Design, Fabrication and Hydrodynamic Analysis of a Biomimetic Robot Fish

Donya Mohammadshahi, Aghil Yousefi-koma, Shahnaz Bahmanyar, Hassan Ghassemi, Hessam Maleki

***Abstract*—**The purpose of this paper is design, fabrication and hydrodynamic analysis of a biomimetic robot fish that is fabricated at Advanced Dynamic and Control Systems Laboratory (ADCSL), University of Tehran. In order to fabricate a fish-like swimming robot, comprehensive hydrodynamic and structural analysis was performed. All of these followed by extensive study of the biology of the fish especially their maneuverability and propulsion system. Swimming principle is achieved from Carangiform swimming mode. This is the swimming mode of fish that use their tail and peduncle for propulsion. Employing servomotors, oscillating mechanism, latex shell, and plexy tail, a tiny model of robot fish has been fabricated and tested. Experiments show smooth, repeatable, and controllable motion of the robot fish. In order to evaluate hydrodynamic forces, Computational Fluid Dynamic (CFD) method was used besides test results. It provides helpful results to optimize performance parameters in the process of design and fabrication.

***Keywords*—** Biomimetic Underwater Robot Fish, Design and Fabrication, Hydrodynamic analysis, Propulsion

I. INTRODUCTION

IN nature, fish has astonishing swimming ability after thousands evolution. It is well known that the tuna swims with high speed and high efficiency, the pike accelerates in a flash and the eel could swims skillfully into narrow holes. Such astonishing swimming ability inspire the researchers to improve the performance of aquatic man-made robotic systems namely Robotic Fish.

Underwater robots are increasingly used in many marine and military fields such as exploring the fish behaviors, detecting the leakage of oil piping, sea bed exploration, mine counter measures, robotics education [7].

Also, most of marine vehicles use propellers for their propulsion. Propellers are not efficient mechanism in small underwater vehicle. The main reason is the production of vortices perpendicular to the direction of motion. Due to their orientation, these vortices do not produce thrust, though they increase power consumption [2].

In 1994, MIT successfully developed an 8-link, fish-like machine RoboTuna, which may be the first free-swimming robot fish in the world. RoboTuna and subsequent RoboPike projects attempted to create AUVs with increased energy savings and longer mission duration by utilizing a flexible posterior body and a flapping foil (tail fin) that exploits external fluid forces to produce thrust [8].

In last twenty years, biologists, increasingly interested in the mechanics of living organisms [4-6], have considered many biomechanical studies of living fishes and the mechanical properties of their tissues. Just this year, two books providing an overview of fish biomechanics and physiology have appeared [12, 18] and a number of recent review papers describe new results on the biomechanics of fishes relevant to locomotion through water [3, 9-18].

At the same time, engineers have increasingly begun to fashion underwater robotic vehicles based on inspiration from living fishes. An alternative design for solving this problem is biomimetic design; therefore the oscillating foil seems to be helpful. Conceptual design, for accurate modeling based on swimming pattern seems to be necessary at the first step. The inspiration model in this paper is a Carangiform fish. They generate thrust principally via body and caudal tail fin motion [3].

In the process of optimizing the performance parameters of ADCSL robot fish, a 2D model of robot fish is considered. This model simulates the oscillating of fish tail and the movement of its peduncle. Through Computational Fluid Dynamic, CFD, analysis performance parameters of robot fish are evaluated and improved by changing different design parameters.

II. SWIMMING MODE

Fish swim with pushing water away behind them. In this part, we discuss the carangiform categories, a swimming

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method of fish, in the viewpoint of the mechanical design of a fish robot. Trout and Salmon are fish typical of those using this swimming method [9].

A. PRINCIPLE OF SWIMMING

Carangiform fish push water away behind them with using both oscillation of a tail fin and motion of a body. The robot fish that is designed and fabricated in Advanced Dynamic and Control System Laboratory (ADCSL) of Tehran University is a kind of Carangiform fish-like model. It uses body foil for propulsion. In fact, the propulsive force is due to positive and negative pressure gradients that are produced by oscillating motion of the fish tail and the movement of its body. Fig. 1 shows the pressure distribution around fish body. Moreover fish using this method have a triangular tail fin generally [9].

