World Academy of Science, Engineering and Technology
International Journal of Marine and Environmental Sciences
Vol:8, No:4, 2014

Open Science Index, Marine and Environmental Sciences Vol:8, No:4, 2014 publications.waset.org/9999284.pdf

Fish Locomotion for Innovative Marine Propulsion Systems

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***Abstract*—**There is an essential need for obtaining the mathematical representation of fish body undulations, which can be used for designing and building new innovative types of marine propulsion systems with less environmental impact. This research work presents a case study to derive the mathematical model for fish body movement. Observation and capturing image methods were used in this study in order to obtain a mathematical representation of *Clariasbatrachus* fish (catfish). An experiment was conducted by using an aquarium with dimension 0.609 m x 0.304 m x 0.304 m, and a 0.5 m ruler was attached at the base of the aquarium. Progressive Scan Monochrome Camera was positioned at 1.8 m above the base of the aquarium to provide swimming sequences. Seven points were marked on the fish body using white marker to indicate the fish movement and measuring the amplitude of undulation. Images from video recordings (20 frames/s) were analyzed frame by frame using local coordinate system, with time interval 0.05 s. The amplitudes of undulations were obtained for image analysis from each point that has been marked on fish body. A graph of amplitude of undulations versus time was plotted by using computer to derive a mathematical fit. The function for the graph is polynomial with nine orders.

***Keywords*—**Fish locomotion, body undulation, steady and unsteady swimming modes.

I. INTRODUCTION

FISH and most aquatic animals are efficient swimmers, which have remarkable maneuverability, capability to follow desired trajectory, and are able to stabilize themselves according to currents and surges. A fish swims by exerting force against the surrounding water. There are exceptions, but this is normally achieved by the fish contracting muscles on either side of its body in order to generate waves of flexion that travel the length of the body from nose to tail, generally getting larger as they go along. The vector forces exerted on the water by such motion cancel out laterally, but generate a net force backwards, which in turn pushes the fish forward through the water. Most fishes generate thrust using lateral movements of their body and caudal fin (Fig. 1). 15% of the fish families use median (dorsal and anal fins) and/or paired (pectoral and pelvic) fins (MPF) locomotion as their routine propulsive means [1]. Within MPF propulsion system, many fishes such as knifefish, triggerfish and bowfin, routinely use the long-based undulatory body/fins as the sole means of locomotion, as well as for maneuvering and stabilization. However, they cannot swim as fast as fishes that use bodies and caudal fins [2]. The undulating elongated ribbon-like fins have high performance swimming, precise maneuvering and low speed stability, which not only can adapt to cruise swimming in calm waters, but also slow swimming, turning manoeuvres and rapid acceleration from stationary in structurally complex surroundings, such as turbulent waters and seashore areas.

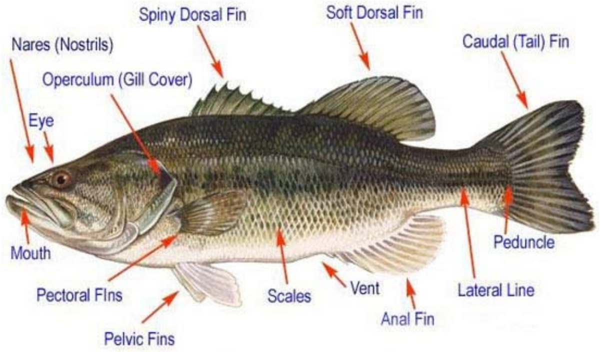

Fig. 1 The terminology to identify fish fins [3]

Study and research on fishes and other aquatic creatures help in understanding how their biological counterparts are functioning [4]. Currently, there is an increase of interest toward designing and building vehicles (biomimetic robots) that imitate fish motion, with the idea that such crafts would be more efficient, and/or more maneuverable than propeller-driven vehicles [5]. Biomimetic robots may be quite stealthy since they do not suffer from the cavitation noise generated by conventional marine propellers. Biomimetic robots may also borrow their senses and structure from other animals, such as insects and birds [6]. Development of underwater vehicles is one of the areas where biomimetic robots can potentially perform better than conventional robots. Robotics engineers are able to combine the study and the findings of biology and engineering, while other researchers can actively explore lightweight or micro-robotic fish using smart materials for actuation and locomotion [7]. Another reason for the focus in biomimetic propulsion systems is the increasing awareness to preserve the environment. The marine ecological environment has been deteriorating because of human interaction with them. One extremely destructive tool used by such human interaction is the propeller, the main propulsion systems used by most current water vehicles. The broadband noise from marine propellers cavitation may have severe acoustic effects

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on marine wildlife, like changes of behavior, 'masking' of other signals, or causes temporary (or permanent) hearing trauma.

