Design and Fabrication and Hydrodynamic Analysis of a Fish Robot for Underwater Surveillance

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Abstract: *Condition and performance monitoring of underwater equipment and infrastructure is of one the major concern for marine industries. In the past two decades, several technique and methods have been developed for efficient monitoring of marine structures. Fish robots potentially can be used as an efficient device for under water monitoring.*

The design is aimed at high maneuverability, efficiency and the ability to control velocity suitable for underwater surveillance. To control this robotic fish, a four-channel radio controller with 40 kHz frequency, was used. Swimming mode of this robotic fish is categorized in carangiform swimming mode that use its tail and peduncle for propulsion and is faster, and has better maneuverability compared to its counterparts. It should be noted that the flexible tail could enhance the efficiency of the robotic fish swimming.

Employing a servo motor, flexible tail and pulley and rope mechanism, the robotic fish was designed and tested. The experimental tests indicate the maneuverability and the smooth swimming of the robotic fish.To optimize the design and manufacturing of the robotic fish, the hydrodynamic forces and proper function of the body form under water were analyzed using ANSYS fluent and computational fluid dynamics (CFD) method.

The present Robotic Fish significantly enhance the performance and functionality of Robotic Fish for underwater surveillance.

Keywords: *Fish robot, Flexible tail, Design and fabrication, Hydrodynamic analysis,Computationalfluid dynamics (CFD), User-defined function (UDF)*

1. INTRODUCTION

Today, mankind has realized that his existence depends on the preservation of the environment and animals that the most important of which are water resources such as rivers and oceans. Therefore, we constantly need to ensure their protection. One of the best possible ways to observe the underwater world is through robotic fish. So far, many researchers have been conducted on how tooptimize the function of the robotic fish. In this project, only the mechanism of the fish body movements is considered. In fish swimming, there are mainly two types of propulsion, i.e., the Body and/or Caudal Fin (BCF) propulsion [1,2] and the Medium and/or Paired Fin (MPF) propulsion [3,4].Most of the fast swimmers adopt BCF, such as sailfish, tuna, pike, etc. In fact, around 85 % of fish species swim in BCF form. Examples for MPF swimmers are manta ray and box fish. In robot fish development, high speed and high efficiency are the main pursuits. As a result, most of existing robot fish adopts BCF as the way to generate thrust.

In general, the flapping motion of the robotic fish which is made of BCF mechanism can be divided into 3 categories 1. Multi-linked structure [5,6] 2. Full-bodies flexible robotic fish [7,8] 3. Manufactured robotic fish from SMA and PZT materials [9,10]. In the first category, the control mechanism of the fish tail movement is so complex and costly but its maneuverability is high. In the second category, wind and water powered actuators were used to manufacture the robotic fish and the structure of the fish body is complex and costly and there is no control over the swimming of the fish. In third category, the thrust force is low but the mechanism of the structure and control is so simple and low cost. In this project, the aim is manufacturing a low cost robotic fish with a simple control mechanism that is able to maneuver properly and possesses an acceptable thrust force.

According to open literature, most of existing works on fish robot are focused on modeling and simulation. In the present work a fish robot has been designed and fabricated. Several experimental tests and studies have been developed and performed to show the performance and functionality of the proposed system.

2. DESIGNE

The robotic fish consists of two major functional components. These are:

The fish's soft tail for forward propulsion,

Actuator and control board for the tail in the waterproof unit (fish's body).

2.1. Fish Tail

Based on the results previously obtained using test models, we believe that the flexibility of the caudal fin is an important factor for improving the propulsive performance of robotic fish [10]. For this reason, the robot is equipped with a caudal fin made of a flexible material.

