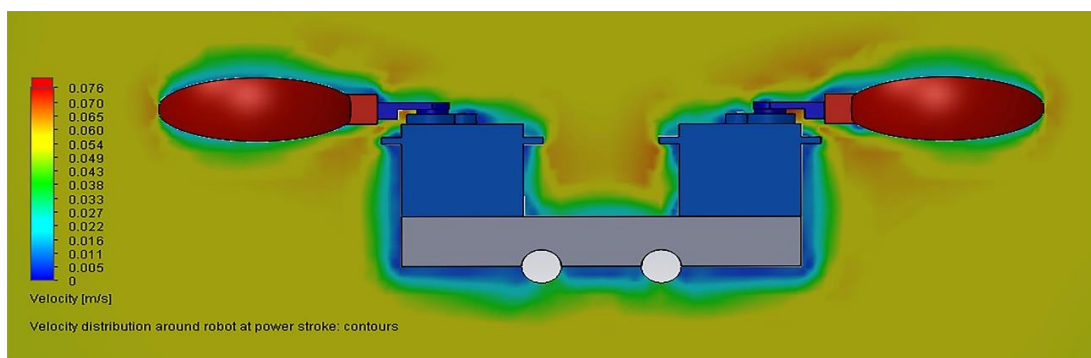


Figure 6. Water velocity distribution around the robot

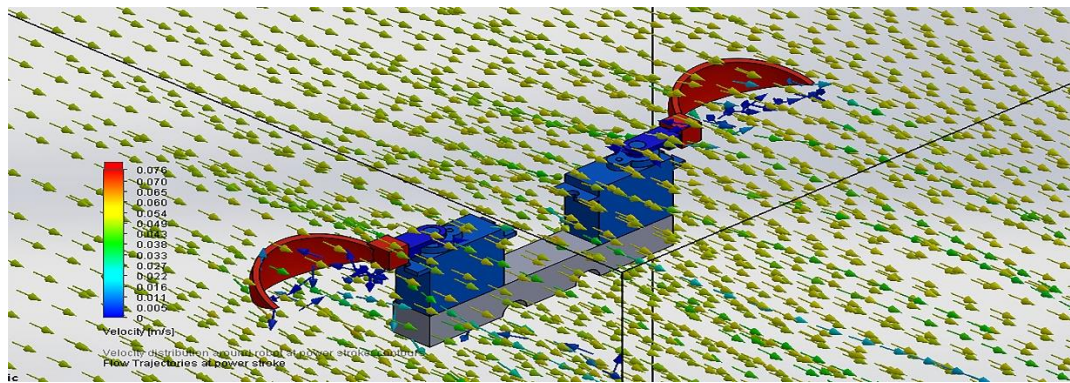


Figure 7. Water flow trajectories during the power stroke.

Since the flow distribution showed a turbulent behavior, we investigate the effect of Reynold number at different angles of attack. Different values of Reynold number were tested the result showed that increasing Reynold number will also increase the hydrodynamic forces generated by the pectoral fins as shown in Figure 8 below:

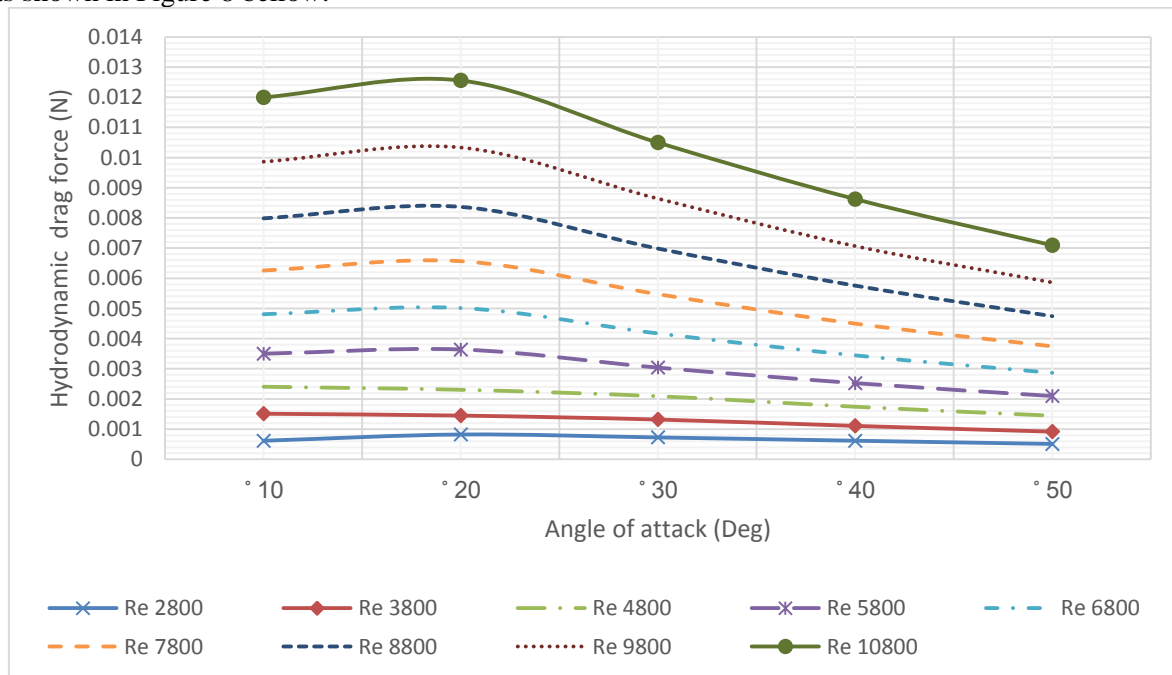


Figure 8. Reynold number at different AoA.

Our goal is to achieve the lowest drag during the power stroke, as can be noticed from the Figure 8 above that the lowest drag force can be obtained when the angle of attack is 50° for all Reynold numbers. In order to enhance the analysis, we further investigate the effect of the drag coefficient at each value of Reynold number for different angles of attack as shown in Figures 9-17.

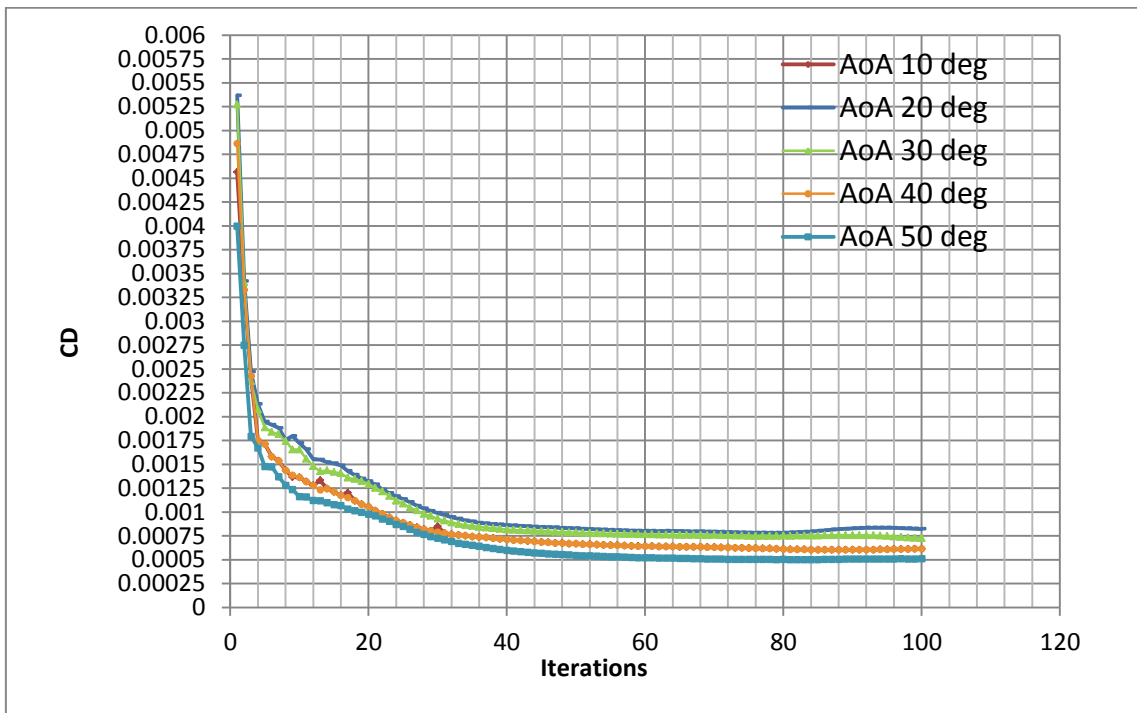


Figure 9 Reynold number at 2800.