The prerequisite in developing such new propulsion systems is the characterisation of the fish propulsion system. In this research work, the body motion of a catfish had been studied during different swimming modes using high speed camera. The oscillation motion of the fish body was converted into mathematical equations, which can provide very useful information for designing new types of marine propulsion systems.

II. Research Instruments and Devices

In this study, the walking catfish, or *Clarias batrachus* (Fig. 2), which had 25 cm body length, was selected to observe and determine the amplitude of its body undulation. This fish has an elongate body that is broader at the head, tapering toward the tail. It is easily recognizable as a catfish, having four pairs of barbells (whiskers) and fleshy, papillated lips. The pectoral spines are large and robust and finely serrated along the margins. The dorsal fin is continuous and extends along the back two-third of the body length. The dorsal, caudal, and anal fins together form a near-continuous margin; the caudal fin is rounded and not eel-like though it is occasionally fused with the other fins [2].

Fig. 2 The walking catfish, *Clariasbatrachus*

A glass aquarium (Fig. 3) was used to observe the catfish locomotion. The working section for this aquarium was 2″ x 1″ x 1″(0.609 m x 0.304 m x 0.304 m) with 50 cm ruler at the bottom of the aquarium, which was used as a reference during the images analysis process. The ruler was placed at the bottom to obtain the actual value of picture to be captured.

Fig. 3 Glass aquarium with 50 cm ruler

In order to analyze the catfish locomotion, a Progressive Scan Monochrome Camera (Fig. 4) was used, capable to record images within milliseconds, to capture progressive pictures of the complicated fish motion. The major specifications of the Progressive Scan Monochrome Camera are:

- 659 (h) x 494 (v) square pixels
- Single channel video output
- High S/N ratio >56 dB
- Shutter speeds from 1/30 to 1/100,000 second in 15 steps

Fig. 4 Progressive Scan Monochrome Camera for the current study

The aquarium was placed at the Marine Technology Center (MTC) of Universiti Teknologi Malaysia, in a good position on a table with adequate visual and enough lighting in order to obtain proper results for the imaging process of fish motion. Fresh water was used to fill the aquarium up to 10 cm height from the base of the aquarium. The level of the fresh water was decided to be set to 10 cm because it would be easy to capture the images in this condition and to keep catfish from jumping out from the aquarium. The camera was placed at 50 cm from the bottom of the aquarium and connected to a laptop to control the snap shots. Seven points had been marked on the catfish body (Fig. 5) using a white marker to acquire fish equation of motion by indicating the locomotion of the catfish. Point 0 was marked at the catfish's head as an origin of the local coordinates system for analyzing the amplitude of body undulation by using Adobe Photoshop CS3 [8] and AutoCAD [9] programs. The distance from point 0 to 1 was 3 cm, and followed by 4 cm, 3.2 cm, 3.5 cm, 3.5 cm, and 2.5 cm. The marks would indicate the catfish's body movement during swimming and give the amplitude of each point on the fish body with reference to point 0.

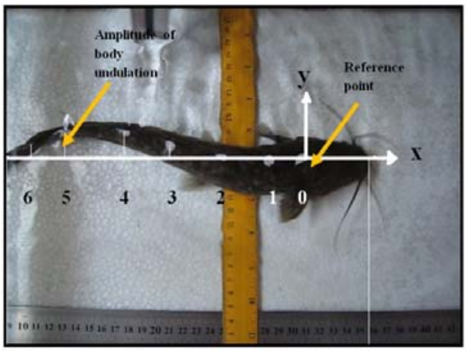

Fig. 5 The marked points on the catfish body

III. RESULTS AND DISCUSSION

Fig. 6 shows different pictures for the motion of catfish with time interval of 0.05 seconds between consequent images. Two different swimming modes for the catfish had been found based on fish body undulation amplitude, steady and unsteady swimming modes. In the steady swimming mode, the body undulation amplitude was continuous and almost similar in each captured frame, while the amplitude of body undulation varied with time in the unsteady swimming mode. The recorded amplitudes of catfish body undulation in the two swimming modes in this study are shown in Tables I and II.

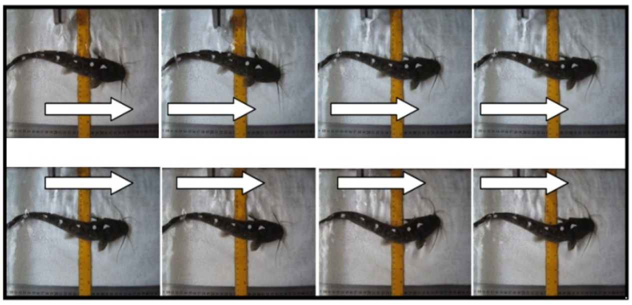

Fig. 6 Sample of captured successive pictures for the catfish

TABLE I
THE AMPLITUDE OF CATFISH BODY UNDULATION IN STEADY SWIMMING MODE

Time (s)	**Amplitude of body undulation (mm)**						
	Point 0	***Point 1***	***Point 2***	***Point 3***	***Point 4***	***Point 5***	***Point 6***
0	0	-2.4	-5.1	-13.3	-20.2	-40.1	-60.1
0.05	0	-3.6	-6.3	-8.1	-11.4	-25.4	-45.8
0.1	0	-1.7	-4.1	-2.2	2.1	-9.1	-20.3
0.15	0	-2.6	0	9.2	18.1	18.1	10.1
0.2	0	0.3	2.3	10.3	15.7	16.3	9.2
0.25	0	0.5	1.1	9.1	17.6	17.4	12.3
0.3	0	2.6	7.8	23.3	38.1	53.3	5.1
0.35	0	0	4.9	23.3	43.2	58.1	65.8
0.4	0	2.2	6.3	25.2	48.2	73.3	80.2
0.45	0	-4.3	3.8	19.3	45.1	75.1	84.8

TABLE II
THE AMPLITUDE OF CATFISH BODY UNDULATION IN UNSTEADY SWIMMING MODE

Time (s)	**Amplitude of body undulation (mm)**						
	Point 0	***Point 1***	***Point 2***	***Point 3***	***Point 4***	***Point 5***	***Point 6***
0	0	0	0	0	0	0	0
0.05	0	-2.5	-4.5	0	3.4	-7.6	-24.3
0.1	0	-3.1	0	10.4	24.4	26.5	18.5
0.15	0	0.5	4.3	23.1	50.4	73.4	69.5
0.2	0	-0.3	-1.1	15.4	42.3	73.4	85.6
0.25	0	-3.2	-10.4	-13.5	5.1	40.4	58.6
0.3	0	3.2	-9.1	-22.2	-17.3	5.4	24.5
0.35	0	0.5	-10.4	-30.4	-44.3	-45.1	-28.3
0.4	0	-3.1	-12	-32.4	-47.8	-65.4	-63.2
0.45	0	3.2	-10.5	-24.3	-46.5	-75.1	-87.1

Each point on the body of the catfish was analyzed frame by frame to observe and determine the undulation amplitude of the catfish body. The amplitude undulations of catfish body, relative to the centre line within time interval of 0.05 seconds during steady swimming mode are shown in Fig. 7. The previous figure was obtained from each frame recorded by the Progressive Scan Monochrome Camera, where the direction of movement of the catfish was from left to right, as shown in Fig. 6. The measured results from Frame 1 at 0.05 seconds showed that, the body of the catfish moved towards more negative values and it had low amplitude undulation, as can be seen from Fig. 7. At point 3, 4, 5, and 6, the undulation amplitude of the catfish was very high, which might refer to the need of the catfish to overcome water friction resistant by producing more body force. Fig. 8 shows the movement of catfish body in unsteady swimming mode and its higher speed in this swimming mode. Undulation of the catfish body clearly varied from one frame to another in the unsteady swimming mode. In addition, the fish body undulation changed dramatically at point 3, 4, 5, and 6 with time in fish unsteady swimming mode.

