

Observation and hydrodynamic analysis of fast-start of yellow catfish (*Pelteobagrus fulvidraco*)^{*}

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Abstract The kinematics and hydrodynamics of the escape response of yellow catfish (*Pelteobagrus fulvidraco*) is investigated. It is observed from digital high-speed camera that all the escape response of yellow catfish is a C-type fast-start, which is characterized by the C-shape of the fish body at the end of the first contraction of the lateral musculature. Based on the analysis of the mass center movement and the performance of the caudal fin, the fast-start process can be divided into two stages: in stage one the fish body rotates rapidly around its mass center and in stage two the fish begins moving straightly. Theoretically, the Weihs' model is employed to obtain the forces, moments and turning angular accelerations acting on the fish during the escape response. The results are in good agreement with the experimental observation. Furthermore, muscle strain at different locations along the body is calculated. At last, the dynamical performance of the escape response is explained.

Keywords fast-start maneuver; yellow catfish (*Pelteobagrus fulvidraco*); digital high-speed camera; Weihs' model; muscle strain.

A fast-start is a high-energy swimming burst starting either from rest or from steady swimming^[1]. The fast-starts are classified into two main types, C-start and S-start, in which the fish body is bent into a 'C' or 'S' shape at the end of the first contraction of the lateral musculature. Fast-starts are important for most fish in escaping predators and achieving prey capture. A fast-start process has two amazing characteristics. One is the turning maneuver. The turning maneuver is carried out very rapidly, with the turning diameter being equal to, or even less than the fish length. The other is the large acceleration from rest. Harper and Blake^[2] found that the maximum accelerations can exceed 25 g for northern pike (*Esox lucius*), where g is the acceleration due to gravity. Therefore, a better understanding of the mechanism of fish fast-start should be very useful to improve the maneuverability of man-made vessels.

In previous researches, many biologists used the electromyography (EMG) to reveal the muscle function in escape response^[3-8]. Meanwhile, investigation on the kinematics and hydrodynamic analysis of fast-starts is still a hot topic^[9-17], which includes kinematical types, distance-time characteristics, effect of temperature, forces, efficiency, and so on.

Although Weihs^[10] built a theoretical model for fast-starts and calculated the thrust force of rudd in 1972, he and also other researchers did not consider the fact that the position of the mass center of fish would change during fast-starts, which will affect the stability of fish swimming. Furthermore, to our knowledge, no work has been done on the angular acceleration, the most important factor of turning. In the present study, the change in both the mass center and the moment of inertia are taken into account during the fish turning. The angular acceleration will be calculated to know the details of turning and to understand more of the mechanism of fast-starts. Furthermore, a behavior of muscle contraction is obtained by calculating the muscle strain, which can explain the dynamical performance.

In this paper, the kinematics and hydrodynamics are analyzed for fast-starts of yellow catfish (*Pelteobagrus fulvidraco*) during the escape process from rest. It should be noted that the kinematics process of the fish is recorded by a high-speed video and the force and moment imposed on the fish are obtained from Weihs' model. Furthermore, muscle strain along the fish body is estimated to understand the fast-start and the whole escape response process is analyzed.

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1 Materials and methods

1.1 Fish

Experiments were performed on the escape responses of yellow catfish (*Pelteobagrus fulvidraco*). The fish was held in a plexiglas tank (70 cm × 70 cm × 50 cm) supplied with aerated, dechlorinated water (Fig. 1). The water temperature was maintained between 8 °C and 12 °C. Four fish with length $L = 22.02 \pm 1.43$ cm and mass $m = 128.5 \pm 10.5$ g were used in the experiments. Before the experiments, the fish were put in the tank containing static water for 24–48 h to accommodate the environment. The dimensions of fish were determined after experiments by measuring freshly anesthetic fish.

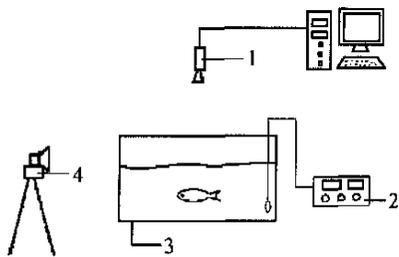


Fig. 1. The recording system used in experiments. 1: Digital high-speed camera; 2: stimulus source; 3: tank; 4: photographic lights.