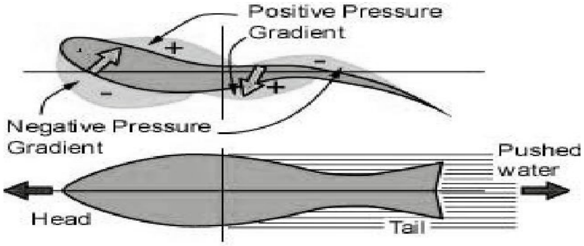


Fig.1 pressure distribution around robot fish body

B. SWIMMING SPEED

The swimming speed of fish is determined by its shape, size and build. Bonito is a fish typical of having a relatively high ratio of the speed to the body length, low shape drag, narrow peduncle, and long lunate caudal fin as it is shown in Fig. 2.

	**Bonito Fish:** Speed = 60 km/h = 16.7 m/s Length = 0.9 m V/L = 18.6

Fig.2 typical shape factors for Bonito fish

By considering typical values for various fish, ADCSL robot fish was designed on the model of Bonito fish.A 3-D model of the robot fish outer shape shows in Fig. 3.

Fig. 3 a 3D model of the outer shape

C. TURNING MODE

ADCSL robot fish turns with only swing of tail fin. As the tail fin is utilized both propulsion and turning, the fish robot gets simple structure and easy control for swimming. ADCSL robot fish swings its tail to one side rapidly from stationary state. In this turning mode, inertia force and friction force of the moving tail and a body are changed to the moment of rotation.

D. UP-DOWN MOTION

As the up-down motion mechanism, ADCSL robot fish has a mechanism for changing angle of up and down direction at its head. The fish robot changes its body to a shape of a wing, and moves up and down by the lift force. It is expected quick response and high dynamic performance in higher range of swimming speed, but the fish robot is needed the higher swimming speed, because it utilizes the lift force.

III. MODELING

The simple fish-like robot discussed in this paper and related earlier works [27, 28, 29, and 30] consists of a planar three-link mechanism immersed in water (Fig.4).

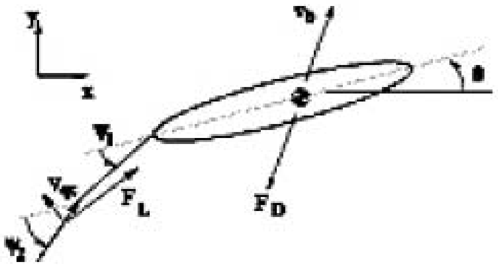


Fig. 4 the carangiform model locomotion

The orientation of the peduncle and tail joints is denoted by $r = [\varphi_1, \varphi_2]^T$, and is measured with respect to the main body reference frame. The forces acting on the system are lift on the tail and drag on the body. The comparatively small effects of lift on the body, drag on the tail, skin friction, and shed vorticity are ignored. As discussed in [30], the drag for a translating and rotating plate is taken to be comparatively small effects of lift on the body, drag on the tail, skin friction, and shed vorticity are ignored. As discussed in [30], the drag for a translating and rotating plate is taken to be

$$F_D = \frac{1}{2}\rho C_d h \int_{\frac{1}{2}-a}^{\frac{1}{2}+a} \left\| \zeta((a+s)e_1) \times e_1 \right\| \zeta((a+s)e_1) ds$$

and the associated moment to be

$$M_D = \frac{1}{2}\rho C_d h \int_{\frac{1}{2}-a}^{\frac{1}{2}+a} \left\| \zeta((a+s)e_1) \times e_1 \right\| (\zeta((a+s)e_1) \times e_1) ds$$

Where ρ is the fluid density, l is the plate length, C_d is the plate’s drag coefficient when its velocity lies a the *y* direction, *h* is the plate height, *a* is the difference in position between the plate’s center of mass and enter of geometry, and

$\zeta((a+s)e_1)$ is an infinitesimal generator giving the body fixed velocity of the plate at the point $a+s$ along the body.