In order to optimize the geometry of the flexible tail, the width was copied from the geometry of a real fish, which was proposed by Alvarado & Toumi, 2006 that shows in figure 1.
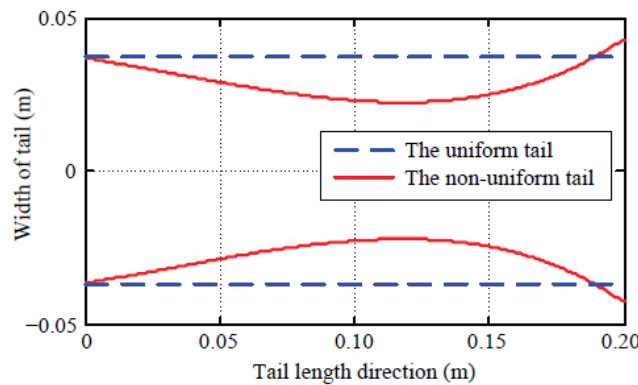

Figure1. *Geometries of tails [11]*

As shown in figure 2, the design of the first section of the robot fish tail was based on the following geometric shape and the second section of the robot fish tail was added to the first section in order to apply force and create moment. To do so, a servomotor and a cable connected to point O were used to create moment in tail and the pressure of water in the opposite direction of moment to the first section of the fish tail can create a wave like movement in the tail. Using this simple mechanism, we were able to create vortex in water and copy the mechanism of a real fish movements. Since the ratio of the first section curve is smaller than the second section, the dynamic analysis bending of the first tail in water is possible through Euler-Bernoulli beam theory [12] as

$$\rho A(x)\frac{\partial^2 h(x,t)}{\partial t^2} + \frac{\partial^2}{\partial x^2}\left[EI(x)\frac{\partial^2 h(x,t)}{\partial x^2}\right] = F(x,t) + L_y(x,t)$$

(1)

where $0 < x < L$ and L is the length of the tail; ρ is the density of the material of the tail; A(x) is the area of cross-section of the tail; E is Young's modulus; and I(x) is the moment of inertia of the area of the cross-section at x about the bending axis. EI(x) is the bending stiffness of the beam.
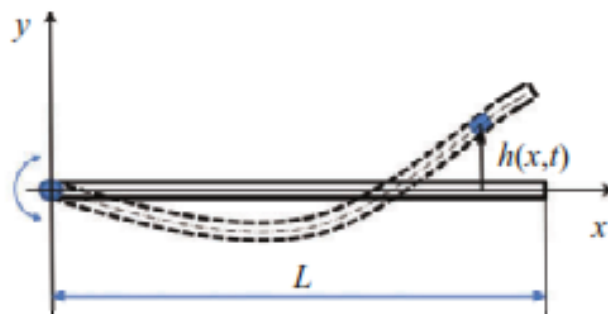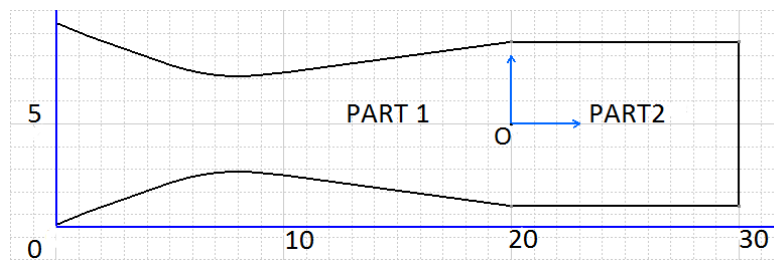

Figure2. *Euler-Bernoulli beam theory*

Figure3. *Caudal fin design*

2.2. Actuator Selection

The pressure of water in the opposite direction of moment to the first section of the fish tail can create a wave-like movement in the tail. Using this simple mechanism, we are able to create vortex in water and copy the mechanism of a real fish movements. Since the ratio of the first section curve is smaller than the second section, the dynamic analysis of the tail is possible through Bernoulli's law.

In past iterations of BCF propulsion mechanism, flexible tail was used with complicated motion design, but in this approach with a simple mechanism using cables and choosing the fish tail from an elastic material, the lateral movement for the tail with suitable force and exceptional speed was created.

