Hydrodynamics Analysis of Fish Movement in Steady Swimming for Modeling of Fish Robot

A. S. Vaghefi and M. Abbaspour

Abstract—**Quantitative morphological and kinematic parameters of fish movement have been studied here. BCF mechanism of two carangiform fish was taped by high speed digital video and undulatory movement of each fish at different velocity was revealed. The amplitude of this wave increases dramatically near the tail and it is very small near the head. Undulatory movement of Pangasius sanitwongsei and Trout with different length and speed were recorded by the digital particle image velocimetry (DPIV) and image processing methods and optimal coefficients of the movement equations and appropriate location of joints are experimentally derived. The velocity of fish movement can be adjusted by changing oscillating amplitude, frequency and the length of caudal fin, respectively. Finally finding in these researches could be applied to design a fish robot.**

Index Terms—**Undulatory movement equation, fish robot, DPIV, Pangasius, Trout.**

I. Introduction

Scientists believe that animals could develop optimal solutions to solve engineering problems. Robotics researchers have been impressed by the incredible swimming ability of the fish for a long time, so they effort to improve the performance of aquatic man-made robotic systems by using undulatory movement instead of conventional rotary propellers used in ships or underwater vehicles. This kind of propulsion is more effective, less noisy and maneuverable than propeller-based propulsion. Therefore a biomimetic robot fish might be used in many military and marine fields such as exploration of fish behavior, leakage detection in oil pipelines, military reconnaissance, seabed exploration and robotic education, etc [1]. AUV (Autonomous Underwater Vehicle) and ROV (Remotely Operated vehicle) robots do not have enough efficiency and accuracy required in many environmental and engineering applications. They will disturb the natural conditions of environment so design of a robot fish with virtue of marvelous propulsive efficiency, high speed and high maneuverability based on the mechanism of carangiform fish with lowest energy consumption is considered [2]. Video images study of fish movement was started by Marey in 1895. Breder compared different methods of fish movement with an emphasis on simple mechanics of body and caudal fins of fish in 1926. Gray presented a Classical theory in this respect and his paradox made a special place in 1933 [3]. Lighthill studied on a new model based on elongated body theory to analyze the carangiform mechanism, the large amplitude elongated body theory and the irregularly amplitude of caudal fin from 1960 till 1970 [4]. MIT university successfully made the first robot fish with eight-link, RoboTuna in 1994. Then, RoboPike were used to study drag reduction in fishlike locomotion. Later, a superior version of RoboTuna, VCUUV (Vorticity Control Unmanned Undersea Vehicle), was made by MIT. The VCUUV was provided with many different sensors, and could realize up-down motion and avoid obstacles, which allow it to be able to navigate autonomously in a 3-D space [5]. An experimental study on hydrodynamics of undulatory fish movement with DPIV technique (digital particle image velocimetry) are made by Lauder et al., which allowed empirical analysis of force magnitude and direction. They studied fin function in four ray finned fishclades; trout, sunfish, sturgeon and mackerel [6]. Design and control of robot fish has been studied at Essex University in England [7].

Undulatory fish movement mode has been studied widely using experimental, numerical and theoretical techniques. Experimental studies have been applied on the real Fish, biomimetic foils and robot fish. Nevertheless, most former studies focused on robot fish and bioimetic foils and less consideration was made on optimization of undulatory movement of real fish. The technical novelty of this paper lies in analysis of undulatory movement of real fish. the flow pattern of caudal fin locomotion was visualized and the kinematic parameters of Trout adn Pangasius sanitwongsei were determined which in turn it ended up to define the equation of fish movement.

II. Basic Parameters in Fish Movement

Classify fishes into groups based on fin use, is a way of considering fish movement. Those fishes swim with their median fins (dorsal and anal) and paired fins (pectoral and pelvic) are termed MPF (median and paired fin) swimmers and those fishes use primarily their body and caudal fin are classified as BCF (body and caudal fin) swimmers. MPF is used to increase the propulsive and maneuverability efficiency at slow speeds, while BCF movement can increase accelerations and thrust force [8]. There are different classification modes of fish movements: anguiliform, subcarangiform, carangiform and thunniform. In anguiliform mode, the whole body influences on thrust force. In subcarangifom mode, the posterior half of the body

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participates in propulsive mechanism. For carangiform mode, the last third of the body length has an undulatory movement. In thunniform mode, thrust is generated by tail movement [9]. Body fish and movement parameters have been shown in Fig. 1.