The value of s varies from $\frac{1}{2}-a$ to $\frac{1}{2}+a$, and the unit vector e_1 is in the direction of the body-fixed x axis.The lift acting on a flat plate $F_l = \pi\rho A(\zeta_{qc} \times e_t) \times \zeta_{qc}$ where ζ_{qc} is the velocity at the plate's quarter chord point as measured in the body frame, e_t is a unit vector pointing along the plate toward its leading edge and A is the plate's area. These equations are a simplification via reduction of those from [30], in recognition of the position invariant nature of the lift and drag forces.

IV. FABRICATION

ADCSL fish robot was built to prove out the mechanical design and control system and was tested in water. Fig.5 shows the four skeletal parts of the robot fish: head, two part body, and the tail that is fixed to the end part of the body considered as one part. The head and each part of the body are connected to next one by a single axis articulated joint. The R/C receiver, three servomotors (servos), servo cranks, and push rod linkages complete the prototype. Besides, a wireless camera is set on the fish head to catch data.

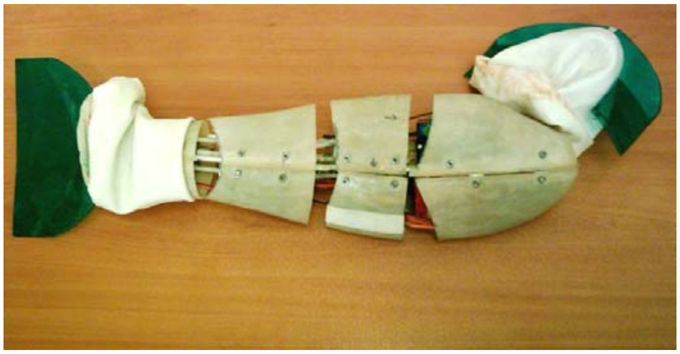
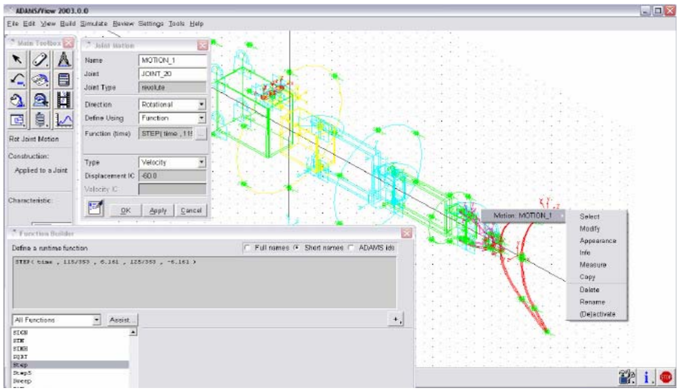


Fig.5.the four skeletal parts of the robot fish

In order to mimic the movement of robot fish and perform dynamic simulation, ADCSL swimming mechanism is modeled using in ADAMS software as shown in Fig.6.



Name MOTION_1
Joint JOINT_20
Joint Type revolute
Direction Rotational
Define Using Function
Function (time) STEP(time ,11
Type Velocity
Displacement IC -60.0

Define a runtime function

```
STEP( time , 115/353 , 6.161 , 125/353 , -6.161 )
```

Fig. 6 swimming mechanism in ADAMS view

Fig.6 shows a schematic of the link mechanism adopted in ADCSL robot fish. In this mechanism, the three servos move the four joints. One is for tail motion and the other bends the waist joint.

Servo 1 moves the head in up and down direction in order to change the fish height in water, and the other two servos provide propulsion by moving the parts to right and left. The swimming speed of 75 cm/s is confirmed with about 3-4 Hz frequency of the tail and waist servos.