2.3. The Control System Architecture

Microcontroller unit(MCU) sends Pulse-Width-Modulation (PWM) signal to the motor driver to control the tail motor's speed, and thus the ossillatory frequency of the tail is control by duty ratio of the PWM signal.

3. FABRICATION

3.1. Material Selection

To choose the right material for the fish tail, several factors are taken into consideration. Firstly, the material needs to be flexible to be able to spring back to the first position after bending so that it can create a wave-like movement of the fish tail while swimming. Secondly, the tail needs to be stiff enough to push the water and not too stiff so that water can have no effect on it. So for this reason High Density Polyethylene (HDPE) sheet with the thickness of 1 mm was used for the tail.

3.2. Electrical Design

For the actuation of the tail, a servomotor was selected. Since servos are fully self-contained, the velocity and angle control loops are very easy to implement, while prices remain very affordable. Servomotors are a conventional and proven technology, and many control platforms currently exist for their implementation.

To create a control signal for servomotor movement, a ATMEGA32 controller with timer of one second was used. The timer count Additive from 0 to the specific number and then downturn to 0 again. One may note that the system clock and clock timer speed are two important parameters.

3.3. Body Construction and Sealing

The head of the robot fish has been designed using solidwork and made by plastic injection technology.

In order to manufacture the fish tail, a sheet of HDPE (High Density Polyethylene) with the thickness of 1mm was provided. Then, the pattern of a fish tail was printed and cut out of HDPE. After cutting the tail of the fish a metal fasteners were installed 10cm far from the beginning of the tail.

All the electrical equipment (including the control board, radio transmitter, servo motor and battery) were installed on a 22x9x0.2 aluminum plate. A disk with the radius of 11 cm was placed between the head and the tail of the robotic fish so that it can function as a support for the tail and the aluminum plate and also function as a sealing lid for the body of the fish. Two holes with the distance of 3cm from the center of the disk and 0.01 diameters were drilled so that the cables can pass through them. The respective cables are connected to the pulley installed on the servo and the tail.The tail and the aluminum plate were clamped to each side of the disk using bolts and knots.
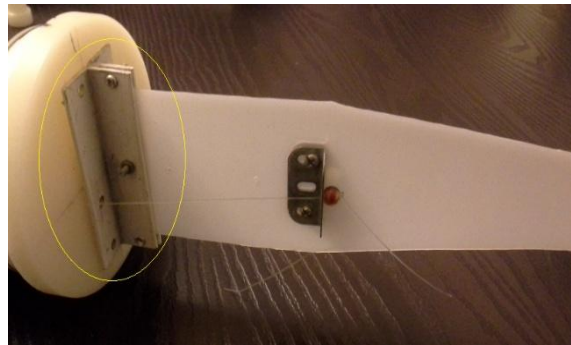
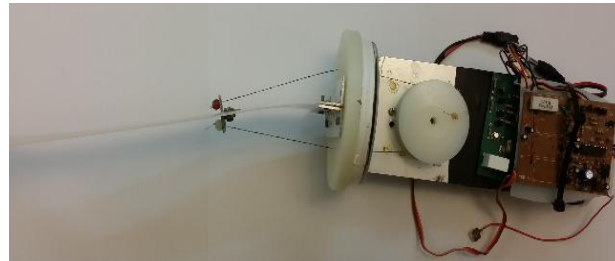**Figure4.** *connecting the tail to the disk*

Figure5. *The Mechanism of robotic fish actuation andmechanical parts assembly*

A plastic cover is used to make the equipment waterproof. This plastic cover (with aerodynamic shape) was chosen and for balancing, Pectoral fins were designed based on a real fish and fabricated with 0.2cm aluminum plate and fixed on the head of the robotic fish

4. EXPERIMENTAL RESULTS

Given the fact that this robotic fish is designed for underwater surveillance, the radius within which the fish swims is of great importance and the less the radius the more efficient the robotic fish functions. The extent to which the fish tail bends, determines the radius of movement and the mechanism of the movement of the robotic fish is designed in a way which is capable of making a U-turn within the radius of 35 centimeters (Table 2). Compare to flexible tailed robotic fish ([7],[8],[9]), the mechanism to control the bending of the robotic fish tail is more efficient in terms of maneuverability.