1.2 Filming procedure

A mesh plate with 10 cm × 10 cm square grids was placed on the bottom of the tank with a device to produce a stimulus to fish. The experimental tank was illuminated by two 1300 W photographic lights and the fish escaping was taken by a high-speed digital video (Speedcam Pro-Lt) with a 12.5–75 mm zoom lens, which has a resolution of 512 × 512 pixels at 1000 fps.

1.3 Analysis

The whole record was transferred into a computer. Fourteen frames were selected from the record and analyzed in detail. The individual points in the fish backbone were marked in every frame, and linked to a smooth curve by using paraspline fit. The data of these points on the curve was obtained by using WinDig Version 2.5. Then, the velocity and acceleration data are derived from the raw distance–time data.

1.4 Sources of error

tem error (SE) and computational error (CE). In this study, SE involves the error due to the lower sampling frequency and the measuring method. For example, the grids and the fish were not at the same plane in experiments. Due to the small aperture of the camera, the position of the fish was projected to the plane of the grid. The resulting SE was about 8.11%. CE was caused by the calculating methods, estimated to be about 11.67%. After the velocity of all points at the fish backbone was obtained, the velocity function, a polynomial (5th order) function, along the fish backbone was given by using a paraspline fit, which causes the large CE.

2 Experimental results

Based on our extensive experimental observation of a lot of fishes, a statistical analysis on the behavior of escape response of yellow catfish indicates that the fish always has the similar kinematical pattern in this experiment. The difference among the experimental observations would be the time of the whole escape process and the turning angle. Even the force and other dynamical parameters in different experiments are on the same order of magnitude. Thus, a typical experimental data is used for kinematical and hydrodynamic analyses.

2.1 Escape response process

In this study, all escape responses of yellow catfish (*Pelteobagrus fulvidraco*) belong to the C-type fast-start. Some typical frames are chosen from one fish's whole film (see Fig. 2). The data of all frames are calculated except frame 1, because the fish stays at rest in it.

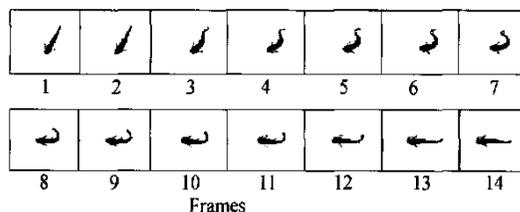


Fig. 2. The escape process of yellow catfish (*Pelteobagrus fulvidraco*). 1: $T = 0.031$ s; 2: $T = 0.040$ s; 3: $T = 0.050$ s; 4: $T = 0.060$ s; 5: $T = 0.070$ s; 6: $T = 0.080$ s; 7: $T = 0.100$ s; 8: $T = 0.150$ s; 9: $T = 0.200$ s; 10: $T = 0.250$ s; 11: $T = 0.300$ s; 12: $T = 0.400$ s; 13: $T = 0.500$ s; 14: $T = 0.600$ s.

At 0.031 s the yellow catfish (*Pelteobagrus fulvidraco*) is stimulated. Then the fish turns an angle clockwise. From 0.100 s the fish stops turning

and swims along a straight line. All curves of the backbones of fish shown in Fig. 2 are redrawn in Fig. 3, where the escape response process is distinctly exhibited and all data of the backbone curves are obtained. The number in the figure refers to the corresponding frame in Fig. 2 and the left end of the curves represents the head of fish.

2.2 MC and MI

The mass center (MC) of fish is an important parameter in the fast-start of fish. Weihs divided the fast-start process into three stages depending on different movements of MC. In previous work, the position of MC relative to the fish body was considered to be invariable. Actually, it is possible that the position of MC changes when the backbone of fish is not straight.