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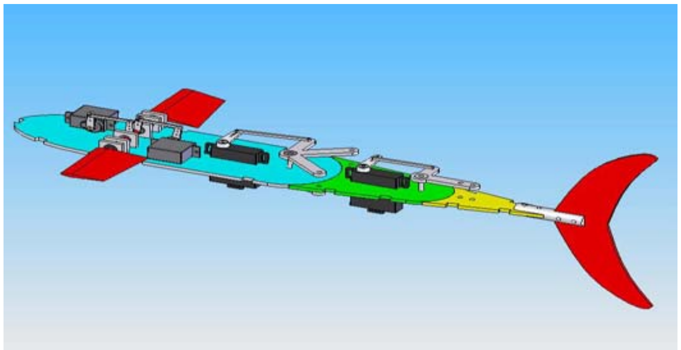


Fig. 7 solid work model of the link mechanism

The outer body of ADCSL robot fish is built from fiberglass that is both light and high resistant as it is shown in Fig.8. Moreover the fins are made of plexiglass. All parts of this body is created by laser cutting and jointed together by special glues named CAT No. 40176 and LOCTITE401. Furthermore the whole system is waterproofed by a Latex cover and silicon skin. Thus, this robot fish can swim in the water.

Fig. 8 the outer body of the robot fish and its waterproof skin

ADCSL robot fish is controlled by a six-channel radio control (R/C) device associated with a micro controller. Fig.9 shows servomotors, control board and radio control receiver.

Fig. 9 servomotors and controller

Specifications and Details of ADCSL robot fish is listed in Table.1.

Table.1 specification and details of the robot fish

Specification	Details
Shape	Shark
Swimming Mechanism	Carangiform
Propulsion Mechanism	Body Foil
Weight	~1400g
Length	~60cm
Width	~12cm
Bord	~20m
Speed	~70cm/sec
Pay Load	~600g
Operation Time	~20min
Charge System	Battery Li-Po

The final model of ADCSL robot fish is shown in Fig. 10.

Fig. 10 final model of the robot fish

ADCSL robot fish swims so smoothly that even real fish do not escape from it as we observed in the laboratory pool. It is successfully tested in water as shown in Fig.11.

Fig. 11 ADCSL robot fish in a water pool

V. Hydrodynamic Analysis

The estimation of hydrodynamic forces posing on the robot fish is of high importance. It gives an essential anticipation of propulsive force. In addition, dynamic analysis of the surrounding fluid by Computational Fluid Dynamic, CFD, plus simulation of the fluid flow helps a lot in the process of designing the robot fish. It will be even possible to control the eddies with a perturbation flow control instrument.

The CFD analysis objective is to simulate the flow passed the tail of the robot fish in the forward motion. CFD analysis also evaluates the thrust performance of the tail using the actual 2D tail kinematics. In this analysis the fluid was supposed to be single phased and the flow to be distributed and incompressible. Here a 2D robot fish is modeled. Fig. 12 shows the top view of the meshing of the robot fish. In the solving process the fluid around the robot fish is meshed in two different cases. In the first case, it is assumed to have a fixed robot fish and a moving flow.

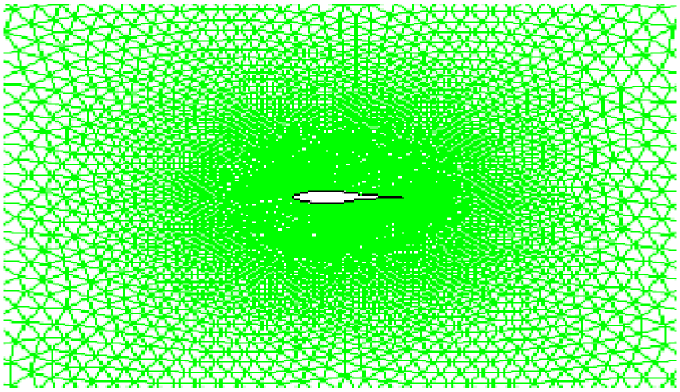


Fig. 12 the robot fish mesh

Fig. 13, Fig.14, and Fig. 15 present the velocity, pressure, and vorticity countors around the fish respectively at the speed of 75 cm/s CFD analysis results show smooth flow around the fish as a consequence of the streamlined body shape of the robot fish.