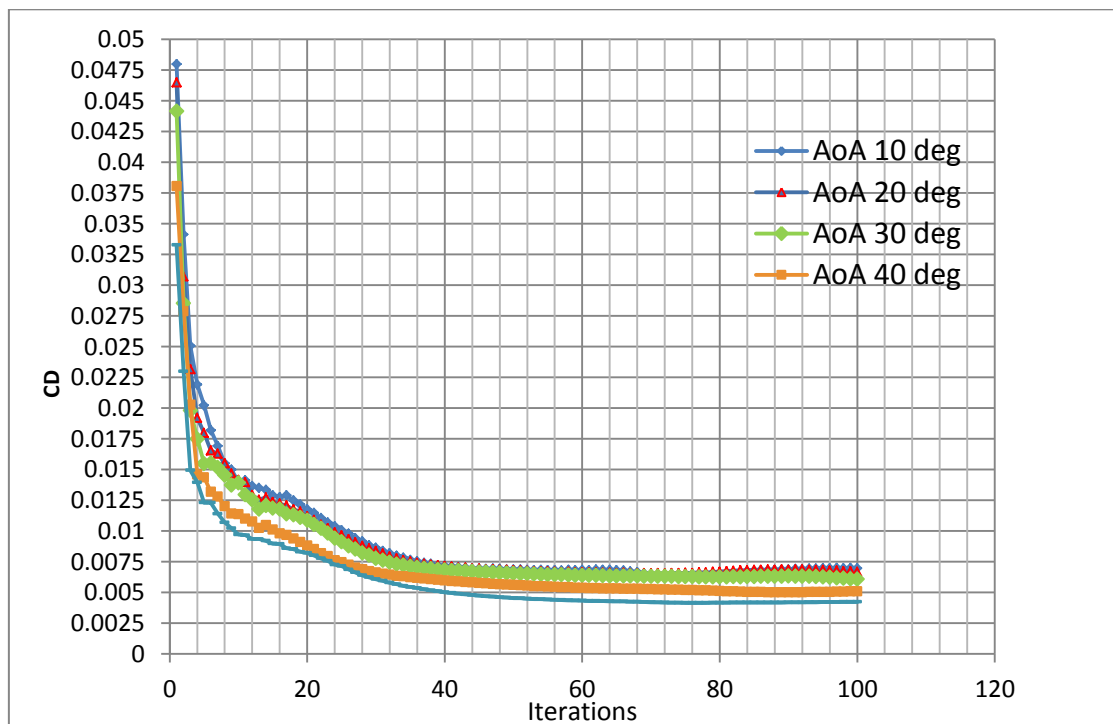


Figure 10. Reynold number at 3800.