It can be seen from Fig. 3 that the backbone does not always keep a straight line and has different shapes in different frames. Therefore, the positions of both MC and MI (moment of inertia) are not constant. Here, MC and MI of yellow catfish in all frames of Fig. 2 are calculated, as listed in Table 1. The x -direction is the tangential direction of the backbone by taking the fish head as origin, while the y -direction is chosen to form a right-hand system of the axes. For the data of MC, x is the ratio of the length between MC and the head to the fish body length, and y is that between MC and the backbone. Positive y represents that MC is on the right side of the fish. In Table 1, we can see that the position of MC nearly does not vary in the whole start process (the largest change in the x -direction being about 1.70% relative to the fish body, and in the y -direc-

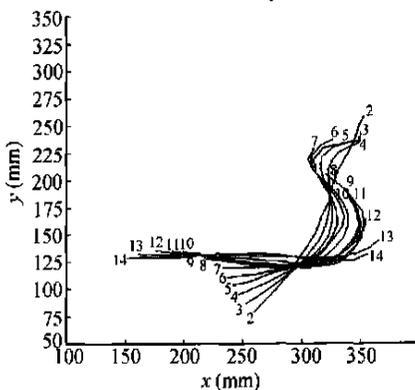


Fig. 3. Escaping patterns of yellow catfish (*Peltabagris fulvidraco*). The backbones of the fish at all frames are shown. The number refers to the corresponding frame being the same as that in Fig. 2. From left to right, curve starts from head to tail.

tion about 2.52%). Hence, it is reasonable to assume that yellow catfish always keeps the MC position at 27% of the fish length in the whole escape response process.

Table 1. The fish's MC and MI in different frames of Fig. 2

| Time (s) | The position of the centre of mass (L^y) | The moment of inertia $\times 10^6 (\text{g} \cdot \text{mm}^2)$ |
|----------|--|--|
| 0.031 | (0.278, 0.00000) | 0.207 |
| 0.040 | (0.277, 0.00817) | 0.204 |
| 0.050 | (0.274, 0.01230) | 0.195 |
| 0.060 | (0.267, 0.02280) | 0.166 |
| 0.070 | (0.261, 0.02310) | 0.158 |
| 0.080 | (0.263, 0.01830) | 0.144 |
| 0.100 | (0.261, 0.02500) | 0.148 |
| 0.150 | (0.267, 0.02520) | 0.171 |
| 0.200 | (0.274, 0.00811) | 0.190 |
| 0.250 | (0.274, 0.01300) | 0.192 |
| 0.300 | (0.277, 0.00567) | 0.200 |
| 0.400 | (0.277, 0.00266) | 0.201 |
| 0.500 | (0.278, 0.00270) | 0.207 |
| 0.600 | (0.278, 0.00000) | 0.207 |

a) The x -direction is the tangential direction of the backbone (head as origin) in the calculation, and y -direction is chosen to form a right-handed pair of axes. The length unit is L , which is the length of the fish body.

Meanwhile, the value of MI changes from $0.207 \times 10^6 \text{g} \cdot \text{mm}^2$ to $0.144 \times 10^6 \text{g} \cdot \text{mm}^2$ (the change is about 30.4%). It is obvious that the value of MI cannot be regarded as a constant in the fast-start process of yellow catfish.

2.3 Kinematics of escape response

In order to obtain the quantitative results, the following procedure is adopted. The velocity, $V_n(T)$, is calculated based on the spatial positions of the specific points along the backbone measured from five successive frames and defined as

$$V_n(T) = \frac{1}{2} \left[\frac{\mathbf{R}_n^{T+2dt} - \mathbf{R}_n^{T-2dt}}{4dt} + \frac{\mathbf{R}_n^{T+dt} - \mathbf{R}_n^{T-dt}}{2dt} \right], \quad (n = 0, 1, \dots, 20), \quad (1)$$

where the subscript n represents the number of points with the same length Δl from each other in the stretched straight configuration from the fish head, T means the time of frame (Fig. 2), dt represents the interval between adjacent frames, V_n is the velocity vector, and \mathbf{R}_n^T denotes the coordinates of the point measured in frame at time T . Note that the values of dt and Δl are not constant when T changes, as listed in Table 2, which can decrease the error. The calculated distribution of normal velocity along the backbone for all frames is shown in Fig. 4.