4.1. Effect of Changed Frequency of Flapping Motion

The robotic fish was tested for frequencies from 0.5HZ to 2HZ and fixed amplitude of 7.5cm. the results is shown in table 1. As it can be seen in table 1, the speed increase until f=1.25HZ but after that, the servomotor cannot handle the amplitude and it cause reduction in both speed and amplitude.

Figure6. *Fabricated Robotic Fish*

Table1. *Forward swimming speed and tail's displacement at various frequencies and A=7.5cm*

tail Frequency of actuation (HZ)	Forward Swimming speed (cm/s)
0.5	12
0.75	14.8
1	18.1
1.25	18.8
1.5	18

4.2. Change Offset

Changing the offset of the tail actuation, resulted in the robotic fish turning. The turning direction of the robot is opposite to the changing offset direction. Results of different offsets are presented in table 3.

Table2. *Turning performance of the robotic fish with different offsets af F=0.5HZ*

Amplitude (cm)	Change offset (degrees)	Circle Trajectory radius(m)	Speed of turning swimming (rad/s)
7.5	2	7.5	$\frac{\pi}{5}$
	6	3.40	
	13	1.90	
	21	0.60	
20.1	29	0.35	$\frac{\pi}{3}$

4.3. Power Consumption Calculation

The supply voltage of the control board was set at 5 Volt and the outputs of the servomotor are:

Torque0.255N.m, Speed6.98rad/s, Power1.78w. Battery Ni-Cd, Capacity =700mAh

Based on specifications of servomotor and the battery, the servo can operate up to 170minutes.

4.4. Added Load at the Center of Gravity

To test the capability of the robot in carrying additional equipment (camera, GPS, etc.) a different load was attached to the robot's center of gravity. With f=0.5Hz and A=7.5cm, the forward velocity reduced as shown in table 4.

Table3. *Forward Swimming Speed with Additional Load*

Amplitude (cm)	Load (gram)	Forward Swimming speed (cm/s)
7.5	100	12
	500	11
	900	9.8
	1300	9
	1700	7
	2100	5.8
	2500	4.5
	2980	Sink

Figure7. Shows the rate of reduction of swimming speed by adding load to the center of mass of the robot. As it shown in graph 1, each kilogram causes, the reduction in speed by 15 percent.

5. NUMERICAL EXAMPLE

The weight of the robot is 1kg and its length is 61cm. In this novel design, the tail was so flexible that it can be as similar as possible to the shape of a real fish's body. The tail actuation was produced by using a servomotor connected to the tail through cable strings. The robotic fish uses a 40 KHz radio transmitter to control its forward swimming and steering. The turning movement is created by implying offset angle to the tail propulsion. This Robot has the capability to carry a maximum of 2.98kg weight for extra accessories. The robotic fish was tested with different actuation frequencies and amplitudes. The maximum speed at f=1.25HZ and A=7.5cm was v=0.188m/s.

6. COMPARING SWIMMING SPEED

We compared our model with three other robotic fishes with flexible tail from the literature. The results of this comparison is shown in table 5. (Other samples to compare are all submerge)

Table4. *comparing swimming speed*

Robotic fish	Forward Swimming speed(BL/s)	Forward Swimming speed(cm/s)	Total length (cm)
[7]	0.15	10	66
[8]	0.44	15	33.9
[9]	0.1	3	30
Float	0.308	18.8	61
Submerge	0.1	5.8	61

6.1. Effect of Changed Amplitude

The robotic fish was tested for the displacement of the tip of the tail from 8cm to 18cm and fixed frequency of 1Hz. The results is shown in table 2. As it can be seen in the table 2, the speed increases by increasing the amplitude.

