2012 International Conference on Environment Science and Engieering
IPCBEE vol.32(2012) © (2012)IACSIT Press, Singapoore

Experimental Hydrodynamics Imaging of Trout in Steady Swimming

S. Ali. S. Vaghefi[1,+], M. Abbaspour [1, 2]

[1] Department of mechanical engineering, Science and Research Branch, Islamic Azad University (IAU), Tehran, Iran

[2] Department of mechanical engineering, Sharif University of Technology (SUT), Tehran, Iran

Abstract. This paper presents a quantitative characterization of caudal fin. Steady swimming of Trout was studied experimentally and taped by high speed digital video and undulatory movement of fish was drawn. The amplitude of this wave increases dramatically near the tail and it is very small near the head. Then undulatory movement equation of fish swimming was studied and the second order function which describes wave amplitude of Trout was found.

Keywords: Movement equation, Undulatory, Fish swimming, BCF, Video image

1. Introduction

We would have marveled at the graceful way in which fish swim, turn and accelerate [1]. In nature, fish propels it by the undulatory motion of its body and has gained wonderful swimming ability of the Thousands years of evolution. The tuna swims with high speed and high efficiency. The pike accelerates in a flash and the eel can swim skillfully into narrow holes [2]. Many researchers have been investigated to answer this question. Fish swim mode have been studied extensively using experimental, theoretical and numerical techniques. Experimental studies have been applied on the real Fish, robot fish and biomimetic foils.

In1994, the first robot fish named robotuna was developed at MIT [3]. In 1998, Anderson et al. studied on the flow around two – dimensional flapping foils as function of the angle of attack and the Strouhal number. The Strouhal number is defined as St=f.A/u, where f denotes the frequency of foil oscillation, A denotes the characteristic width of the created jet flow and u is the speed of the foil. They presented wake patterns as function of the Strouhal number and angle of attack [4]. In 2002, Lauder et al. studied hydrodynamics of fish movement with digital particle image velocimetry (DPIV) which allows empirical analysis of force magnitude and direction. They examined fin function in four ray finned fishclades; sturgeon, trout, sunfish and mackerel [6]. In 2004, Gilbert characterized quantitatively the complex Three dimensional kinematics of pectoral fin swimming in bluegill sunfish. He taped swimming fish at several speeds in a flow tank that is 45 cm long by 18 cm width and 18 cm hight. Flow pattern was visualized with the high speed camera (500 fps) and high resolution (1024 x 1024 pixels) [5].In 2007, Lauder et al. presented that the dorsal fins produce vortices that are encountered by the caudal fin. These vortices can increase the thrust produced by caudal fins.

In this study the flow pattern of caudal fin locomotion was visualized and the kinematic parameters of Trout were determined which in turn it ended up to define the equation of fish swimming.

2. Fish Swimming Mode

Several design characteristics in fishes are useful to design, robotic devices for propulsion purposes in underwater vehicles. One of the main characteristics is swimming mode [7]. One way of considering fish locomotion is to classify fishes into groups based on fin use. Hence fishes swimming with their median fins (dorsal and anal) and paired fins (pectoral and pelvic) are termed MPF (median and paired fin) swimmers,

[+] Corresponding author. Tel.: +982126564735; fax: +982126564735.
E-mail address: sadrvaghefi@yahoo.com.

while fishes using primarily the body and caudal fin would be classified as BCF (body and cauda fin) swimmer (fig1) [8].

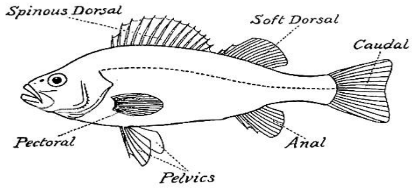


Figure 1. Illustrates median and paired fins.

MPF is used at slow speeds, to increase the maneuverability and propulsive efficiency while BCF movement can increase thrust force and accelerations [7].