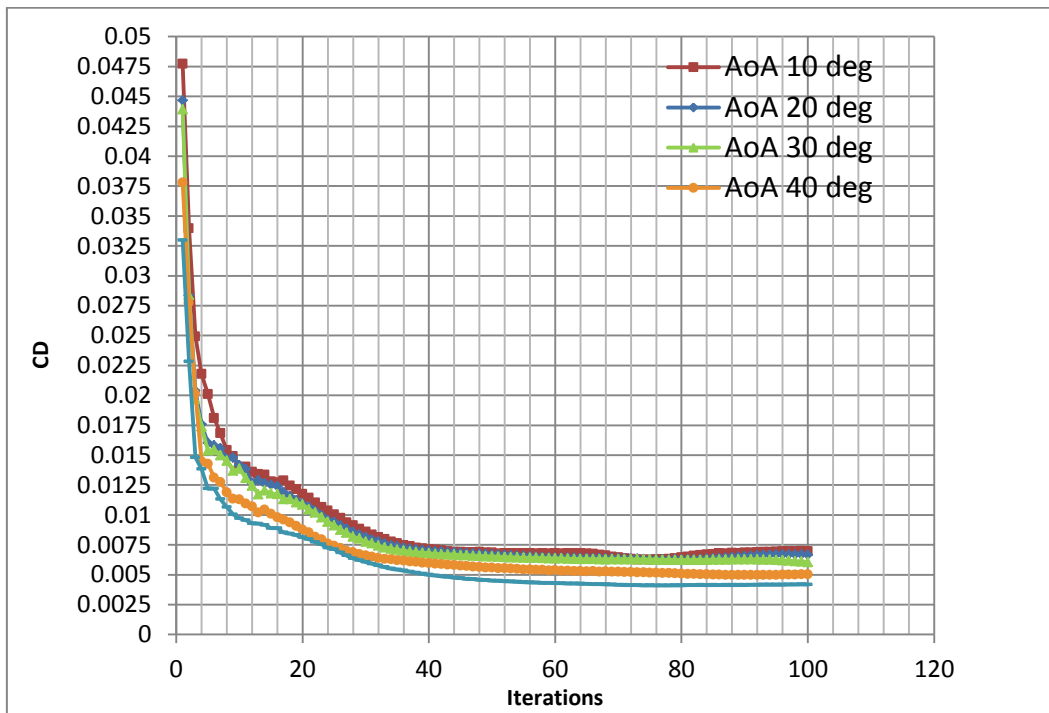


Figure 11. Reynold number at 4800.

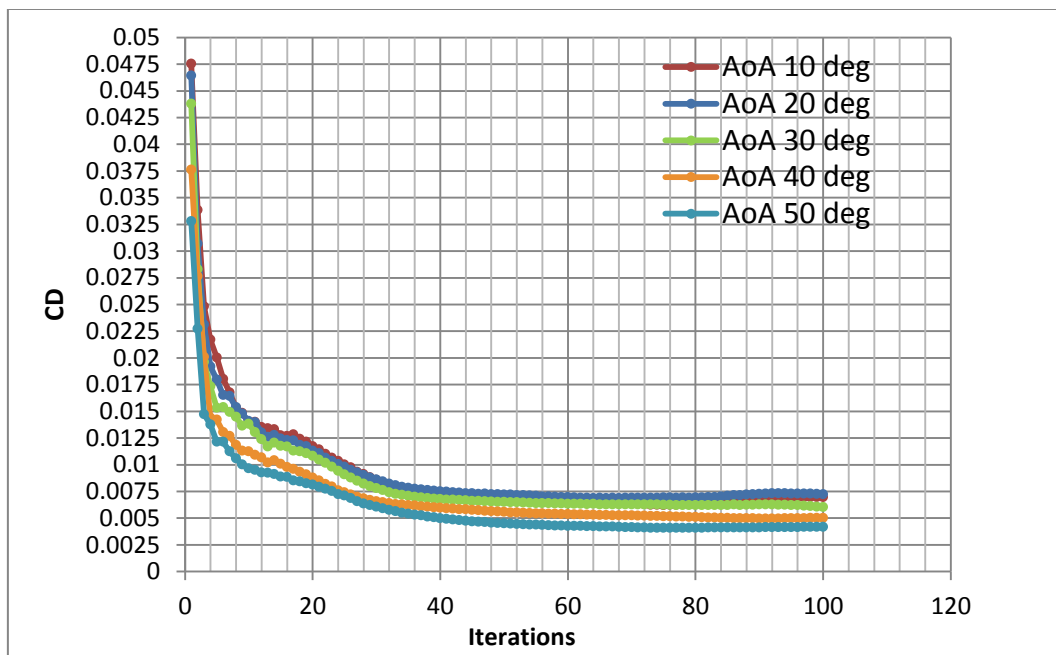


Figure 12. Reynold number at 5800.