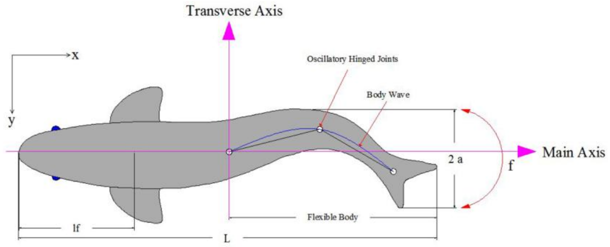

Fig. 1. Illustrates Body fish and movement parameters.

Three parameters in fish movement have been defined; Reynolds number, Strouhal number and shape number [10].

Reynolds number shows the ratio of inertial over viscous forces:

$$Re=u.L/v \tag{1}$$

where u is speed of fish movement, L is body length of fish and v is kinematic viscosity of water. Re is only useful as an order of magnitude and high Re number, means that viscosity is not very important but has several important consequences such as vorticity, wake, added mass and turbulent flow which may vary many of flow parameters, like lift and drag coefficients. Fish movement generates a reverse Karman vortex street in its backward wake of the flow by body and caudal fin. This phenomenon is independent of the Reynolds number but depends strongly on the Strouhal number:

$$St=f.A/u \tag{2}$$

where f is the tail-beat frequency, A is the amplituede of undulatory movement of tail and u is the average velocity of fish movement [10], [11]. In fish movement, St number almost lies between 0.25 and 0.35 to have more effective force. Strouhal number is the ratio of unsteady to inertial force [12]. In this paper, Shape number define as (L_f/L), the ratio of front part of the fish which has the minimum amplitude in undulatory movement to the total length of the fish (Fig. 1). This is a major point and displays less variation of head to the more variation of the body and caudal fin. In fact, it is a fixed point in fish body [13].

III. Materials and Method

A Trout with 27.3 cm length (Fig. 2) and a Pangasius sanitwongsei with 9 cm length (Fig. 3) were studied in a glassy tank that was 90cm long by 30 cm wide and 45 cm high. Trout were obtained from SardAb Meadow Hatchery, Alborz, Iran and housed in laboratory of IAU. Pangasius sanitwongsei is a freshwater fish species in the shark catfish family of order Siluriformes and native to the Mekong River basin and Chao Phraya River basin in Thailand. They are classified in BCF and carangiform mode, and simulated fish robot create undulatory movement with a series of oscillatory hinge joints which are placed at the last 1/3 part of the body. The water was at 20 ℃ and kinematic viscosity was $\nu=1.005\times10^{-6}(m^2/s)$. Two fishes with different L_f/L were chosen; 0.150 and 0.280, for Trout adn Pangasius sanitwongsei respectively.

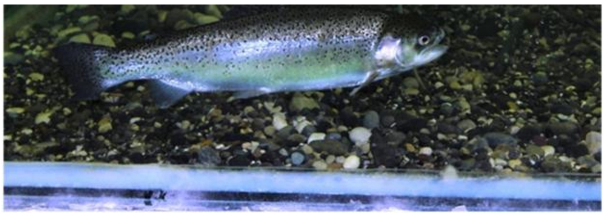

Fig. 2. Trout was studied in this experimental work at 20 ℃ (±0.5 ℃).

Fig. 3. Pangasius sanitwongsei was studied here.

To study fish movement behavior, the images were videotaped by a cube3 camera at 2500 fps at maximum resolution, maximum frame capture rate of 120,000 fps. Fig. 4 shows the experimental apparatus employed in this study. A planar slice of the flow was illuminated with a 100mW Nd.Yag laser ($\lambda=532^{nm}$) aimed at the 45 °front-surface mirror positioned below the flow tank. Flow pattern was seeded with polystyrene small particles (40-60micro meter). Experimental apparatus and DPIV set up have been shown in Fig. 4 and Fig. 5.

Fig. 4. Experimental apparatus in IAU:aquarium in laboratory.