Table5. *Forward swimming speed at various tail's displacement and F=1Hz*

Amplitude(cm)	Forward Swimming Speed(cm/s)
4	11
5.5	13.5
7.5	18.1
9	18.5

Lighthillproposed that BCF flapping can be described by the traveling wave model below:

$$y(x,t) = (c_1 x + c_2 x^2)\sin(\frac{2\pi}{\lambda}x + \omega t) \qquad (2)$$

Where y and x are sideward and forward displacements respectively, t is the time, c_1 and c_2 are the linear and quadratic wave amplitudes, λ is the body wave length and ω is the wave frequency.

The type of swimming method of the robotic fish is based on BCF method, so the propulsive wave curve can be described by equation (2).

7. 2D HYDRODYNAMIC SIMULATION MODEL

7.1. Dynamic Analysis of the Surrounding Fluid

The 2D geometry and the tetrahedronal mesh of the robot fish is generated by GAMBIT. Figure 8 shows the top view of the meshing of the robot fish. In the first step of the design,the water flow and the dynamic analysis of the surrounding water is simulated by CFD (computational Fluid Dynamic). In the dynamic analysis of the water flow surrounding the fish robot, the speed of water flow was adjusted 14m/s and the robotic fish was fixed and the pressure, velocity and vorticity (Fig. 9,10,11) countors were analyzed. Given the smooth flow around the robotic fish and where the vortex is formed, it can be concluded that the geometrical shape of the robotic fish is efficient for swimming.
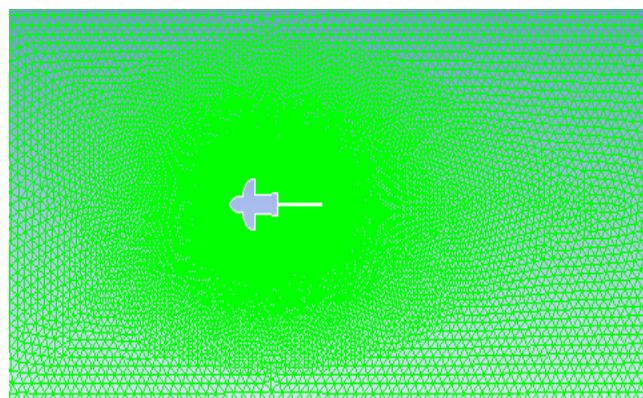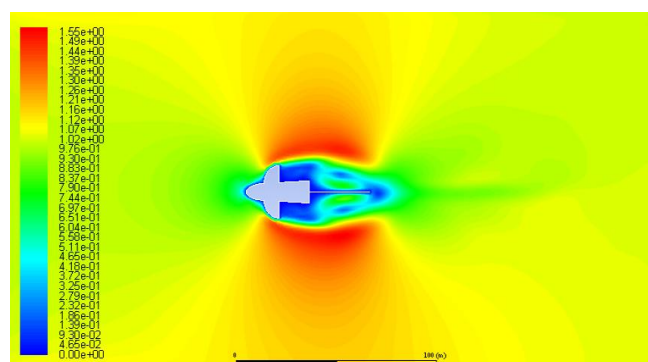

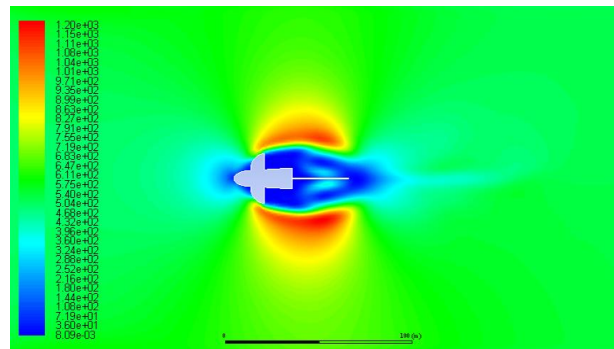**Figure8.** *The robot fish mesh*

Figure9. *The pressure countors*
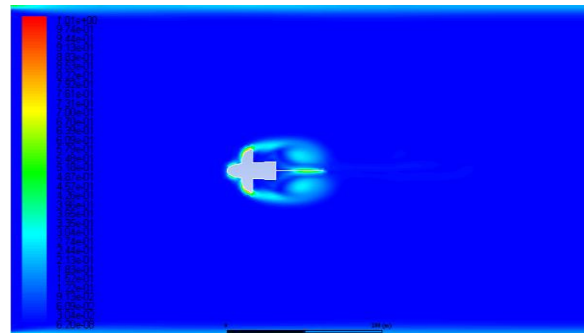
Figure10. *The velocity countors*