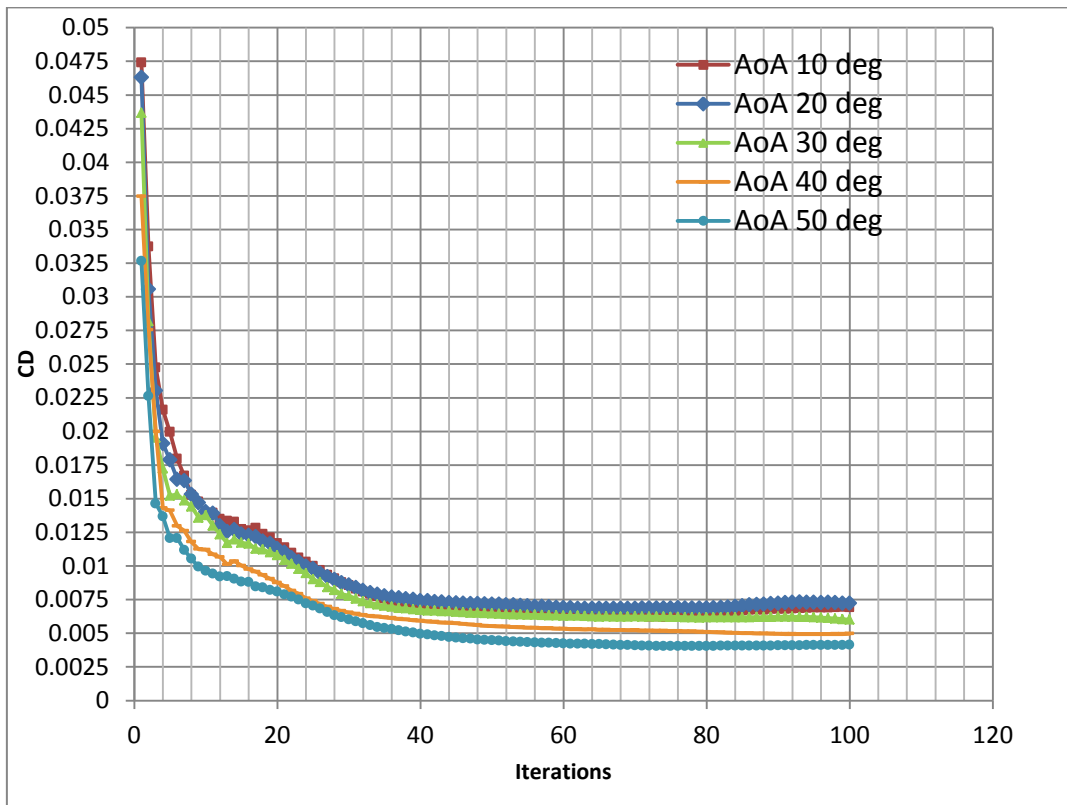


Figure 13. Reynold number at 6800.

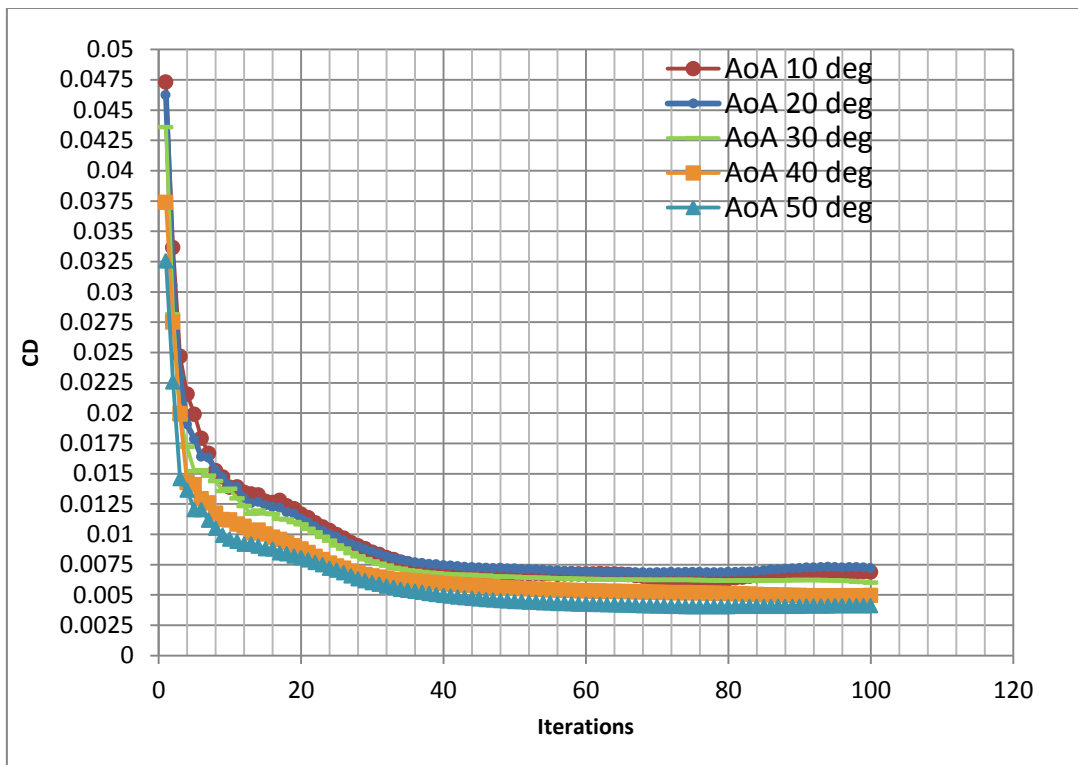


Figure 14. Reynold number at 7800.