3. Basic Parameters

There are several important non – dimensional numbers in fish swimming. In 1988, Webb defined three main factors which participate in fish swimming; Reynolds number, Strouhal number and shape [9].

The Reynolds number is the ratio of inertial forces over viscous forces, where, $Re=u.L/\nu$. u is the velocity of fish swimming, L is the length of the fish body and ν is kinematic viscosity of water. Another non - dimensional parameter which participates in fish movement, is Strouhal number defined as $St=f.A/u$, where, f is the tail-beat frequency, A is the amplituede of undulatory movement of tail and u is the average velocity of fish [1,7,9]. The Strouhal number is the ratio of unsteady to inertial force [12].

Fish swimming was described using a traveling wave [11]:

$$y_{body}(x,t) = a(x)\sin(kx+\omega t) \qquad (1)$$

where, y_{body} is the transverse displacement of body and caudal fin, k is the number of waves; $k=2\pi/\lambda$ and λ is the wave length, $\omega= 2\pi f$ and f is the frequency, x is the displacement along the main axis and t is time. Finally a(x) is the second order function which it describes wave amplitude[10],

where, $a(x)= c_2x^2+c_1x+c_0$. (2)

4. Materials And Methods

Trout with 27 cm length (Fig.3) was studied in a glassy tank, that was 90cm long by 30 cm wide and 45 cm high. The water was at 20^{oc} and kinematic viscosity was $\nu=1.005\times10^{-6}(m^2/s)$.

Figure 3. Trout was studied in this work

To evaluate fish swimming 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 summarizes the experimental apparatus in these studies. A planar slice of the flow was illuminated with a 100mW Nd..Yag laser ($\lambda=532^{nm}$). Flow pattern was seeded with polystyrene small particles (40-60micro meter). Fish swimming was visualized several times for each fish and finally some suitable frames were chosen. Figure 5, shows five frame of Trout in steady swimming at constant velocity.

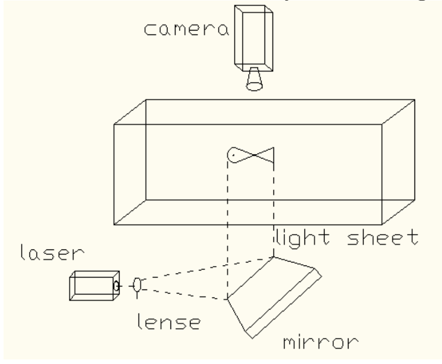


Figure 4. Schematic of the experimental set up. Images of swimming fish were obtained with the high –speed video camera aimed at the 45° front-surface mirror positioned below the flow tank.

5. Results

In these experimental study, fish swimming of Trout was observed and taped. Among all video images, two suitable captures were chosen. Figure 5 displays five sequence images of Trout by total length 27 cm and Δt=20msec. These images reveal undulatory movement of fish tail while, it is passing half of wave length. Each image sequence was 20 msec. According to these video images, frequency, amplitude, wave length and velocity of swimming fish were obtained. Then two dimensionless parameters, Reynolds number and Strouhal number were found.

Figure 5. Five original images of Trout by L=27cm at Δt=0.02s has been shown. Undulatory movement of caudal fin has been displayed here. Half of wavelength has been represented at 80msec.

Table 1 shows summary of fish swimming variables of two cases, with different velocity. These parameters were obtained from experimental results. As it has been shown, 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 and subcarangiform 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 [7].

Table1. Summary of fish swimming variables of Trout

	L(cm)	Lf(cm)	A(cm)	f(1/s)	u(cm/s)	St	Re
Trout	27.3	4.10	3.9	6.25	72.56	0.336	1.97×10^5
			4.1	5	64.66	0.317	1.76×10^5

All measurements tabulated from experimental results of Trout with different velocity. A displays amplitude, f displays frequency and u displays velocity

According to the video images, pattern of body undulatory movement of Trout was drawn in Fig.6. It shows body outlines taken from movements of fish swimming of Trout with total length, L=27cm. This picture displays one tail-beat cycle was recorded at intervals of 20ms. Fish swimming variables, amplitude, frequency and velocity can determine from this picture. This image illustrates the amplitude of undulatory movement increases near the tail and it is very small near the head.