Figure11. *The vortices countors*

7.2. Defination of the Swimming Movement of the Robot Fish

At this stage, in ANSYS fluent the alternative movement of the fish robot was defined according to Eq.(2) where c_1=0.03, c_2=0.07, k=$\dfrac{2\pi}{\lambda}$=0.35, ω=2π using UDF(USE-defined distribution) and also the swimming of the robotic fish was simulated using dynamic mesh. The swinging period of the oscillating movement of the fish tail in the simulations equals 1s. distribution of pressure surrounding the fish is shown in figure 12. These figures illustrate that low energy is needed to move the tail of the robotic fish.

7.3. Pressure Distribution

At t=0.25s (Fig.12(a)) the tail of the fish start swinging from the extreme right side to the left the positive pressure is generated on the right side of the tail and it has a wilder distribution than the negative pressure on the left side. The focus of the positive pressure is mostly near the tip of the tail that generate trust along left-forward. The generated pressures are due to the pushed back water by the tail. Also, since the amplitude of the tail movement reduces from tip to the end. Therefore, the amount of positive pressure increases from the end of the tail to the tip and as a result the vortex is generated near the tip of the tail and a big amount of water is pushed towards the right side of the tail.

At t=0.75s(Fig.12(b)) the whole process is reversed.
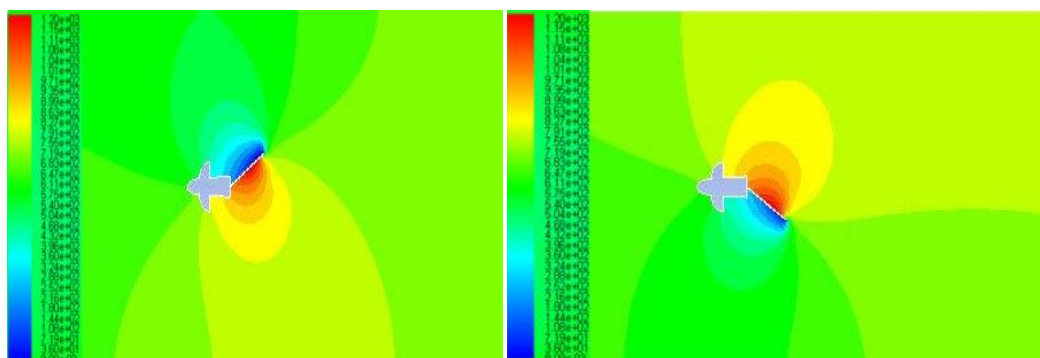
a. reaching the extreme right rotation position (t = 0.25 s)   b. reaching the extreme left rotation position (t = 0.75 s)

Figure12. *The pressure distribution around the robot fish.*

7.4. Velocity

The velocity was analyzed at the same moment that the pressure was analyzed. The velocity countorare shown in figure13.

