A study on the mechanism of morphing features of tuna median fins during C-turns

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Abstract. The median fins of tuna can morph in position and shape to enhance their hydrodynamic performance. Based on the C-turn kinematic equations and the self-propulsion swimming numerical model, the hydrodynamics of the median fins in different morphing forms (erected and depressed forms) are analyzed under the condition of three-degree of freedom (3DoF) self-propulsion, and then the assisted-turning mechanism of the median fins is clarified. The results show that the erected median fins have higher hydrodynamic forces, which can not only increase the yaw speed, but also reduce the turning radius to a certain extent.

1. Introduction
In July, 2017, Pavlov et al. [1] published a paper on Science, pointing out that there is a unique bio-hydraulic system at the base of the second dorsal fin and anal fin (called median fins) of bluefin and yellowfin tuna, which can quickly and accurately change the shape and area of the median fin. Similar to the hydrofoils on both sides of the bottom of hydrofoil, a lateral lift will be produced by the median fins when there is a certain angle between the incoming velocity and the plane of the fins. Tuna can adroitly adjust the forms of their median fin to improve the lift and drag characteristics of the fin, and thereby achieve superior overall kinematic performance.

In most research results, the median fin of tuna has been neglected or simplified into a fixed structure, which makes it difficult to reflect the fin’s morphing features. Pavlov et al. [1] constructed a morphing model for the second dorsal fin and gluteal fin of tuna, and obtained the hydrodynamic curves for both erection and depression of the median fin under static conditions by using hydrodynamic numerical analysis. By comparison, they reached the conclusion that the median fin has a larger lift-drag ratio in an erected form when the yaw angle is 1-8°, which may facilitate the tuna’s turning maneuver.

This paper intends to optimize and expand the simulation model proposed by Pavlov et al. On the one hand, by simulating the autonomous swimming process of tuna, the hydrodynamic conditions of the median fin are analyzed under the condition of three degrees of freedom (3DoF) self-propulsion, which can better clarify the mechanism of assisted turning of the median fin than the lift-drag ratio analysis under static conditions. On the other hand, the morphing features of the median fin were extended to the first dorsal fin, and the effects of the morphing forms of the three median fins (erected and depressed) on the turning performance of tuna were discussed. In fact, the first dorsal fin of tuna can also fold and stretch. Because the surface area of the first dorsal fin is relatively larger, it is of great significance to analyze the influence of its different states on the C-turn behavior of tuna.
2. Tuna model

Taking the real yellowfin tuna as the mold, the three-dimensional model of tuna was obtained by the reverse mold technology. A proper number of marker patches are arranged on the model, and the tuna is scanned into a point cloud image using a portable 3D scanner. Nonetheless, a large number of scattered fragments are distributed in the point cloud images, which cannot be directly applied to numerical analysis, so it is necessary to clean the images and reconstruct the model. In the process of model reconstruction, local details of tuna including the mouth, pectoral fin and tail fin, can be simplified appropriately. These simplifications will not have a great impact on the results because the focus of the research is the morphological changes of tuna median fin. Hence, it is the relative amount rather than the absolute amount of hydrodynamic forces among the various forms that deserves more attention. The final tuna simulation model in this study adopts the structure proposed in Ref. [2], as shown in Figure 1.

![Figure 1. Morphing form of median fins. (a) Erected form; (b) Depressed form](image)

3. Turning Equation

The C-turn can be divided into three stages: preparation stage, propulsive stage, and glide stage [3-4]. In the preparation stage, the caudal fin swings to one side, the front half of the body basically remains stationary, and the flexible back half bends into a C-shaped form, and the radius of curvature gradually decreases during the swinging process. When the caudal fin reaches the maximum swing, it swings back quickly, and the second half of the body gradually stretches until the C-turn ends. Tuna swings greatly in the second half, producing a turning moment, thus realizing rapid turning. Subsequently, the tuna enters the glide stage, during which its tail fin remains stationary and the tuna relies only on inertial force to glide forward. In the whole process, the median fins play an auxiliary role, and its morphing form will directly affect the turning effect.

According to the previous numerical simulation research, it is a commonly-used method to control the autonomous swimming of fish by using the motion law of fish midline [5-7]. In this paper, the kinematic equation of the midline of the fish is defined to realize the C-turn of tuna. The morphing displacement of the first half (rigid section) of tuna is very small when it is swimming, and the linear kinematics equation can be expressed as:

$$
\begin{align*}
\frac{dx(l,t)}{dl} &= \frac{d}{dl}(l) \quad (l < l_0) \\
\frac{dz(l,t)}{dl} &= 0
\end{align*}
$$

