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Experimental Hydrodynamics Analysis of Trout Locomotion for Simulation in Robot-Fish

M.Asadian Ghahferokhi*, M. Abbaspour

Department of Mechanical Engineering, Sharif University of Technology (SUT), Tehran, Iran

ABSTRACT

This paper presents quantitative morphological and kinematic parameters of carangiform fish which is used for design of a robot fish based on an improved kinematic propulsive model. The swimming speed of Trout can be adjusted by changing oscillating frequency, amplitude and the length of oscillatory part, respectively, and its orientation is tuned by different joint's deflections. Experimental studies on steady swimming of four similar size trout are fulfilled with digital particle image velocimetry (DPIV) and image processing methods and optimal equations of motion are empirically derived. The oscillating amplitude increases dramatically from 1/3 of body and is very small near the head. So the second order function which describes wave amplitude of Trout undulatory movement equation was found and the oscillatory motion of the biomimetic robot fish will be designed according to this equation. In this method within an aquarium using a high speed digital camera (Cube 3) up to 128000 fps and a 4000mW laser source, imaging the mechanism of swimming is performed and using image processing code to find experimentally the optimal coefficients of the motion equation, appropriate location of joints and so on. Modeling carangiform fish-like swimming motion with maximum wave amplitude about twenty percent of body length is experimentally derived.

KEYWORDS: Fish Hydrodynamics, Fish swimming, Robot fish, Image processing, DPIV.

1. INTRODUCTION

In nature, fish propels its body by the undulatory motion and gained wonderful swim ability in thousands years of evolution. Tuna swims with high speed and efficiency. Pike accelerates in a flash and Eel can swim skillfully into narrow holes. According to mechanics appearance, there is a question; Are they more efficient than a propeller driven underwater vehicle? Many researchers have studied experimentally or theoretically on fish swimming mode to answer this question.

ROV[1] and AUV[2] robots do not have sufficient efficiency and accuracy required in many engineering and environmental applications and they will disturb the natural conditions of environment so design of a biomimetic robot fish with virtue of high speed, tremendous propulsive efficiency and high maneuverability based on the mechanism and anatomy of carangiform fish with minimum energy consumption is considered [1].

Fishlike propulsion including undulation and oscillation generates the main thrust of the robot fish, which makes the fish more efficient, maneuverable and noiseless. These advantages are of great benefit to practical applications in marine and military fields such as undersea operation, military reconnaissance, leakage detection, aquatic life-form observation, and so on [2].

Cinematography study of fish propulsion was begun by Marey in 1895 [3] and Breder in 1926 [3], compared different methods of fish propulsion with an emphasis on simple mechanics of body and tail fins of fish. Classical theory of Gray and his paradox (1933) [3] created a special place in this area. Afterward, further discussions were about the maximum attainable speed of fish such as tuna fish that swim more than 20m/s and the dolphins more than 15m/s [3].

In 2002, Lauder et al. studied hydrodynamics of fish movement with DPIV which allows empirical analysis of force magnitude and direction. They examined fin function in four ray finned fishclades; sturgeon, trout, sunfish and mackerel [4].

In recent years, most studies on robot fish focused on exploring the hydrodynamic mechanism of fishlike swimming, and constructing autonomous underwater vehicles with the efficiency and maneuverability of real fish. The first robot fish, Robotuna, was built in 1994 at MIT University. It was about 4 feet length and did not have specific control system and ability to change the depth. Information transmission was done through cable in experiments. Subsequent RoboPike were used to study drag reduction in fishlike locomotion. Later, an improved version of RoboTuna, Vorticity Control Unmanned Undersea Vehicle (VCUUV), was constructed by Draper Laboratory of MIT. The VCUUV was equipped 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 workspace [5].

Various activities took place to develop the efficiency of underwater robots. For example, PPF-01 was the first prototype robot built in Japan Maritime Research Institute in 1999 to show the mechanical design and control system and no ability to swim. The recent model (PPF-09) had capability of vertical movement and turning by pectoral fins, but it had some problems such as replacing the battery and sealing of imperfect body [6].

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[1] Remotely operated underwater vehicle
[2] Autonomous underwater vehicle

***Corresponding Author:** M.Asadian Ghahferokhi, Department of Mechanical Engineering, Sharif University of Technology (SUT), Tehran, Iran.
E-mail: m.asadian@gmail.com

Designing and manufacturing of three robot fish covered with shiny flakes has been done at Essex University in England. These robots are 50 cm long, 15 cm height and 12 cm wide [7].