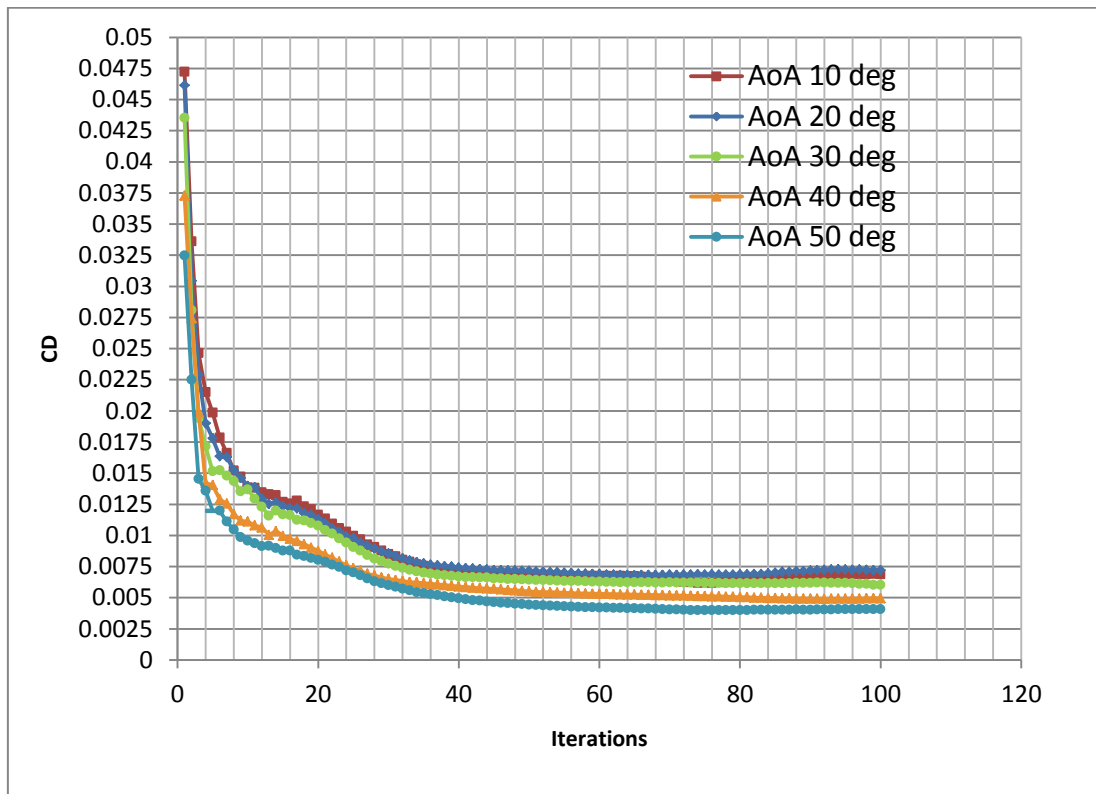


Figure 15. Reynold number at 8800.