Fig. 5. Digital Particle Image velocimetry (DPIV) set up.

Fish movement was visualized several times for each fish and finally some suitable frames were chosen. Fig. 6 and 7 show five frames of Pangasius sanitwongsei by 9cm body length and Trout by 27.3 cm body length at Δt=20msec respectively.

Fig. 6. Five original images of Pangasius sanitwongsei by L=9cm at Δt=0.02s. Undulatory movement of caudal fin has been presented. Half of wavelength has been represented at 80msec.

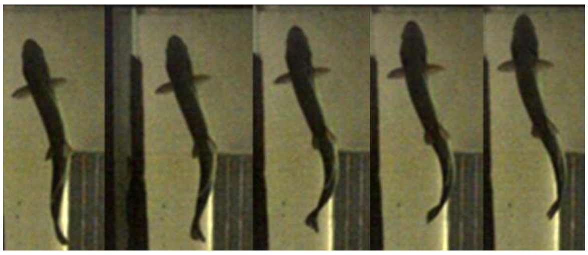

Fig. 7. Five original images of Trout by L=27.3 cm at Δt=0.02s. Undulatory movement of caudal fin has been presented here.

In this paper, Pangasius sanitwongsei and Trout which is classified in carangiform mode and BCF is selected as the model of fish robot and the body's undulations are completely confined to the last 1/3 part of the body and flexible body is represented by a series of oscillatory hinge joints.

IV. Results

In this experimental trial, undulatory movement of fish were studied and recorded. Among all video pictures, two suitable images were chosen for each case. Fig. 6 and Fig. 7, displays five sequential images of Pangasius sanitwongsei by total length 9 and Trout by total length 27.3 cm at Δt=20msec. These images present undulatory fish movement while, it is passing half of the wave length. According to these video pictures, velocity, frequency and amplitude of fish movement were obtained. After that, two basic parameters, Strouhal number and Reynolds number were found. Table I shows summary of fish movement variables of Trout and Pangasius sanitwongsei which were obtained from experimental studies.

TABLE I: Summary of Fish Movement Variables of Trout and Pangasius Sanitwongsei. All Measurements Tabulated from Experimental Studies of Fish. F Displays Frequency, A Displays Amplitude, and U Displays Velocity. Amplitude and Velocity Have Been Shown as a Proportion of Total Length

	L (cm)	L_f (cm)	F (1/s)	A (cm)	U (cm/s)	Lf/L	St	Re
Trout	27.3	4.10	6.25	0.143L	2.66L	0.150	0.336	1.97×10^5
			5	0.150L	2.37L		0.317	1.76×10^5
Pangasius	9.00	2.52	8.33	0.133L	5.38L	0.280	0.210	0.43×10^5
			6.25	0.328L	5.67L		0.360	0.46×10^5

Fig. 8. Patterns of body undulatory movement of Trout by L=27.3cm at Δt=20msec.

Fig. 9. Patterns of body undulatory movement of Pangasius sanitwongsei by L=9cm at Δt= 20msec.

According to the video pictures, pattern of body undulatyro movement of Trout and Pangasius sanitwongsei were drawn. Fig. 8 and Fig. 9, show body outlines taken from movements of Trout with L=27.3cm and Pangasius sanitwongsei with L=9cm. These pictures show one tail-beat cycle were recorded at times of 20ms. Fish movement variables, frequency, amplitude and velocity could be found out from these images and illustrate the amplitude of this wave increases dramatically near the tail and it is very small near the head for both of them.

Fig. 10 shows undulatory movement of caudal fin of Trout and Pangasius sanitwongsei in steady swimming. The time interval between sequential plotted tail positions is 20msec. The original experimental recording time is 200 msec. This figure represents undulatory movement of caudal fin of Pangasius sanitwongsei in compare with Trout, has been perfected such a sinusoidal form. It could be understood, undulatory movement of caudal fin has been perfected such a sinusoidal form, when L_f/L increased. There is an acceptable consistency between this subject and the experimental studies of four Pangasius sanitwongsei with different L_f/L [13].