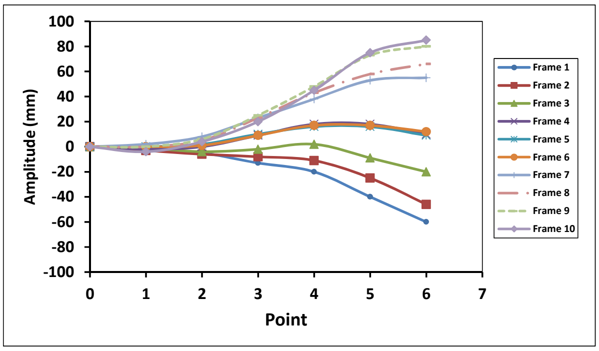

Fig. 7 Movement of catfish body undulation in steady swimming mode

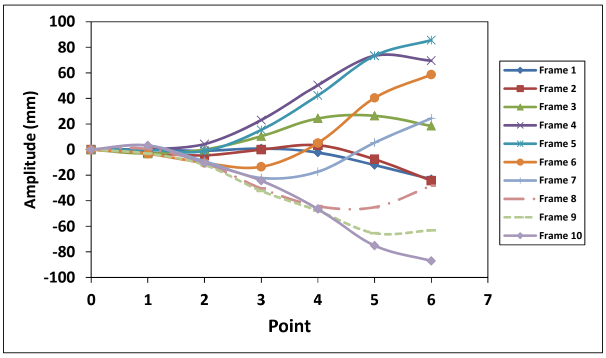

Fig. 8 Movement of catfish body undulation in unsteady swimming mode

The results of each point on the body of the catfish were analyzed to obtain the amplitude of fish body undulation for one period of time in both steady and unsteady swimming modes, as shown in Figs. 9 and 10. In the steady swimming mode (Fig. 9), the undulation of catfish body had very low amplitude of motion for each point on the fish body at time range from 0 to 0.3 seconds, while the amplitude of motion changed dramatically from 0.3 to 0.45 seconds. Point 6 was located at the catfish’s tail, and this point had very high amplitude of undulation during swimming, as shown in Fig. 9. In unsteady swimming mode (Fig. 10), the catfish body had changed dramatically at each point. As shown in Fig. 10, at 0.2 seconds, the undulation amplitude by catfish body is very high. At time 0.1 to 0.3 seconds, the amplitude of undulation was in a positive direction and was in a negative direction at time 0.3 to 0.5 second. The elongate catfish body had been undulating quickly and also moved faster, causing higher amplitude. Finally, in order to obtain the equation of motion for the catfish based on the seven marked point, LAB Fit software [10] was used to derive the equation as shown in Tables III and IV.

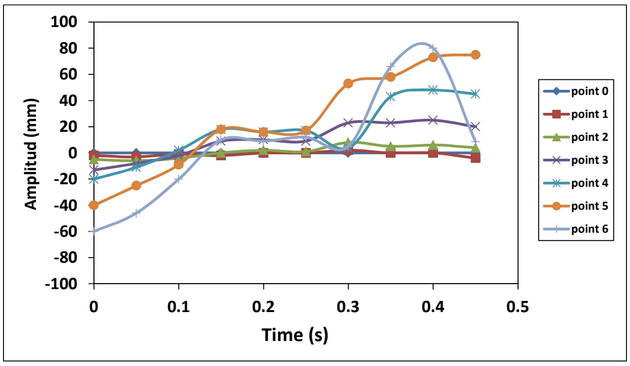

Fig. 9 Variation of catfish fish body undulation amplitude with time in steady swimming mode

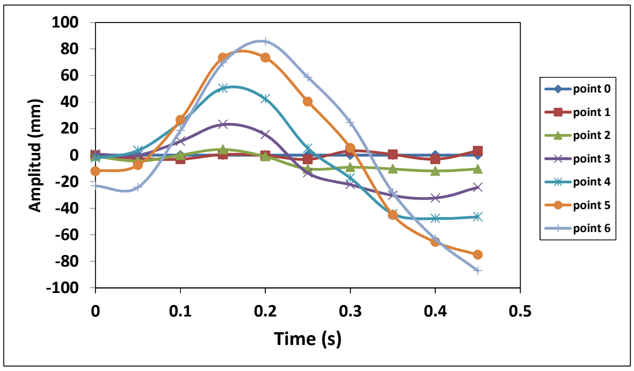

Fig. 10 Variation of catfish fish body undulation amplitude with time in unsteady swimming mode

TABLE III
THE MATHEMATICAL EXPRESSIONS FOR THE MOVEMENT OF CATFISH IN STEADY SWIMMING MODE (Y IS POINT DISPLACEMENT AND T IS TIME)