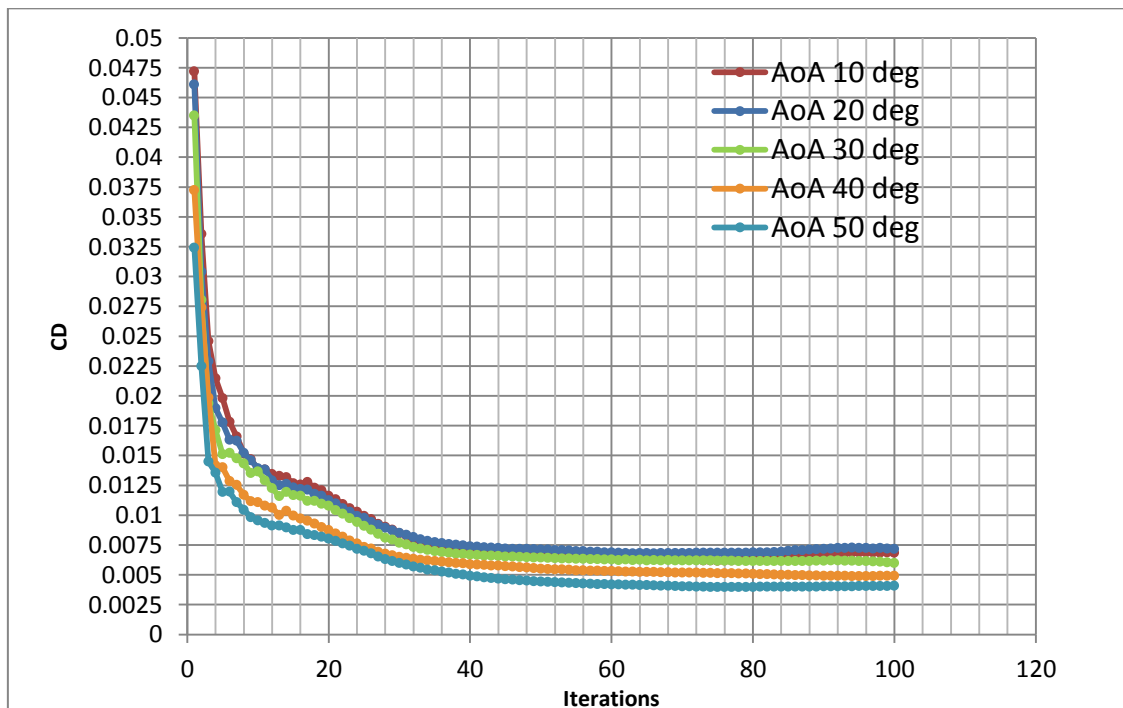


Figure 16. Reynold number at 9800.

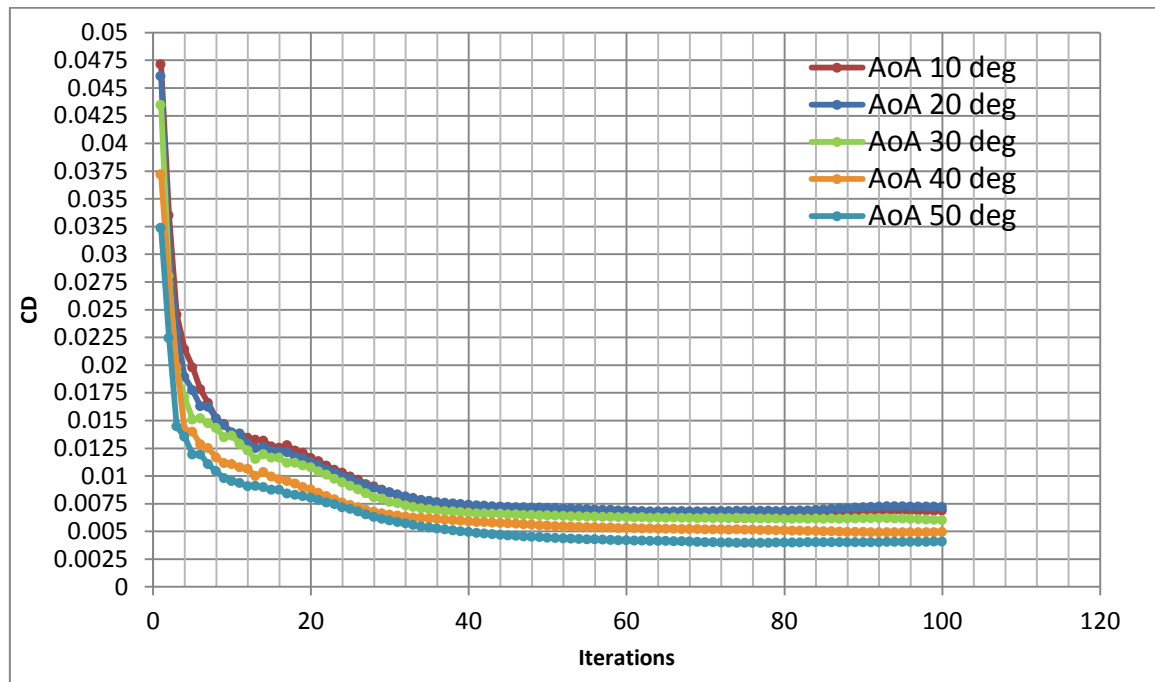


Figure 17. Reynold number at 10800.

4. Conclusion

In this study we designed a novel model for swimming robot based on the pectoral fin as the main propeller element of the robot. The design is implemented under SolidWorks software with the aid of CFD. Different fin angles of attack under different Reynold numbers were investigated and the optimum angle was about 50°. The generated hydrodynamic drag force is calculated and the results showed that as the angle of attack increases the total hydrodynamic forces will increase too which will, in turn, increases the overall velocity of the robot.

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