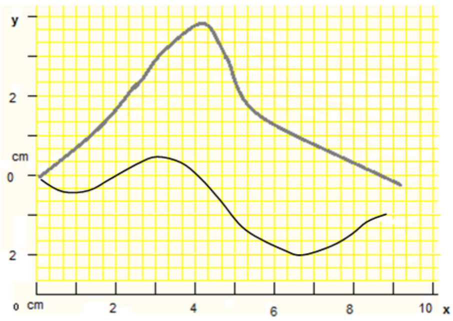

Fig. 10. undulatory movement of caudal fin of Trout by L=27.3cm and Pangasius sanitwongsei by L=9cm.

V. Discussion

In this work, Pangasius sanitwongsei by total length 9 cm and aTrout by total length 27.3 cm were studied. Fish movement was taped with camera high speed digital video system and undulatory movement of caudal fin has been drawn. Fig. 8 and Fig. 9 show body outlines taken from fish movements of Trout and Pangasius sanitwongsei respectively. Fish movement variables, frequency, velocity and amplitude can conclude from these images. These pictures illustrate the amplitude of this wave increases near the tail and it is very small near the head. According to Table I, summary of fish movement variables of two cases, with different velocity were revealed. These parameters were obtained from experimental results. As it has been presented, Re has obtained in the region of adult fish swimming ($10^3<Re<5\times10^6$), where, inertial forces are powerful and viscous forces are neglected. In carangiform modes, for high speed swimming ($10^4<Re<10^6$), thrust is optimal for a specific realm of *St*, where, $0.25<St<0.40$ [8]. So, it could be understood, for this realm of velocity, u=2.37LT^{-1} and u=2.66LT^{-1} for Trout and u=5.38LT^{-1} and u=5.67LT^{-1} for Pangasius sanitwongsei, thrust force is optimal.

Fish movement has been described using a traveling wave [14], [15]:

$$y_{\text{body}}(x,t) = a(x)\sin(kx+\omega t) \quad (3)$$

where, y_{body} is the transverse displacement of body and caudal fin, $\omega= 2\pi f$ and f is the frequency, k is the number of waves; $k=2\pi/\lambda$ and λ is the wave length, x is the displacement along the main axis and t is time. $a(x)$ is the second order function which it described wave amplitude,

$$\text{where, } a(x)= c_2x^2+c_1x+c_0. \quad (4)$$

So, $a(x)$ for Trout and Pangasius sanitwongsei have been calculated in steady swimming by experimental test

As it has been described earlier, undulatory movement of Trout studied, where frequency of body-caudal fin and wave length were 6.25 1/s and 0.122m respectively. Fish movement was calculated at four sequences at intervals of 20 ms and movement trajectories were found. Fig. 11 shows Pattern of body-caudal fins undulatory movement of Trout by L=27.3cm at different times. Fish swam at constant velocity, u=0.72 m/s.

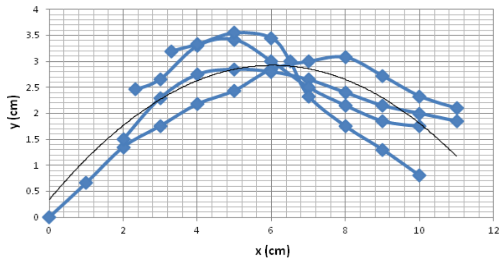

Fig. 11. All patterns of body-caudal fins undulatory movement of Trout by L=27.3cm. time-averaged movement pattern has been shown here.

To get the time-averaged movement equation, all patterns of body-caudal fins undulatory movement of Trout by L=27.3cm, were drawn in Fig. 11. So the second order function which it describes wave amplitude, was found. The generated equation in this work for time-averaged movement which it was found from Fig. 11, is;

$$y=-0.0710x^2+0.8577x+0.3367 \quad (5)$$

Then, undulatory movement of Pangasius sanitwongsei was calculated, where frequency of body-caudal fin and wave length were 8.33 1/s and 0.092 m respectively. Fish movement has been calculated at four sequences at intervals of 20 ms and movement trajectories were found. Fig. 12 explains Pattern of body-caudal fins undulatory movement of Pangasius sanitwongsei by L=9cm at different times. Fish swam at constant velocity, u=0.48 m/s.