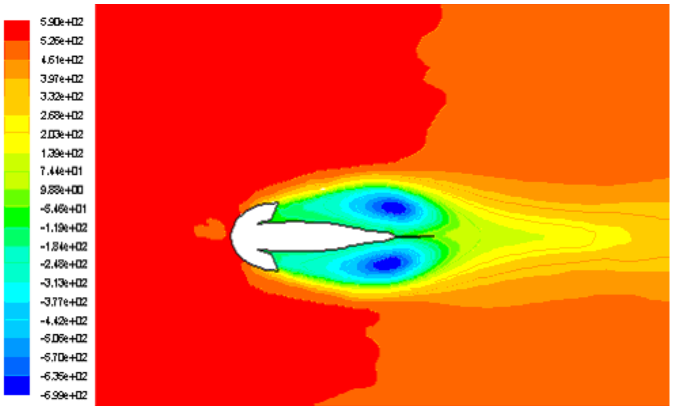


Fig. 13 the pressure countors in the steady motion

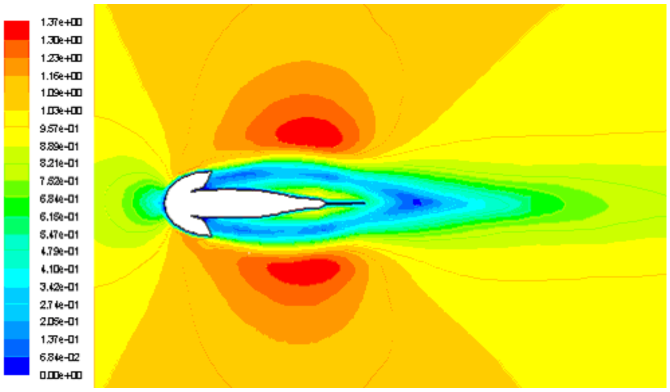


Fig. 14 the velocity countors in the steady motion

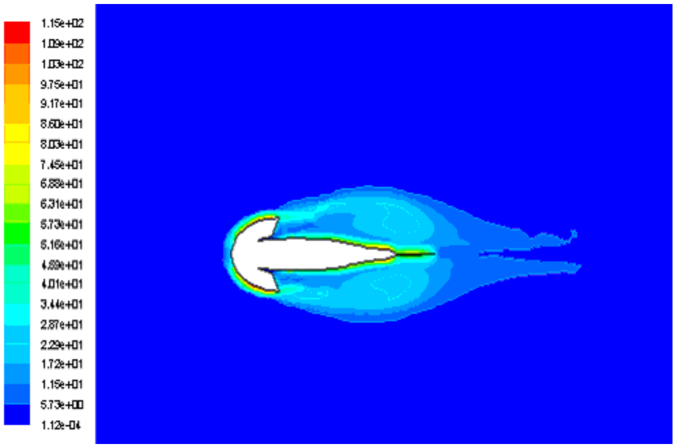
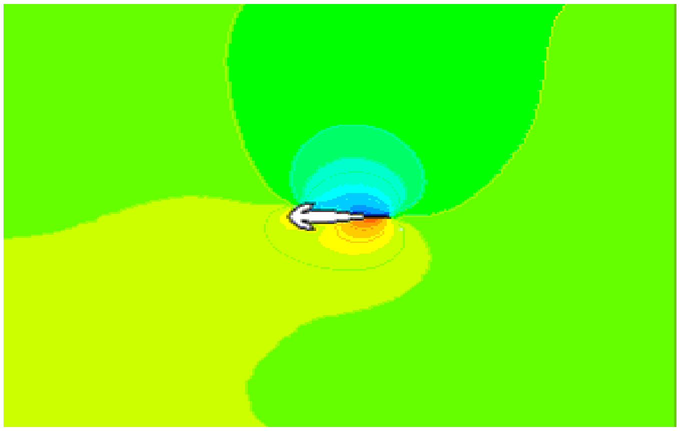


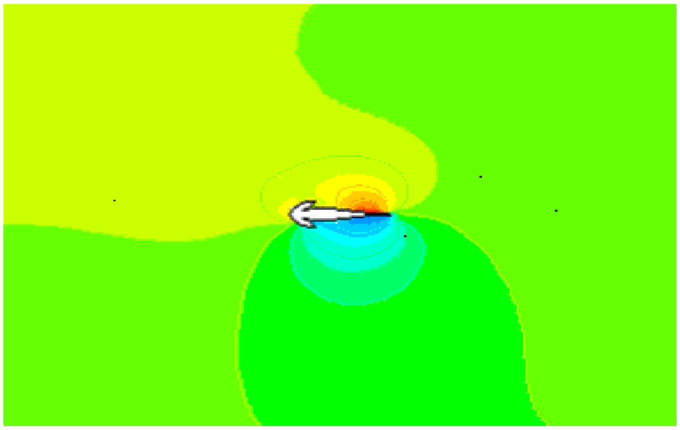
Fig. 15 the vortices countors in the steady motion

In the second case, the robot fish has real motion. It pushes water back by oscillating motion of its tail and the movement of its body. This mechanism is able to react quickly with high efficiency.