Table 2. The value of dt (s) and Δl (L^a)

| | | | | | | | | | | | | | |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| T (s) | 0.040 | 0.050 | 0.060 | 0.070 | 0.080 | 0.100 | 0.150 | 0.200 | 0.250 | 0.300 | 0.400 | 0.500 | 0.600 |
| dt | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.005 | 0.005 | 0.005 | 0.010 | 0.010 | 0.020 | 0.030 | 0.030 |
| Δl | 0.071 | 0.048 | 0.059 | 0.059 | 0.059 | 0.059 | 0.059 | 0.059 | 0.059 | 0.059 | 0.063 | 0.063 | 0.063 |

a) The length unit is L , which is the length of fish body.

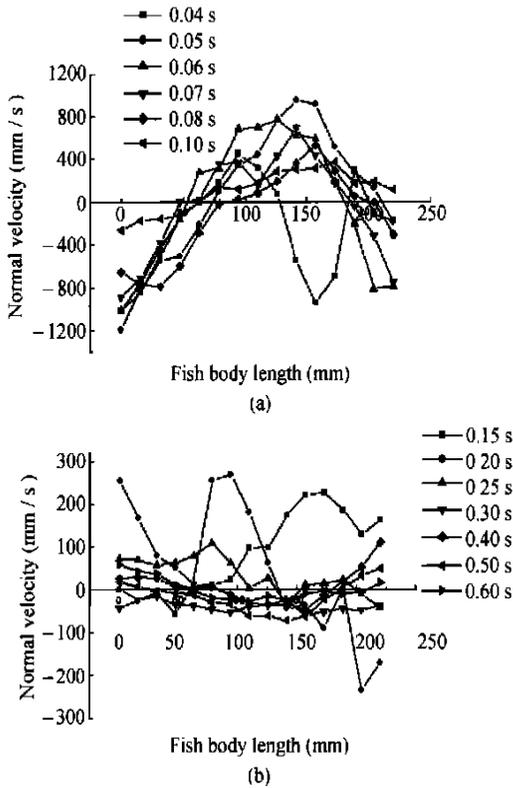


Fig. 4. Local velocities perpendicular to the backbone of the yellow catfish (Fig. 2) as a function of position along it from head to tail (a) Curves of frames 2–7 (Fig. 2); (b) curves of frames 8–14 (Fig. 2).

2.4 Forces and moments

The Weihs' model is applied to calculate the propulsive forces produced by the fins and body of a fish during the fast-start process. The formulation is expressed as

$$F = -\frac{\partial}{\partial t} \int_0^L m_a w n dl - \sum_{j=1}^k L_j, \quad (2a)$$

$$L_j = \frac{1}{2} \rho A_j V_j^2 C_{Lj} \alpha_j, \quad (2b)$$

where m_a is the added mass affected by a longitudinal section of the body of length dl , which moves in the direction perpendicular to the backbone. The added mass is calculated by

$$m_a = \frac{1}{4} \pi \rho d^2 \beta, \quad (3)$$

where d is the depth of section, β the added mass coefficient^[18], w the velocity of each fish section perpendicular to the backbone, L_j the force caused by

the momentum shedding from fin j , and n the unit vector perpendicular to the backbone. The other terms are the length of fish L , the length of longitudinal section dl , the water density ρ , the number of sharp-edged surfaces k , the surface area of j -th fin A_j , the velocity of the fin V_j , the coefficient of lift C_{Lj} , and the angle of the attack of a fin relative to its direction of motion α_j . The detailed formulation relevant to Eq. (2) can be found in Ref. [11].

The total forces and moments of each frame shown in Fig. 2 are listed in Table 3. The forces are denoted in a laboratory coordinate, the origin is at the position of MC, the x -direction directs to the head of fish and is tangent to the backbone at the initial time, the y -direction is normal to the x -axis and directs to the left side of fish. The moments in the counter-clockwise are positive.