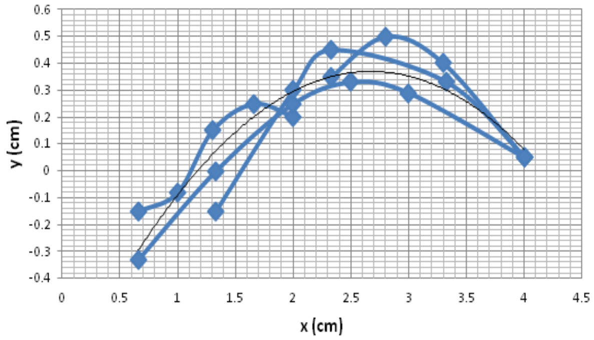

Fig. 12. All patterns of body-caudal fins undulatory movement of Pangasius sanitwongsei by L=9cm. time-averaged movement pattern has been shown here.

To get the time-averaged movement equation, all patterns of body-caudal fins undulatory movement of Pangasius sanitwongsei by L=9cm, were put together in Fig. 12. So a second order function was fitted using second order regression which can describe wave-like motion amplitude. Therefore, the generated equation in this work describes the time-averaged movement pattern of caudal fins;

$$y=-0.1641x^2+0.8774x-0.8035 \quad (6)$$

VI. Conclusions and Future Directions

In this paper, it has been realized that there are three influenced parameters on speed control of robot fish: frequency of fish movement, amplitude and length of the undulating part of fish body. It is studied that fish in nature use a combination of amplitude and frequency for speed control. Velocity of fish movement increases with frequency, and f will estimate a constant when the desired speed is achieved. A second order function obtained in these experimental studies is the basis of speed control method and adjusts the transverse movement of robot at a constant frequency. The amplitude of fish movement is controlled by C1, and the second order is controlled by C2. Fig. 13 and Fig. 14 show some envelope of the fish body wave. According to these experimental results, the maximum wave amplitude for Pangasius sanitwongsei is about 2.1 cm in tail and it is about %23 of its body length. It is about 4.35 cm or %16 of its body length for Trout. So, these Figures reveals that amplitude of fish movement increases dramatically near the tail and is very small near the head. These figures represent undulatory movement of caudal fin of Pangasius sanitwongsei in compare with Trout, has been perfected such a sinusoidal form.

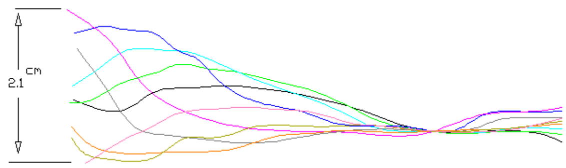

Fig. 13. Amplitude of traveling body waves of Pangasius sanitwongsei by L=9cm.

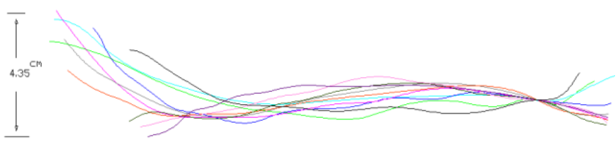

Fig. 14. Amplitude of traveling body waves of Trout by L=27.3cm.

Furthermore, undulatory movement of caudal fin has been perfected such a sinusoidal form, when Lf/L increased. According to the observation on real fish, not all oscillation parts of fish body take part in the thrust production at all time. In most of time, only 1/3 posterior part and particularly only the caudal fin produces thrust force. In other words, with the increase of the ratio of front part of the fish which has the minimum amplitude in undulatory movement to the total length of the fish, efficiency and velocity of fish movement extremely increase, but maneuverability reduces to a certain level. Moreover, the number of simplified joints in oscillatory part is essential to design a fish robot, then increasing the joints causes the better maneuverability.

On the other hand, new method for simulation of body traveling wave of fish robot has been found. Here the amplitude of the traveling wave has been simulated into two parts. The first part, top of the head to the first hinge near the pectoral fin, which has been shown with L_f and quadratic wave amplitude. The second part from this major point to end of the tail has been shown with linear wave amplitude. Finally equation of fish movement have been calculated and the second order function which describes wave amplitude of Trout and Pangasius sanitwongsei was found. These relations can be applied for mathematical modeling of fish robots. However, some numerical evaluations of these cases can support these findings.

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