(1)

where $l$ is the arc length of the midline of tuna fish; $l_0$ is the initial length of the flexible section; $x(l,t)$ and $z(l,t)$ represent the morphing displacement of tuna in X and Z directions at the time $t$, respectively. It is assumed that the midline of the second half of the fish's flexibility is an arc with $R(t)$ as the radius at a random moment of the C-turn. $R(t)$ changes with the time $t$. Assume that $R_0$ is the minimum arc radius, then $R(t)$ can be expressed as:

$$
R(t) = \frac{R_0}{\theta(t)}
$$

(2)

where $\theta(t)$ is the curvature function of the midline of the fish’s flexible section, which is defined as

$$
\theta(t) = \frac{2}{1 + 10^{b(t)}} \cdot \frac{1}{1 + 10^{k_1 - k_2 t}}
$$

(3)

where $b$ depends on the duration of the C-turn; $k_1$ and $k_2$ are related to the duration of the preparation and propulsive stage of the C-turn, respectively.
According to the geometric relationship of fish swing, the motion equation of the midline of tuna flexible section can be expressed as:

\[
\begin{align*}
    x(l,t) &= l_0 + R(t)\sin\left(\frac{t-l_0}{R(t)}\right) \\
    y(l,t) &= R(t) - R(t)\cos\left(\frac{t-l_0}{R(t)}\right)
\end{align*}
\]

(Tytell and Jing et al. [7-8] measured that the duration of the first two stages of C-turn initiation of bluegill sunfish and crucian carp was about 57 ms and 260 ms, respectively. Tuna has a larger size, stronger rigidity and less mobility than bluegill sunfish and crucian carp. Therefore, it is defined in this paper that the whole tail swing process of tuna lasts for 0.5 s (T=0.5 s). The flexion time is about 0.292 s (T1=0.292 s), the swing time is about 0.208 s (T2=0.208 s), and the ratio of T1/T2=1.40, which is close to the experimental data of 1.28 and 1.5 obtained by Tytell and Jing et al., respectively [7-8]. The initial length of the tuna’s flexible section is 0.57 m. The parameters are set follows: \( b=0.39 \), \( k_1=4.0 \) and \( k_2=15.0 \).

4. Numerical Computation Method

During C-turns, tuna can only swim on the X-Z plane and has three degrees of freedom (3DoF) of movement. At this time, the kinetic equation of tuna can be solved by Newton's theorem:

\[
\begin{align*}
    m \frac{dV_x}{dt} &= m\alpha_x = F_x \\
    m \frac{dV_z}{dt} &= m\alpha_z = F_z \\
    I_y \frac{d\omega_y}{dt} &= I_y\alpha_y = M_y
\end{align*}
\]

where \( m \) is the mass of tuna; \( V_x \) and \( V_z \) are the swimming speeds of tuna along the X and Z directions, respectively; \( F_x \) and \( F_z \) are hydrodynamic forces on tuna in X and Z directions; \( \omega_y \) is the turning angular velocity; \( I_y \) is the moment of inertia around the Y axis; \( M_y \) is the rotational moment around the Y axis; \( \alpha_x \), \( \alpha_z \) and \( \alpha_y \) are acceleration along the X and Z directions and angular acceleration in Y direction, respectively.

During C-turns, the position of tuna in the flow field is constantly changing, so the spatial mesh of computing domain needs to be updated in real time. The flexible morphs of the tail pendulum can be realized by diffusion smoothing and local mesh reconstruction. Realization of the autonomous swimming of tuna relies on the whole movement of computational domain [9]. In the process of numerical simulation, the morphing trajectory of tuna and the 3DoF motion law in the computational domain are calculated by writing the user defined function (UDF) according to Equations (4) and (5), respectively.

In order to reduce the number of meshes and the calculation workload, the flow field is divided into inner and outer calculation fields, as shown in Figure 2. The external flow field is a cuboid with a size of 10×7×5 m, which is divided by the hexahedron mesh. Given the complexity of tuna surface and mesh reconstruction, the internal flow field (3×2.2×1.2 m) containing the fish body is divided by unstructured meshes. The mesh size of fish surface is less than 8mm, while the mesh size of median fins and tail fin is about 3mm. Mesh encryption is carried out around the tuna and tail area to ensure mesh quality and calculation accuracy when computing domain is updated. Because the tuna swims autonomously, and there is no external inflow, the velocity and pressure gradient at the boundary of entrance, far field and exit of the computational domain are set to zero. When the median fins are erected and depressed, the values of various parameters should be the same, including flow field size, turbulence model, step size, iteration times, convergence criteria, etc., to ensure the rationality and reliability of the comparison between them.
5. Results and Analysis

5.1 Swimming performance

When the tuna swims autonomously in the sea, it usually does not slow down to zero velocity before turning, but first reduces to a reasonable speed to improve the turning efficiency. Assuming that the initial forward speed $V_x = -8.0$ m/s (swimming along the negative direction of X), the curves of forward speed $V_x$, lateral speed $V_z$ and turning angular speed $\omega_y$ of tuna in the forms of erection (E) and depression (D) of median fins are shown in Figure 2.