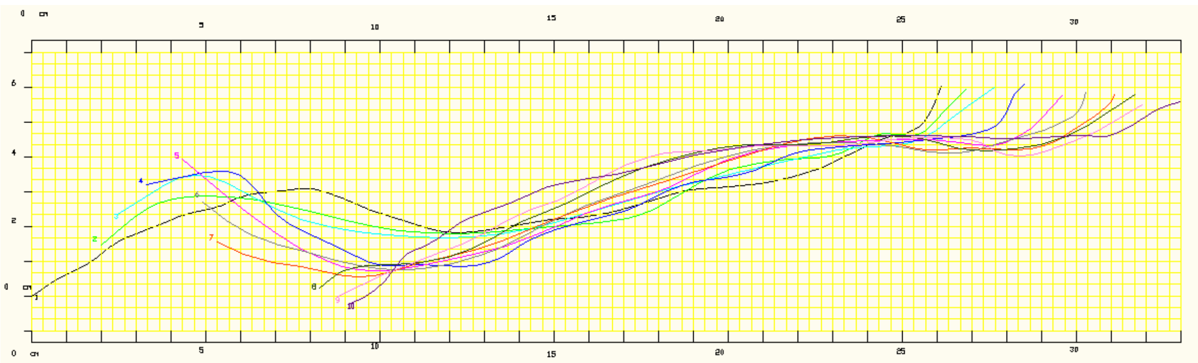


Figure6.Patterns of body undulatory movement of Trout by L=27cm at Δt=20msec.

Fig.7 shows undulatory movement of caudal fin of Trout in steady swimming. The time interval between sequential plotted tail positions is 20msec. The original experimental recording time is 200 msec.

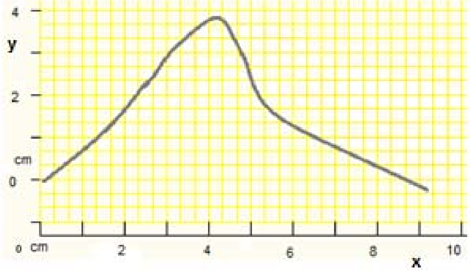


Figure7. undulatory movement of caudal fin of Trout by L=27 cm. The original experimental recording time is 200 msec.

6. Discussions

In this experimental trial, body undulatory movement of Trout was studied. Fish swimming was taped with high speed digital video camera system and undulatory movement of caudal fin was drown. Fig.6 shows body outlines taken from movements of fish swimming of Trout with total length, L=27cm. Fish swimming variables, amplitude, frequency and velocity can determine from this picture. This image illustrates the amplitude of this wave increases dramatically near the tail and it is very small near the head. Fig.7 shows undulatory movement of caudal fin of Trout.

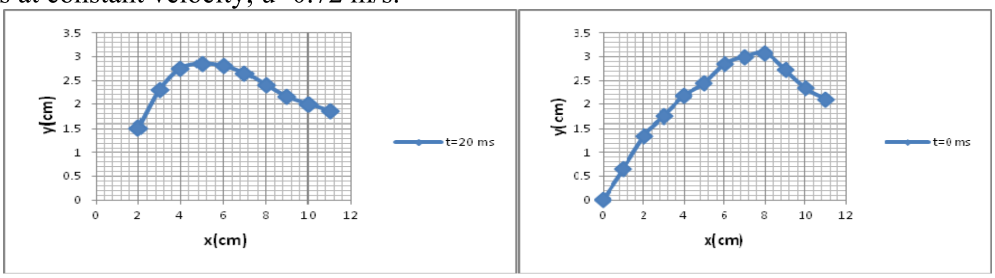
Fish swimming was described using a traveling wave [11]:

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

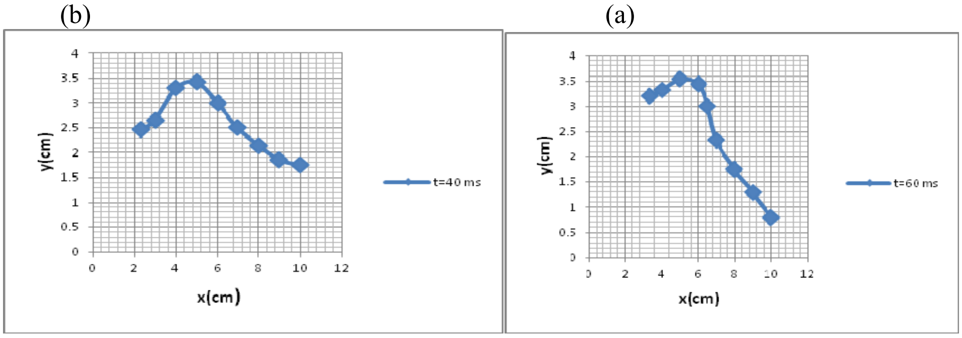
where, y_{body} is the transverse displacement of body and caudal fin, k is the number of waves; $k=2\pi/\lambda$ and λ is the wave length, $\omega= 2\pi f$ and f is the frequency, x is the displacement along the main axis and t is time. finally a(x) is the second order function which it described wave amplitude[10],

where, $a(x)= c_2x^2+c_1x+c_0$ (4)

In this work, a(x) for Trout was calculated in steady swimming by experimental trial. Then fish swimming was observed and taped. According to the video images, pattern of body undulatory movement of Trout by L= 27 cm was drawn. These patterns were shown in Fig.6. In these experimental studies, undulatory movement frequency of body-caudal fin and wave length of Trout were 6.25 1/s and 0.122 m respectively. Fish swimming was studied at four sequences at intervals of 20 ms and movement trajectories were found. Figure 8 shows Pattern of body-caudal fins undulatory movement of Trout by L=27cm at different times. Fish swims at constant velocity, u=0.72 m/s.



(b) (a)



(c) (d)

Figure8. Pattern of body-caudal fins undulatory movement of Trout by L=27cm at four sequence at intervals of 20 msec. Fish swims at constant velocity, u=0.72 m/s.

To find the time-averaged movement equation, all patterns of body-caudal fins undulatory movement of Trout by L=27cm, were drawn in Fig.9. Then 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.10, is;

$$y=-0.0710x2+0.8577x+0.3367 \quad (5)$$

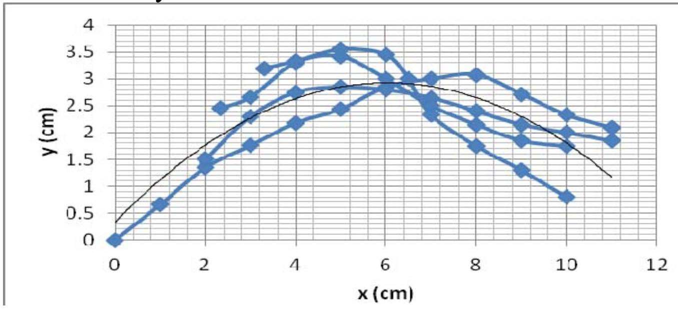


Figure9. All patterns of body-caudal fins undulatory movement of Trout by L=27cm. time-averaged movement pattern has been presented here.

7. Conclusions And Future Directions

In this paper, kinematic parameters in steady fish swimming of Trout were studied and pattern of body undulatory movement of Trout was presented. This image illustrates the amplitude of this wave increases dramatically near the tail and it is very small near the head. Also movement equation of fish swimming was studied and the second order function which it described wave amplitude of Trout was found;

$$y=-0.0710x^2+0.8577x+0.3367$$

These relations can be applied for mathematical modeling of robot fishes. However, some numerical evaluations of these cases can support these findings. However, some numerical evaluations of these cases can support these findings.

8. References

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