However, in previous research, major activities focused on robotics and there is less consideration to the main goal of this research such as optimization of motion equation and fish like swimming. The technical novelty of this paper lies in an improved approach to design a robot fish based on a simplified kinematics model in which its second order function of body wave amplitude and orientation of body joints are determined, and complex hydrodynamic analysis is avoided.

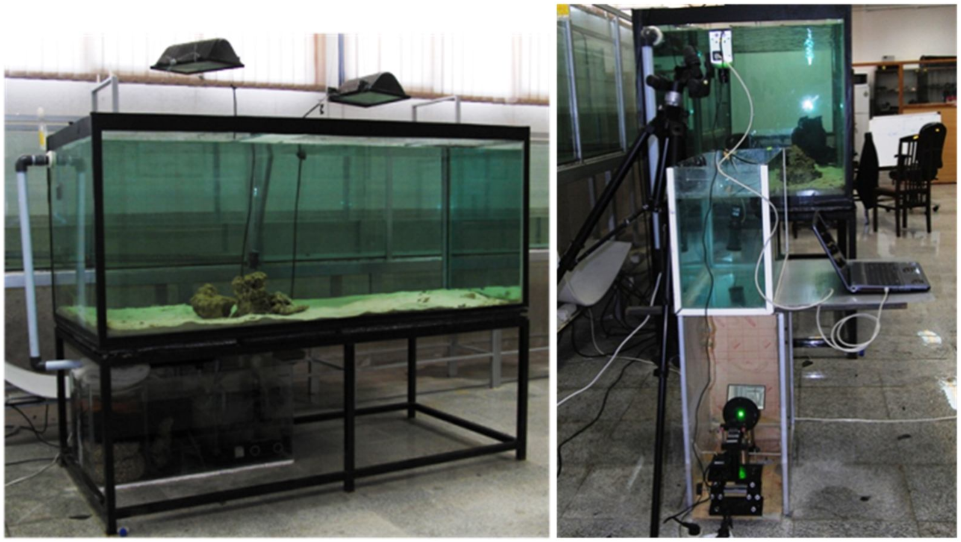
2. METHODOLOGY

Trout were obtained from SardAb Meadow Hatchery, Alborz, Iran and housed in 3750·liter tanks (250×150×100 cm) with circulation mechanism of cold fresh water at 15°C (±1°C) (figures 1 and 2A). Fish were fed with commercial trout pellets daily and acclimated to laboratory conditions for one week before experiments. Trout were lightly anesthetized by standard medicine to allow morphological measurement. Four animals of similar size (total body length, L, 25.8±5%·cm, breadth, B, 3.81±3%·cm and height, H, 5.96 ±3%·cm) were selected for swimming trials (figure 1).

Figure 1. Trout swam in maintenance aquariumat 15°C (±1°C)

In this research, data on the biomechanics and kinematics of Trout swimming were derived from analysis of high speed video recordings of Cube 3 Camera(up to 128,000 fps)above the test tank (90×45×30 cm) as shown in figure 2B. A 4,000mW Nd-Yag laser (λ=532nm) was used as the light source. The light was expanded with a plano-convex cylindrical lens and a plano-concave lens to obtain a light sheet. The flow was visualized with laser-induced fluorescent particles. We made the particles by adsorbing Rhodamine B to the particles (Specific weight is 1.02 and diameters of the particles were in the range of 0.042 - 0.063 mm). Laser produces a horizontal light sheet at the 45° front-surface mirror positioned below the test tank and the camera captures the light sheet and fish which were swam in the centre of the working area from above (figure 2B).

Several design characteristics such as posture, trajectory and swimming mode in fishes are useful for underwater robot design. Hence fishes swimming with their median fins (dorsal and anal) and paired fins (pectoral and pelvic) are termed MPF (median and paired fin) swimmers, while fishes using primarily the body and caudal fin would be classified as BCF (body and caudal fin) swimmer. MPF is used at slow speeds, to increase the maneuverability and propulsive efficiency while BCF movement can increase thrust force and accelerations [8].



(A) (B)

Figure 2. Experimental apparatus in Science and Research Branch, Islamic Azad University (IAU):
(A) Trout'smaintenance aquarium in laboratory (B) Digital Particle Image Velocimetry (DPIV) Setup.

In this paper, trout which is categorized in BCF and carangiform swimming mode is chosen as the model of robot fish and the body's undulations are entirely confined to the last 1/3 part of the body and flexible body is represented by a series of oscillatory hinge joints (figure 3).