Table 3. Forces and moments on the escape response of the yellow catfish

| Time (s) | Total Force (N) | | Moment (N·m) |
|----------|-----------------|---------|--------------|
| | F_x | F_y | |
| 0.031 | 0 | 0 | 0 |
| 0.040 | 3.4400 | -1.7100 | -0.00985 |
| 0.050 | 4.3000 | -1.4100 | -0.17800 |
| 0.060 | -0.0406 | 2.9900 | -0.00652 |
| 0.070 | -1.2800 | 5.4900 | 0.00532 |
| 0.080 | 0.7890 | 1.0600 | -0.09030 |
| 0.100 | 0.6090 | -0.2190 | -0.06530 |
| 0.150 | -0.4630 | 0.1660 | 0.03940 |
| 0.200 | -0.1380 | 0.2860 | 0.03310 |
| 0.250 | 0.1080 | 0.2960 | -0.00136 |
| 0.300 | 0.0809 | 0.0689 | -0.00270 |
| 0.400 | -0.0513 | -0.0976 | -0.00999 |
| 0.500 | -0.0467 | 0.0305 | 0.00453 |
| 0.600 | -0.0418 | 0.2550 | 0.02140 |

2.5 The strain of muscles

Here, a parameter S , which represents the strain of muscles (the extent to which the muscles at any position stretch and shorten around its mean length during swimming), is employed. By assuming that S depends on the radius of curvature (calculated from the angles described in Fig. 5) and on the width of the body at the particular body position, the parameter is then defined as

$$S = \frac{\Delta l}{l} = \frac{D}{2r}, \quad (4)$$

where Δl is the relative change length, l the length of a body segment, D the body width at the concerned point, and r the radius of curvature. Apparently, S will be higher when the body is more curved (large angle and short radius of curvature) and wider (Fig. 5). A simple geometrical model, as shown in Fig. 5, is used to explain the meaning of Eq. (4).

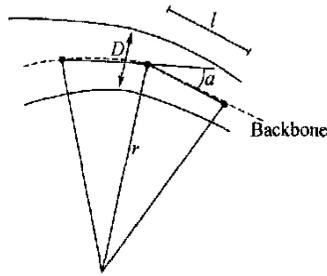


Fig. 5. Schematic diagram illustrating how S was calculated. l is the length of a body segment (m), D is the width of the body (m), r is the radius of curvature (m), α is the angle between adjacent body segments (radian).

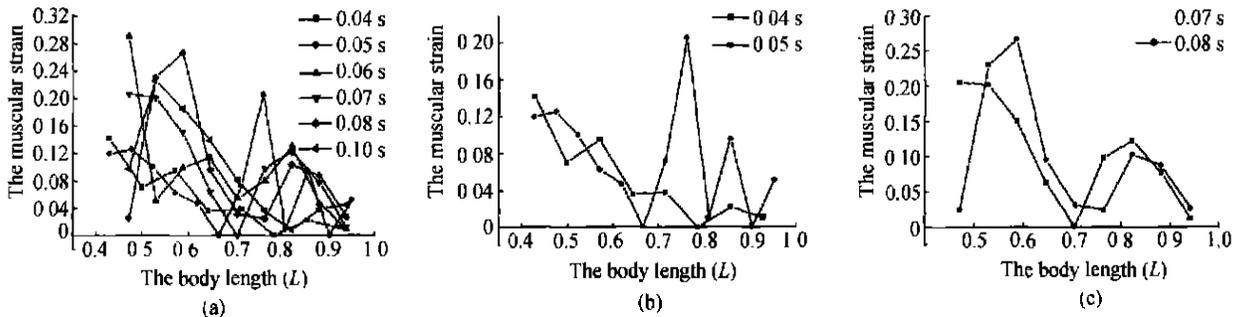


Fig. 6. The value of S . The unit of x -direction is L , the fish's body length. (a) The strain curves at frames 2—7 (Fig. 2); (b) The strain curves at 0.04s and 0.05s; (c) The strain curves at 0.07s and 0.08s.

an estimation of muscular contraction differences between different body locations.