Point	Equation of motion
1	$y = - 2.4 - 2080.19*t + 103221.74*t^{2} - 2019959.7*t^{3} + 20779953*t^{4} - 1.2470413E08*t^{5} + 4.5203303E08*t^{6} - 9.7449395E08*t^{7} + 1.1494362E09*t^{8} - 5.7071214E08*t^{9}$
2	$y = - 5.1 - 2077.31*t + 108144.1*t^{2} - 2249298.5*t^{3} + 24656713*t^{4} - 1.5670502E08*t^{5} + 5.9622533E08*t^{6} - 1.3370307E09*t^{7} + 1.6273046E09*t^{8} - 8.2808037E08*t^{9}$
3	$y = - 13.3 - 1315.659*t + 82609.109*t^{2} - 1907401.8*t^{3} + 22877437*t^{4} - 1.563115E08*t^{5} + 6.2903502E08*t^{6} - 1.472355E09*t^{7} + 1.8515369E09*t^{8} - 9.6609057E08*t^{9}$
4	$y = - 20.2 + 241.33687*t + 4544.8431*t^{2} - 331359.64*t^{3} + 6729826.8*t^{4} - 62067112*t^{5} + 3.013345E08*t^{6} - 7.9927324E08*t^{7} + 1.0968471E09*t^{8} - 6.0970769E08*t^{9}$
5	$y = - 40.1 - 821.0949*t + 79192.368*t^{2} - 2170029.2*t^{3} + 29656252*t^{4} - 2.226641E08*t^{5} + 9.5901795E08*t^{6} - 2.3593138E09*t^{7} + 3.0798922E09*t^{8} - 1.653831E09*t^{9}$
6	$y = - 60.1 + 12247.206*t - 626030.03*t^{2} + 12766828*t^{3} - 1.353298E08*t^{4} + 8.32678E08*t^{5} - 3.087152E09*t^{6} + 6.794345E09*t^{7} - 8.16519E09*t^{8} + 4.121453E09*t^{9}$

TABLE IV
THE MATHEMATICAL EXPRESSIONS FOR THE MOVEMENT OF CATFISH IN UNSTEADY SWIMMING MODE (Y IS POINT DISPLACEMENT AND T IS TIME)

Point	Equation
1	$y = - 4.16E-06 - 1245.5*t + 66341.08*t^{2} - 1462504.3*t^{3} + 16893709*t^{4} - 1.11917E08*t^{5} + 4.3927825E08*t^{6} - 1.0075E09*t^{7} + 1.245668E09*t^{8} - 6.40574E08*t^{9}$
2	$y = - 0.90 - 1174.7243*t + 56595.184*t^{2} - 1176723.2*t^{3} + 13370798*t^{4} - 88626625*t^{5} + 3.4923791E08*t^{6} - 8.0344648E08*t^{7} + 9.948725E08*t^{8} - 5.1175438E08*t^{9}$
3	$y = 0.79 - 3595.0387*t + 188441.89*t^{2} - 3944232.4*t^{3} + 43798814*t^{4} - 2.812085E08*t^{5} + 1.0737648E09*t^{6} - 2.4023054E09*t^{7} + 2.905144E09*t^{8} - 1.4652586E09*t^{9}$
4	$y = - 2.3 - 2636.8729*t + 148766.55*t^{2} - 3249078.8*t^{3} + 37994488*t^{4} - 2.553618E08*t^{5} + 1.01182E09*t^{6} - 2.33287E09*t^{7} + 2.893318E09*t^{8} - 1.491384E09*t^{9}$
5	$y = - 12.1+ 153.80518*t + 907.95591*t^{2} - 281133.71*t^{3} + 7847454.5*t^{4} - 79231256*t^{5} + 3.942903E08*t^{6} - 1.0505215E09*t^{7} + 1.4401786E09*t^{8} - 7.9921117E08*t^{9}$
6	$y = - 23.2 - 3737.329*t + 181561.09*t^{2} - 3614582.8*t^{3} + 40214148*t^{4} - 2.61783E08*t^{5} + 1.014076E009*t^{6} - 2.30007E09*t^{7} + 2.818563E09*t^{8} - 1.440014E09*t^{9}$

The mathematical expressions shown in Table IV represent the undulation of the body of the catfish as it traverses the tracks. The equations can be used as input into the control systems of the fish-like robots as described in [6].

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IV. CONCLUSION

The objective of the study was to obtain the equations of fish locomotion and relate them to its propulsion system. Catfish or '*Clarius batrichus'* was chosen to measure the amplitude of fish body undulation. The equations of fish locomotion, as a function of time, were expressed mathematically as polynomials of ninth order. The results of this research work can be used for designing new types of marine propulsion systems with less environmental impact or building bionic fish robot. The new propulsion system can overcome many problems of conventional propulsion systems such as vibration, erosion, cavitation and also reduce air pollution by reducing the amount of carbon dioxides that are released into the atmosphere.

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