Moreover the robot fish has a turning mode, in which its body will rotate to the intended direction and start to wave. In this way the radius of turning will decrease. It also has a mechanism to move its tail and head, up and down. After meshing the solution region and solving the problem the following result is obtained. The pressure distribution around the fish is shown in Fig.16. This figure shows that the fish needs low energy for its propulsion.



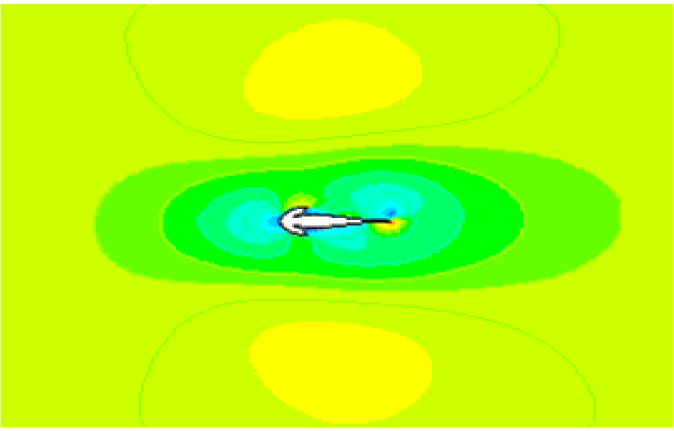
a) tail waving to the right



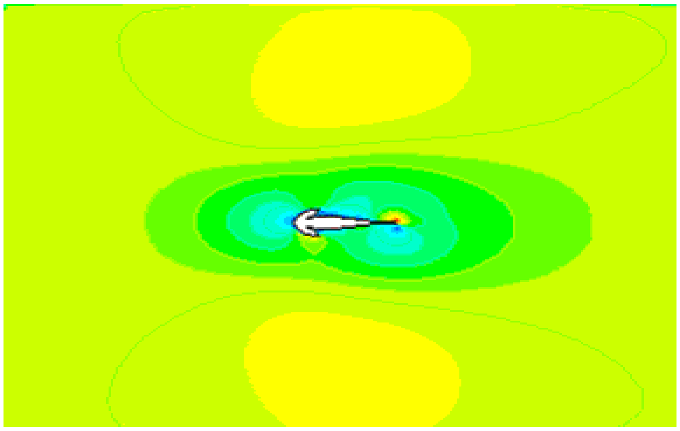
b) tail waving to the left

Fig. 16 the pressure distribution around the robot fish at t/T=1.15.

Fig. 17 shows that the tail produce vortices that pass to the downstream. These vortices can potentially enhance the thrust and produce low turbulence in the downstream.