3 Discussions

3.1 Classification of C-start of yellow catfish

Weih's^[11] first gave the kinematical description of a C-type fast-start and defined three kinematical stages for fast-starts: a preparatory stage in which the straight-stretched fish bends into a C shape, a propulsive stage in which the fish executes a reverse bend, and a variable stage, which may be a subsequent power stroke, steady swimming or unpowered coasting. In the present study, based on our experimental data, it seems more reasonable to divide the escape response of yellow catfish, C-type fast-start, into two

The length along the body axis is considered to be invariable, hence l (the length of one body segment) is also $r\alpha$, where α is the angle between two adjacent body segments. If D is the body width at the concerned point, the length of the convex side of the body segment is represented as $l + \Delta l = \alpha(r + D/2)$, and the length of the concave side is $l - \Delta l = \alpha(r - D/2)$. There is $S = \Delta l/l = D/2r$, with $l = r\alpha$; thus, $S = D\alpha/2l$. We have calculated the value of S at all body points except the last one (the tail tip) and the first six points (representing the inflexible head). Only from 0.040s to 0.100s, the value of S is calculated, and others are not necessary. The results are given in Fig. 6 (a), where the unit of x -direction is L .

This technique has first been used by Rome^[19] and his results have been verified by the independent technique of sonomicrometry^[20]. The similar method was also used to study the swimming of eel^[21]. In fact, since the anatomical structure of muscles of yellow catfish is unknown, the parameter S calculated here should be only qualitatively correct, i.e. only as

stages with different movements of MC. The reason is that the C-starts of yellow catfish start from rest in our experiment, while the C-start of fish begins from steady swimming in Weih's' research.

Figure 7 shows the track of MC of fish. Carefully observing Figs. 2 and 7, we can divide the whole process into two stages; stage one from 0.031s to 0.100s with frames 1—7 in Fig. 2 and stage two from 0.100s to 0.600s with frames 8—14 in Fig. 2.

In the first stage, the MC of fish remains at the initial position, the head of fish rotates to the final direction of the required turn and the tail is rotating in the opposite direction. It should be noted that the backbone of fish bends into a S-shape in the early pe-

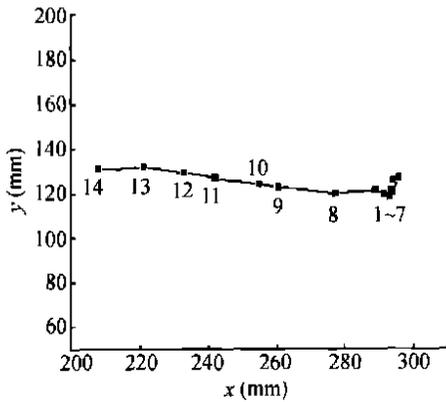


Fig. 7. The track of the centre of mass of fish. 1–7; $T = 0.031\text{--}0.100\text{ s}$; 8; $T = 0.150\text{ s}$; 9; $T = 0.200\text{ s}$; 10; $T = 0.250\text{ s}$; 11; $T = 0.300\text{ s}$; 12; $T = 0.400\text{ s}$; 13; $T = 0.500\text{ s}$; 14; $T = 0.600\text{ s}$.

riod of the first stage (Fig. 2). Usually, the process is still regarded as C-start, because although the tail of fish has a double bend in this stage, the main part of fish body bends into a C-shape. It was confirmed by Domenici^[22] in their experiment showing similar phenomena. The double bend of the tail causes the special hydrodynamics behavior, which will be analyzed later.

At the end of the first stage, the head of fish approaches the final direction of movement. After that, the fish stops the turning and the tail is flicked to produce the propulsive force. In the second stage, the MC of fish moves along a straight line. In this stage, the fish will swim from accelerated motion firstly to cruising at last.

3.2 Angular acceleration

Since in the C-starts the fish rapidly changes its moving direction to escape the predators, the angular acceleration is an important dynamical parameter. Next, we study the turning angular acceleration around MC, which is defined as

$$\ddot{\varphi} = \frac{\dot{M}}{I}, \tag{5}$$

where M is the moment, I is the moment of inertia and $\ddot{\varphi}$ is the turning angular acceleration. The data of M and I can be obtained from Tables 1 and 3. The calculated results of moment and angular acceleration are shown in Fig. 8.