At t=0.25s(Fig.13(a)) the tail of the robotic fish is swinging from right to left and the vortex shads from the tip to the end counterclockwise that causes the generation of pressure from right to left. Therefore, the generated pressure contributes to the movement of the tail.
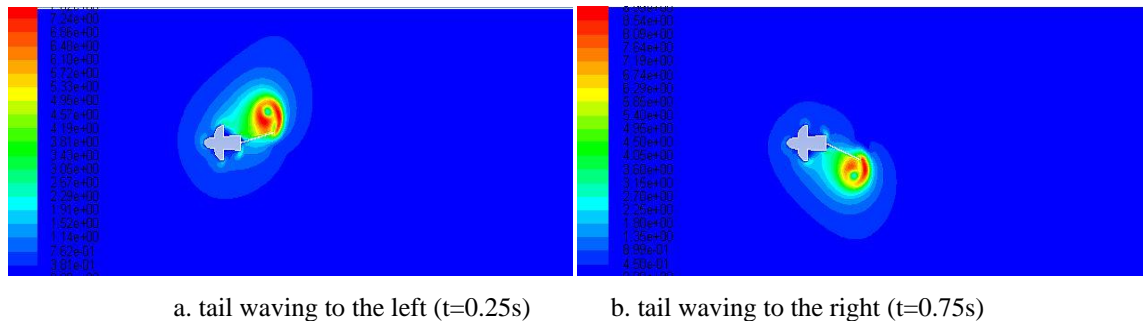
At t=0.75s(Fig.13(b)) the whole process is reversed.

a. tail waving to the left (t=0.25s)   b. tail waving to the right (t=0.75s)

Figure13. *Velocity distribution*

7.5. Force

The frequency of lateral motion of robotic tail in ANSYS is adjusted to 1 hertz and the drag and lift forces produced by the fish tail are analyzed (Fig.14).

Diagram A illustrates the peaks of lift coefficient in a full cycle of tail movement.

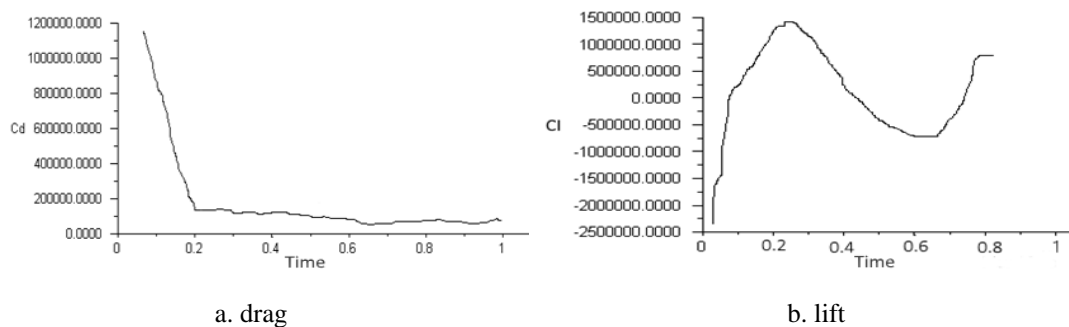Diagram B shows drag coefficient in a full cycle of tail movement which is almost zero.

a. drag   b. lift

Figure14. *Calculated variations of drag and lift coefficients with movement of the tail.*

8. CONCLUSION

A biomimetic robotic fish was designed and fabricated. The model was based on the body of the golden Trout that is categorized in carangiform swimmers. The swimming of the robotic fish was evaluated using CFD, the results of which played an important role to optimize the performance over the course of the design. based on the obtained results, the formation of the vortex and its effect on the lateral movement of the tail and the way it pushes the water that leads to the thrust, were explained. This robot was developed a simple and low cost design with an acceptable efficiency compared to the robots mentioned in the literature. Also the velocity and maneuverability of the fish while making a U-turn, was compared to the flexible tail ones and the result was successful.

The main application for this robotic fish is underwater surveillance and condition monitoring.

For this, the robot was equipped with a GoPro camera with remote control and wireless transmitting signal. The camera was activated and start recording video and capturing images when the robot reached the desired location and the output was observed trough the receiving device. The detail of this work and case studies would be discussed with details in the future paper.

For the future work, it is proposed to design an aerodynamic body to get better efficiency and speed also optimizing the tail thickness. In addition, adding the ability to this robot to dive and rise would be

a fabulous idea. Also installing sensors like sonar, GPS and image processing unit (IPU) can be the next step to improve this model. Also optimizing the speed of tail's lateral movement can improve the swimming speed.

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