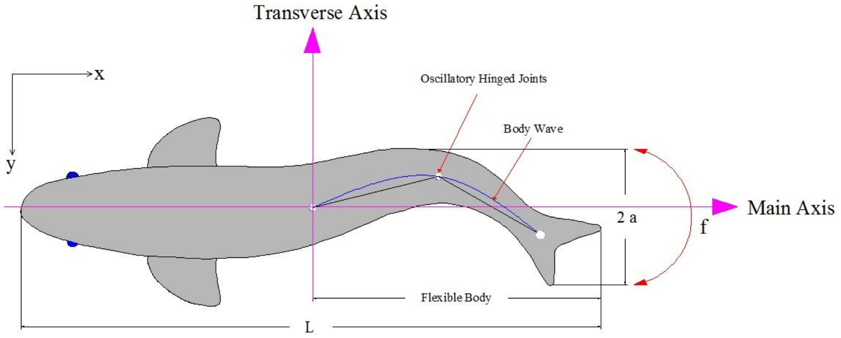


Figure 3. Schematic of Trout's Deformation& Body Traveling Wave

3. RESULT AND DISCUSSION

As the gathered information from the literature, there was a traveling wave passed from the head to the tail fin in the carangiform fish's body, and the amplitude of the traveling wave increased from the nose to the tail of the fish. As shown in figure 3, the body midline is assumed to take the form of a traveling wave given by (1 and 2) [9,10]:

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

$$A(x) = [C_0+C_1x + C_2x^2] \qquad (2)$$

Y_{body}: Transverse displacement of body and caudal fin cm.
$A(x)$: Second order function described as wave amplitude cm.
x: Displacement along main axis cm.
$k = 2\pi/\lambda$ Body wave numberRadian.cm^{-1}.
λ: Wavelength of body wave cm.
C0: constant coefficient.
C_1: Linear wave amplitude envelope.
C_2: Quadratic wave amplitude envelope.
$\omega= 2\pi f = 2\pi/T$ Body wave frequency Radian.s^{-1}.

Figure 4 displays nine selected of fifty six images which is taken consecutively at f = 300 Hz and Δt=18.67 msec. These images reveal undulatory movement of fish in half of wavelength (mean λ/2 = 11.31 cm). Times between tracings are in milliseconds so each image sequence was about 20 msec. The steady swimming speed of trout was recorded at mean $1.46 \cdot L.s^{-1}$ and thrust is produced by means of a rather stiff caudal fin and oscillating body wave.

Figure 4. Nine selected images of Trout by L= 25.8 cm at interval Δt=2ms.

According to these images, both transverse displacement of body and longitudinal movement along main axis are derived (figure 5), so the $C_1$and C_2 coefficients are obtained and second order function described as wave amplitude at time-averaged movement is denoted as (3) (figure 6):

$$A(x) = [0.094 - 1.359\ x + 0.285\ x^2] \qquad (3)$$

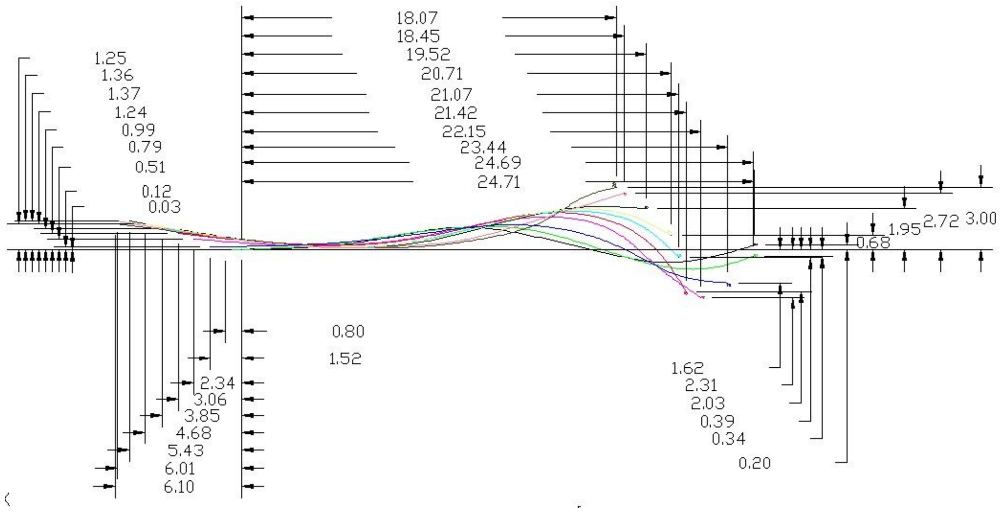


Figure 5. Body traveling waves dimensions in different sampling time.