a) tail waving to the right

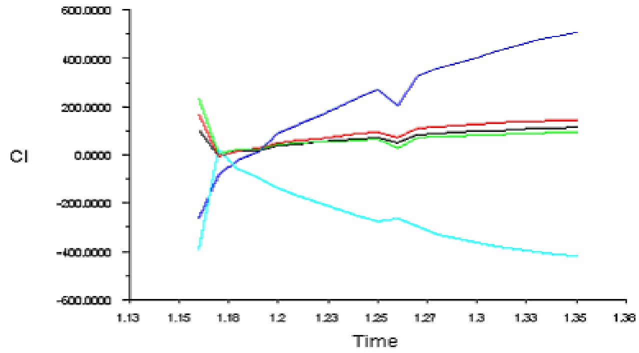


b) tail waving to the left

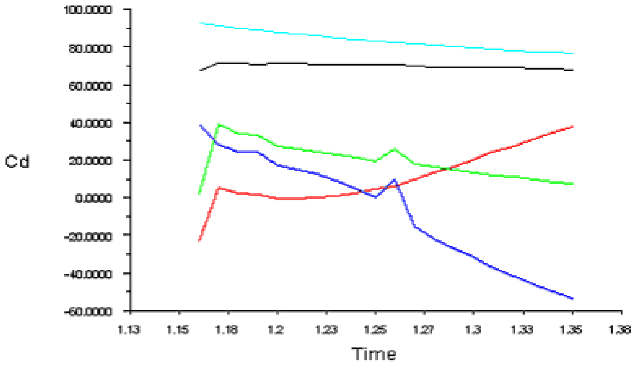
Fig. 17 the pressure distribution around the robot fish at t/T=0.7.

Another significant finding of the analysis is the smooth flow around the tail that causes a high performance as it is shown in Fig. 17.

CFD analysis can also provide hydrodynamic forces that are produced by the robot fish tail. Fig.18 shows of the mean value of the hydrodynamic coefficients produced by the robot fish in the steady analysis.



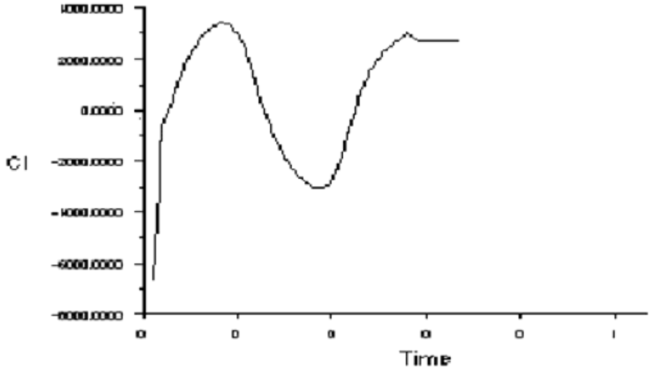
a) lift



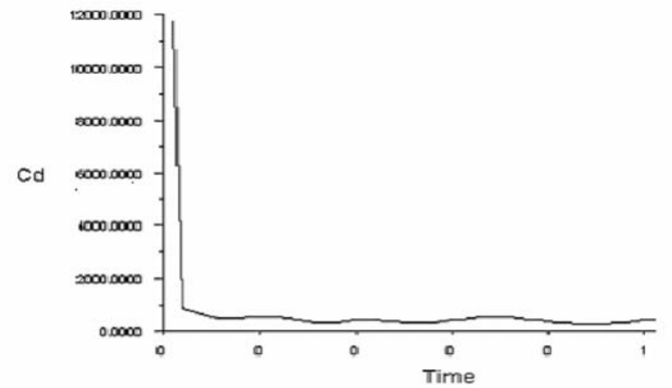
b) drag

Fig. 18 the computed temporal variation of the drag and lift coefficient for the tail motion.

Fig.19 shows two components of the forces produced by the tail waving in the unsteady analysis. In first diagram the lift coefficient and it is observed that there are large peaks of lift during the full cycle. Second diagram shows that the drag coefficient over one cycle is small.



a) lift



b) drag

Fig.19 the computed temporal variation of the drag and lift coefficients with tail waving in the unsteady motion.

The first diagram shows the lift coefficient that has large peaks during the full cycle, and the second diagram shows that the drag coefficient over one cycle that becomes too small after the starting time.

VI. CONCLUSION

The principle objective of this project was to design, fabricate and analyze an undetectable, light and effective biomimetic robot fish that can be utilized in research and commercial applications. The fish push water away behind it by using both oscillation of its tail fin and motion of the end part of its body. The magnitude of propulsion is a function of the tail size, angle, waving frequency, and flexibility as well. This is one of the difficulties of robot fish design since their propulsion force varies to a large extent. Consequently, stability, control, and navigation of these fascinating small creations are challenging issues. The propulsive force induced by the robot fish provides the input for stability and control system. In order to evaluate these forces, Computational Fluid Dynamic (CFD) method was used besides test results. It provides helpful results to optimize performance parameters in the process of design and fabrication. The actual robot fish was fabricated and tested successfully.

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