Whether the median fins are erected or depressed, the speed change trend of tuna in three directions is similar. During the C-turning stage of the caudal fin, the forward speed $V_x$ drops from 8.0 m/s to around 5.1 m/s due to the loss of the tail thrust, and then drops rapidly to about -0.7~0 m/s at $t = 0.5$ s. When $V_x$ velocity changes from negative to positive, tuna has finished turning and swimming. Unlike the forward speed $V_x$, the lateral speed $V_z$ does not always increase, but increases first and then decreases. During $t=0$~0.38 s, $V_z$ increased rapidly from zero to about 2.3~2.6 m/s, and then decreased gradually and slowly. This is because the tuna has started to turn at this time, and the direction of fluid force on tuna has changed, which makes the speed of tuna decrease. The angular velocity $\omega_y$ formed an inverted U-shaped trend in the early stage of caudal fin bending, reaching the maximum value of 6.8~7.0 rad/s at $t=0.2$ s, and then decreasing to the minimum value of -1.0~1.57 rad/s at $t=0.45$ s. During $t=0.5s$~0.7s, $\omega_y$ gradually rises. After the completion of the C-turn, $\omega_y$ stays stable around zero.

![Figure 2](image_url)

Figure 2. The forward velocity $V_x$, lateral velocity $V_z$, and turning angular velocity $\omega_y$ of tuna in the erected (E) and depressed (D) forms.

Although the trend of movement speed is similar, the swimming performance of tuna is different under different forms of the median fins. Before $t=0.2$ s, the erected and depressed forms of the median fins have little influence on the velocities $V_x$, $V_z$ and $\omega_y$ in three directions. At this time, the bending and swinging of the caudal fin are the decisive forces to regulate tuna swimming. When $t>0.3s$, the median fins begin to assist in influencing the swimming performance of tuna. When the median fin is in an erected form, due to the increase of the inflow area, the fluid resistance is relatively large, which leads to a greater decline in the forward speed $V_x$ of tuna in the initial stage, and finally obtains a higher turning speed. When $t=2s$, $V_x$ is 0.96 m/s in an erected form and 0.40 m/s in a depressed form. Similarly, when the median fins are erected, the lateral lift increases with the increase of the frontal area, which leads to the larger lateral velocity $V_z$ of tuna. When $t=0.3s$, $V_z$ is 2.56 m/s in the erected form and 2.16 m/s in depressed form. However, when $t=0.5$ s, the tuna in the erected form has started to turn, and the direction of water flow has changed, which makes the lateral velocity $V_z$ drop faster. The reduction of lateral speed has a better effect on turning, because smaller lateral speed may mean a smaller turning radius, which is helpful to improve the turning maneuverability of tuna. The varied forms of the median fins also have some influence on the turning angular velocity $\omega_y$. In most cases, the angular velocity $\omega_y$ in an erected position is higher than that in a depressed position. This shows that the erected form is more conducive to the turning maneuver. When $t>0.5s$, $\omega_y$ in an erected form can return to zero axis quickly. This means that the erected median fins not only facilitate the turning maneuver, but also improve the stability of tuna.
5.2 Turning Performance
An important indicator for the turning performance is the yaw angle \( \theta \). As shown in Figure 3, when \( t=0-0.4s \), the tuna mainly relies on C-turns of its tail fin to realize yawing. When \( t \) is around 0.4 s, the yaw angle \( \theta \) reaches the maximum value of 1.82~1.97 rad. At this stage, the form of the median fins has little influence on the yaw angle \( \theta \). After the C-turn of the caudal fin is completed, the erected median fins begin to show the function of assisted turning, which promotes the yawing of the tuna. When \( t>0.6s \), the rising slope of the yaw angle \( \theta \) in the erected mode is obviously larger than that in the depressed mode. Take for example the case when \( t=2.0 \) s, the yaw angle \( \theta \) when the median fins are erected is 2.1 rad, which is 17.3% higher than that in the depressed form.

Usually, high maneuverability requires not only a high turning speed, but also a small turning radius. The forward displacement of the fish (\( x \)) is one of the indicators of the turning radius. When the median fin is erected, the forward velocity (\( V_x \)) of the tuna decreases more sharply with the increasing fluid resistance, resulting in a relatively short forward displacement \( x \). As shown in Figure 4 and 5, the farthest point of the forward displacement \( x \) of the center of gravity of tuna is -1.01 m in the erected forms and -1.35 m in the depressed form. At this time, the increase of the forward resistance of the median fins is beneficial to reducing the turning radius and strengthening the turning maneuverability of tuna.

![Figure 3. The yaw angle \( \theta \) of the tuna with the erected (E) and depressed (D) median fins](image)

![Figure 4. The trajectory of the tuna’s COM in the erected (E) and depressed (D) forms.](image)

6. Conclusion
After a long period of evolution, tuna has become a complex and sophisticated system. Any slight change in the morphology and structure of the fish may cause changes in its overall performance. During C-turns of tuna, the morphological changes in the median fins show the following characteristics:

1. The morphing characteristics of the median fins can affect the swimming performance of tuna, causing an increase in the forward velocity \( V_x \) and angular velocity \( \omega_y \), and a decrease in the lateral velocity \( V_z \).

2. The erected median fins can assist the turning performance, which cannot only improve the yaw speed, but also reduce the turning radius to a certain extent. When \( t=2.0s \), the yaw angle \( \theta \) in erected from is 17.3% higher than that in the depressed form, while the forward displacement \( X \) decreases by about 0.34 m.
Figure 5. The C-turn process of the tuna, (a) depressed form, (b) erected form.

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