After analyzing the data in Fig. 8, we can see that in the first stage of C-start, due to sudden contraction of muscle in fish, the fish obtains a big angular acceleration and completes the turning action. It is

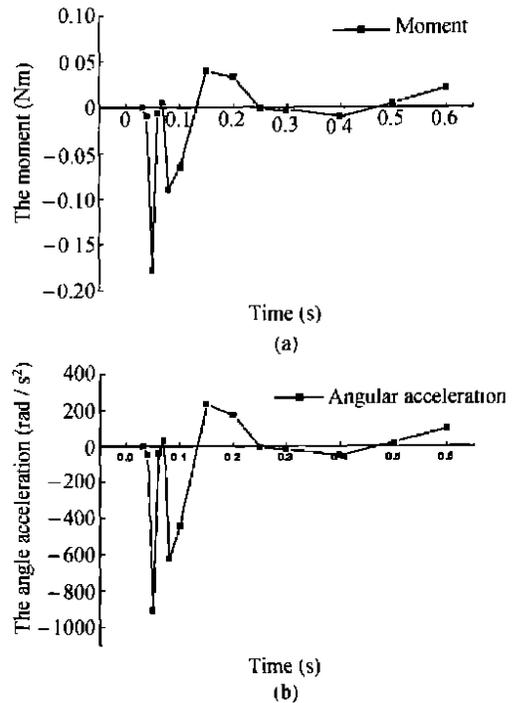


Fig. 8. The moment (a) and the turning angular acceleration (b).

interesting that there are two peaks of moment in the first stage, which shows that the muscle contracts twice. This is a special phenomenon for the C-start of fish with double bend.

3.3 Hydrodynamic analysis

As shown in Fig. 8(a), the instants corresponding to two peak values of moment are 0.050 s and 0.080 s, respectively, in stage one. Figure 6 shows that the value of muscle strain S has a larger change at the corresponding time, which means that the muscle of fish has two sudden contractions. Comparing these two figures, we find that the time of change in muscle strain is in good agreement with the time of peaks of moment. It explains why the moments at stage one have two peak values.

Furthermore, it is found that the steep changing of S for two instants occurs at different part of the fish body. At 0.050 s, the tail has a large muscular contraction, and at 0.080 s, the middle part of the fish body has a similar large muscular contraction. It indicates that the fish purposefully controls muscular contraction to obtain the larger moment. It is also the characteristic of yellow catfish with double bend in C-start.

In the first stage (frames 1–7, Fig. 2), the calculated total forces (Table 3) are bigger than the

second stage (frames 8–14, Fig. 2), which means that the value of acceleration of MC of the fish should be bigger. But the observation in experiments shows that MC of the fish keeps fixed in the first stage. It is because the direction of the total force in the first stage is changing and the period in stage one is so short that the distance of movement of MC is smaller relative to the length of fish body. At the second stage, the calculated moment is much smaller than the first stage, which means that the moment is not the dominating factor in the motion of fish. It is qualitatively consistent with the experimental results that the fish swims along a straight path.

Although the data obtained by using the Weihs' model can qualitatively reveal the whole process, it should be noted that the model is somewhat credible in this study. We compare the turning angle calculated by Weihs' model with the measured turning angle in experiment. We integrate the angular acceleration from 0.031 s to 0.080 s (the first stage) with a zero initial angular velocity (the fish is still at static state at 0.031 s) and in the calculation the change of MI is considered. The angle predicted using Weihs' model is 35.3° and the measured angle is 40.2° . This is a satisfying result.

Meanwhile it is found in this study that the Weihs' model is not very accurate. For example, in stage one the distance of MC movement calculated by Weihs' model is about 0.0447 m, while MC in the experiment does not move. In the second stage the calculated moments are not negligible, but the fish body stops rotating in experiment. It shows that Weihs' model is an approximate model and modification is necessary.

Based on the present work, it is shown that the analysis method, including the Weihs' model, the moment of inertia, and the muscle strain used in this study can reveal more detailed information. Satisfactory agreement has been obtained with experimental observations of fish movements. Our study is useful for further understanding of the fast-start process.

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