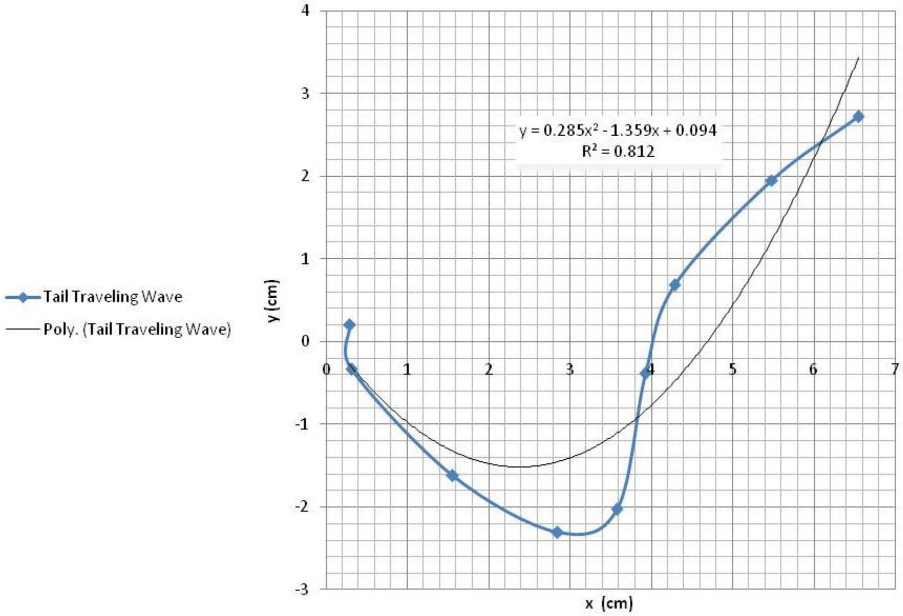


Figure 6. Tail Traveling Waves& Second Order Polynomial of Wave Amplitude

4. CONCLUSION

In this paper, we realized that there are three most important parameters influenced on velocity control algorithms of robot fish: frequency of body wave, amplitude of the posterior body wave and length of the undulating part.

It is observed that real fish in nature use a combination of frequency and amplitude for speed control. Swimming speed increases with the oscillating f, and *f* will approximate a constant when the desired speed is achieved. This algorithm was adopted by MIT's RoboTuna and DRAPER's VCUUV.

In practice, a second order amplitude function obtained in present experiments is the basis of speed control method and adjusts the transverse movement of robot at a constant oscillating frequency. The amplitude of body wave is controlled by C_1, and the second-order derivative is controlled by C_2, Figure 7 shows some envelope of the body wave with different $C_1$and C_2.

According to these experimental results, the maximum wave amplitude for trout is about 4.98 cm in tail and it does not exceed twenty percent of its body length. So, Figure 7 shows that oscillating amplitude increases dramatically from 1/3 of body and is very small near the head.

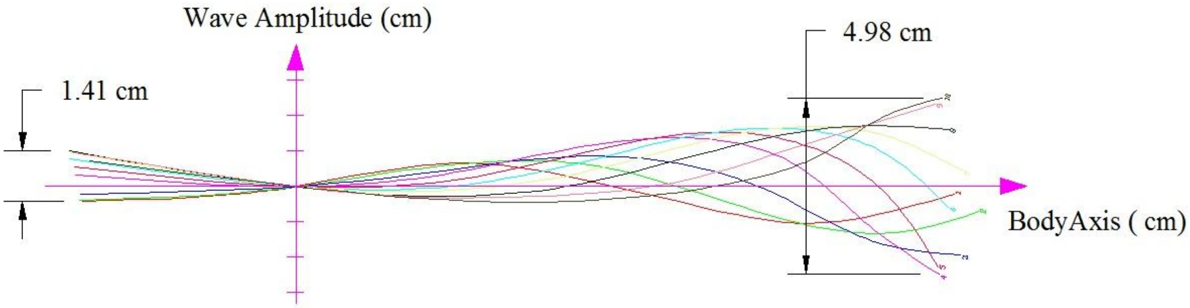


Figure 7. Body Traveling Wave Amplitudes with different $C_1$and C_2.

According to the observation on real trout, not all oscillation parts of body take part in the thrust production at all time. In most of time, only 1/3 posterior portion or especially only the caudal fin oscillates to produce thrust. In a general way, with the decrease of the length ratio of the trout's oscillatory part to that of the fish-body, efficiency and velocity of fish swimming remarkably increase, but maneuverability reduces to a certain extent. Otherwise, the number of simplified joints in oscillatory part is too important in robot design, so increasing the joints causes the better mechanism's maneuverability and redundancy, but the worse swimming efficiency.

5. ACKNOWLEDGMENTS

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