Design, Fabrication and Hydrodynamic Analysis of a Biomimetic Robot Fish

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Abstract: - This paper is a review on design, fabrication and hydrodynamic analysis of a biomimetic robot fish that is made in Advanced Dynamic and Control System Laboratory, ADCSL, at University of Tehran. In order to build a fish-like swimming robot comprehensive hydrodynamic and structural analysis were performed in addition to a lot of try and errors in fabrication. All of these followed by extensive study of 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. Experiments show feasibility and good execution of ADCSL robot fish.

Key-Words: - Biomimetic Underwater Robot Fish, Design and Fabrication, Hydrodynamic analysis, Propulsion

1 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 countermeasures, 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 [19-22]. 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 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.
2 Swimming Mode
Fish swim with pushing water away behind them. In this part, we discuss the carangiform categories, a swimming 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].

2.1 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].

2.2 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.

<table>
<thead>
<tr>
<th>Bonito Fish:</th>
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<tbody>
<tr>
<td>Speed = 60 km/h = 16.7 m/s</td>
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<tr>
<td>Length = 0.9 m</td>
</tr>
<tr>
<td>V/L = 18.6</td>
</tr>
</tbody>
</table>

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

2.3 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.

2.4 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.

3 Fabrication
ADCSL fish robot was built to prove out the mechanical design and control system and was tested in water. Fig.4 shows the four skeletal parts of ADCSL 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.
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.5.

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.

The outer body of ADCSL robot fish is built from fiberglass that is both light and high resistant as it is shown in Fig.7. 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.

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

Table.1. Specifications and Details of ADCSL robot fish

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
<td>Shark</td>
</tr>
<tr>
<td>Swimming Mechanism</td>
<td>Carangiform</td>
</tr>
<tr>
<td>Propulsion Mechanism</td>
<td>Body Foil</td>
</tr>
<tr>
<td>Weight</td>
<td>~1400g</td>
</tr>
<tr>
<td>Length</td>
<td>~60cm</td>
</tr>
<tr>
<td>Width</td>
<td>~12cm</td>
</tr>
<tr>
<td>Bord</td>
<td>~20m</td>
</tr>
<tr>
<td>Speed</td>
<td>~70cm/sec</td>
</tr>
<tr>
<td>Pay Load</td>
<td>~600g</td>
</tr>
<tr>
<td>Mission Time</td>
<td>~20min</td>
</tr>
<tr>
<td>Charge System</td>
<td>Battery Li-Po</td>
</tr>
</tbody>
</table>

The final model of ADCSL robot fish is shown in Fig. 9.
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. 10.

Fig. 9. Final model of ADCSL robot fish.

Fig. 10. ADCSL robot fish in water pool.

Fig. 11. ADCSL robot fish mesh.

Fig. 12. Pressure contour in steady motion.

Fig. 13. Velocity contour in steady motion.

4 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 surrounding fluid by Computational Fluid Dynamic, CFD, plus simulation of fluid flow helps to increase the efficiency of robot in design process. It will be even possible to control the Eddies with a perturbation flow control instrument.

The CFD analysis objective is to examine the flow past on the tail of robot fish that has steady forward motion. CFD analysis also quantifies the thrust performance of tail using the actual 2d tail kinematics described above. In this analysis the fluid was supposed as single phased and the flow as distributed and incompressible. Here a 2D robot fish is modeled. For this analysis the fluid around robotfish is meshed in two cases. Fig. 11 shows the top view meshing of the ADCSL robotfish. In the first case, it is assumed to have fixed body and moving flow.

Fig. 12 and Fig. 13 present the velocity and pressure contours at fish speed of 75 cm/s. CFD analysis results show smooth flow around the fish that it is because of streamlined shape of robot fish’s body.

In the second case, the robot fish has real motion. The robot fish pushes water back by oscillating motion of its tail and the movement of its body. This mechanism that is able to react quickly and totally has high motion efficiency. Also a mode is described for turning, in which the fish's body will rotate to the intended direction and start to wave. In this way the radius of turning will decrease. The robot fish presented in this article, has a mechanism to change the direction of its tail and head, up and down. After meshing the solution region and solving the problem the following result is obtained. Distribution of pressure around fish’s body is shown in Fig. 14. This figure shows that the fish needs low energy for its motion.
Fig. 14. Distribution of pressure around fish at t/T=1.15.

Fig. 15 shows that the tail produce vorticity that pass to the downstream. These vortices can potentially enhance thrust and they produce low turbulence downstream.

Another significant finding of these analysis is the smooth flow around the tail that cause a high performance as it can be seen in Fig. 16.

CFD analysis can also provide hydrodynamic forces that are produced by ADCSL robot fish tail. Fig. 17 shows of the mean value of the hydrodynamic coefficients produced by the tail.

Fig. 17. Computed temporal variation of drag, lift and momentum coefficient for the tail motion.
Fig.17 shows two components of the forces produced by the tail waving. 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. Third part of Fig.17 shows the momentum coefficient has large peak in a cycle.

5 Conclusion
In conclusion the principle goal of this project was to design, fabricate and analyze an undetectable, light and effective biomimetic robot fish that can perform research and perhaps destructive missions. This fish push water away behind it with using both oscillation of its tail fin and motion of end part of its body. The magnitude of propulsion is a function of tail size, angle, waving frequency, and flexibility as well. This is one of the complexities of MAVs since their propulsion force vary to a large extent. Consequently stability, control, and navigation of these fascinating small creations are challenging. In simulation structure of robot fish propulsive force provides the input for stability and control system. In order to evaluate these forces Computational Fluid Dynamic (CFD) method can be used besides test results. Here FLUENT is employed as the hydrodynamic simulation tool. It provides us helpful anticipation to optimize performance parameters in the process of design and fabrication.

References: