Simulation and Functional Mechanism of Tuna Median Fins on Yaw Mobility in Unsteady Flow

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Abstract. Tuna keeps its median fins erect in searching and feeding behaviors. During the process of these behaviors, tuna probably needs to yaw frequently in the wake of a shoal of small fish. This paper aims to clarify the functional mechanism of the erected median fins on yaw mobility in unsteady flow. Firstly, the CAD simulation models with two morphing states of the median fins are constructed by scanning and measuring the physical prototype of real yellowfin tuna. Secondly, the wake environment of the fish school is created by swinging a tuna model back and forth. Lastly, the hydrodynamic analysis of different morphing states of tuna median fins in unsteady flow is carried out. The results show that the lift forces of the median fins increases in the erection state to a certain extent, which is beneficial to the tuna’s yaw motions. Moreover, the hydrodynamics of the tuna’s body also rise due to the interaction between the body and the median fins. This further improves the yaw mobility of the tuna in unsteady flow.

1. Introduction

In 2017, Pavlov et al. [1] report in science that the base of both the second dorsal and anal fins of bluefin and yellowfin tunas exist specific bio-hydraulic system which can adjust the area and shape of median fins. Under the control of lymphatic pressure, the dorsal and anal fins erect synchronously from cruising behavior with prevailing rectilinear motion to searching and feeding behavior with frequent changes of motion direction. Median fins are analogous to hydrofoils producing sideways lift force when the fin plane is at an angle with the fluid flow direction [2]. Morphing median fins, capable of changing their area and shape, are associated with expanded capabilities for producing additional hydrodynamic forces during yaw motions.

As a high-performance object for inspiring the bionics design [3-4], there are many achievements on tuna’s hydrodynamic analysis. Takagia [5], Feilich [6], Xue [7-8], Feng [9], Wang [10], Macias [11] have used numerical methods to study the propulsion performance and flow field distribution of tuna swimming. However, in all of the above studies, the median fins of tuna are either simplified as a fixed structure or removed for various reasons. These simulation cases do not show the morphing characteristics of tuna median fins.

As mentioned earlier, tuna keeps its median fins erect in searching and feeding behavior. Most fish, especially small ones, generally swim in groups to fight against predators and improve swimming efficiency. During the process of feeding and searching, tuna probably needs to yaw in the wake of a shoal of small fish. Different from the steady flow, there are irregular vortices and jets in this shoal wake, making it a complex and variable unsteady flow. The erected median fins may affect their own hydrodynamic forces in unsteady flow, thereby influencing the stability and mobility of the tuna.
Moreover, the erection of the median fins may also change the hydrodynamics of the tuna’s body due to the interaction between the body and the median fins, further affecting the tuna’s swimming performance during yaw motions.

In this paper, the hydrodynamic analysis of different morphing states of tuna median fins in unsteady flow will be carried out, and the functional mechanism of their morphing characteristics on yaw motions will be revealed. And the body-fin interaction and its effect on tuna’s hydrodynamic performance will also be discussed in details.

2. Tuna Model

![Figure 1](image1.png)

Figure 1. The physical prototype of a yellowfin tuna. (a) scanning the physical prototype with a 3D scanner; (b) the point cloud image; (c) the fitting curves of the tuna model.

On the basis of a real yellowfin tuna, the physical prototype is obtained by the reverse molding process. The body and fins of the tuna prototype are covered with marked points, then its profile is scanned into point cloud map by a hand-held 3D scanner, as shown in Figure 1. Because the back of the tuna prototype is black and the scanner can not get the coordinates of these points, the point cloud data is partially missing. In addition, there are scattered patches in the point cloud, so it is necessary to clean and reconstruct the image. In the process of image reconstruction, reasonable simplification is made. The contours of the dorsal, anal and caudal fins are fitted as sine curves by the least square method, while the contours and sections of the body are polynomial and spline curves.

![Figure 2](image2.png)

Figure 2. The morphing states of the median fins. (a) All median fins are erected; (b) All median fins are depressed.

The second dorsal and anal fins with different morphing states are obtained by rotating their fitting curves about point $O_d$ and $O_a$, respectively. Standard symmetric airfoil profiles NACA0015 are used for all the fin sections [12]. During rectilinear cruising, the second dorsal and anal fins of tuna are both depressed, and the first dorsal fin is folded in the groove. In searching and feeding behavior, the second dorsal and anal fins erect synchronously, and the first dorsal fin unfold out of the groove. The CAD model of tuna with two morphing states are shown in Figure 2. The sweep angle of the first dorsal fin, second dorsal fin, and anal fin in the erection state is 35°, 58°, and 61°, respectively. In the depression state, the sweep angle is 0°, 76°, and 79°, respectively.

3. Simulation Configuration

The wake of a real shoal is difficult to create, so it has been simplified to a wake generated by a body swinging back and forth. As shown in figure 3(a), the flow field consists of three computational domains. The outer domain is a cuboid with a size of 8×5×5m, and the two inner domains are two
cylinders with the same size of $\phi 1.7 \times 0.8 m$. Each inner domain has a tuna model, and its COM coincides with the axis of the cylinder. The distance between the two domains is 1.6BL. The tuna in the front domain is cruising with a translation velocity of $v$, while doing pendulum or swing movement. The tuna behind follows the tuna in front at the same translation speed and makes a yaw motion in the wake of the front tuna. Strictly speaking, the wake of an individual tuna is different from that of a real shoal, but it can elucidate the hydrodynamic performance of the median fins in unsteady flow to a certain extent. The pendulum or swing motion law of the tuna in front is expressed as

$$
\begin{align*}
\psi &= -A_0 \cos(2\pi f t) \\
\psi' &= 2\pi f A_0 \sin(2\pi f t)
\end{align*}
$$

where $\psi$ and $\psi'$ is swing angle and swing rate respectively; $A_0$ is the swing amplitude; $f$ is the swing frequency.

There are two kinds of motion in the simulation: pendulum and yaw. In order to avoid the coupling of the two motions and reduce the computational load, the yaw motion is simplify. Different from the continuous yaw motion with constant speed in the previous chapter, here the results are calculated only at several discrete yaw angles. As shown in figure 3(b), during the simulation, the tuna in front swings for a total of three consecutive cycles. In the first period of swing, the $1/2$ sinusoidal ramp is employed to accelerate the tuna behind to the specified yaw angle $\theta$. When the acceleration stage is over, the tuna behind stays still until the flow field tends to be stable, and the data of the last cycle are used for hydrodynamic analysis.

![Figure 3](image.png)

**Figure 3.** The computational domain and the motion law. (a) The outer and inner domain in unsteady flow; (b) The swing and yaw motion law of two tuna models (T is the period of swing).
Figure 4. The unstructured hexahedral meshes of the flow field and tuna model. (a) the volume mesh of the flow field; (b) the surface grid of the tuna model.

Table 1. The simulation configuration.

| Parameter                  | Value                  |
|----------------------------|------------------------|
| Outer domain               | 8x5x5m                 |
| Inner domain               | 1.7x0.8m               |
| Distance                   | d = 1.9m               |
| Turbulence model           | k-ω SST                |
| Swing amplitude            | A₀ = 0.4rad            |
| Swing frequency            | f = 1Hz                |
| Yaw angle                  | θ = 1°, 2°, 4°, 6°, 8°, 10°, 12°, 14° |
| Translation velocity       | v = 10m/s              |
| Time step                  | Δt = 0.0025s           |
| Total number of cells      |                        |
| Erection                   | 2424616                |
| Depression                 | 2381897                |

4. Results and Discussion

4.1. The Hydrodynamics of Median Fins

The detailed parameter settings in unsteady flow is shown in table 1. The k-ω SST turbulence model is the recommended model for all basic hydrodynamic computations in FINE™/Marine [13]. The two major features of this model are a zonal blending of model coefficients and a limitation on the growth of the eddy viscosity in rapidly strained flows. It is suitable for the numerical analysis of tuna swimming. The translation velocity of the tuna model is set as v=10m/s because the swimming speed of tuna is generally 30~50km/h. The swing frequency and amplitude is estimated empirically to be 1Hz and 0.4rad, respectively.
With the erection of the FDF, the hydrodynamic performance of the SDF has changed in unsteady flow. The average L/D ratio of the SDF diminishes by about 51.7%. It indicates that the effect of the SDF is weakened in the erection state. This is similar to the phenomenon in a marathon that the runners in front can reduce the wind drag of the runners behind under certain conditions. Since the FDF is not far in front of the SDF, the flow field of the FDF can also affect the hydrodynamic performance of the SDF. The low pressure area behind the FDF extends to the SDF, reducing the pressure difference between the two sides of the SDF, which results in the decrease of its lift and L/D ratio.

![Figure 5](image1.png)  
**Figure 5.** The drag, lift, and L/D ratio of the anal fin in a period when the yaw angle is 6°. (a) the drag of the anal fin; (b) the lift of the anal fin; (c) the L/D ratio of the anal fin. Note: AF-E-6° (or AF-D-6°) represents the erection state (or depression state) of the anal fin with a yaw angle of 6°.

![Figure 6](image2.png)  
**Figure 6.** The drag, lift, and L/D ratio of the two dorsal fins in the erection and depression states when the yaw angle is 6°. (a) the drag; (b) the lift; (c) the L/D ratio. However, the erection of the FDF makes up for the loss of the SDF. The drag and lift of the FDF are much larger than that of the SDF and AF during yaw motion. Its average L/D ratio is 6.55 at the yaw angle of 6°, which is also higher than the other two fins. It shows that the erected FDF plays a more important role. This result is easy to understand. In the erection state, the area of the SDF and AF is about 57% and 55.6% of that of the FDF respectively. The area increment of the SDF and AF is about 15% and 15.7%, while that of the FDF is 100%. The absolute area of the two median fins, as well as the incremental area, is much smaller than that of the FDF, resulting in less hydrodynamic force.

4.2. The Body-fin Interaction

It needs to be noted that the erection of the median fins affects not only themselves but also the hydrodynamics of the tuna’s body. As shown in figure 7, the lift and drag force of the body also increase as the median fins are erected in unsteady flow. And the average value of the L/D ratio of the body rises from 4.66 to 5.56 at the yaw angle of 6°. An increase of 19.3% in the L/D ratio is very beneficial for tuna in searching and feeding behaviors. Since the tuna’s body is exactly the same in the two morphing states, we believe that the body-fin interaction is responsible for the raised L/D ratio. This is in agreement with the viewpoint of Liu that the body-fin interaction improves thrust in swimming fishes and movable fins contribute to overall swimming performance [14]. One reliable explanation about the body-fin interaction is that the pressure distribution around the body changes when all median fins are erected. The pressure of the body’s upstream surface increases, while the
pressure on the downstream surface decreases, thereby enlarging the pressure difference between the two sides of the body. This leads to an increase in lift and L/D ratio.

Figure 7. The drag, lift, and L/D ratio of the tuna’s body (B) in the erection and depression states when the yaw angle is 6°. (a) the body’s drag; (b) the body’s lift; (c) the body’s L/D ratio.

4.3. The Functional Mechanism

Figure 8(a) shows the average values of the L/D ratio of the AF, Body, SDF, and FDF in two morphing states within a range of yaw angles from 1° to 14° in unsteady flow. It can be seen that the curve trend of L/D ratio with the yaw angle increases at first and then decreases gradually during yaw motion. The L/D ratio reaches its maximum value when the yaw angle is about 4°~8°. Most of the time, the L/D ratio of the body and AF is usually greater in the erection state than in the depression state. And the L/D ratio of the erected FDF is the largest when the yaw angle is below 6°. Their erections can improve the yaw mobility of the tuna.

Figure 8(b) is the mean lift increments of the AF, Body, SDF, and FDF in the erection state within a range of yaw angles from 1° to 14°. With the exception of the SDF, the lift forces of the AF, FDF and body are all increased in the erection state. The FDF has the largest lift increment, followed by the body. Although the lift force of the SDF is reduced in the erection state, its value is small and does not have a significant impact on the yaw motion. As a whole, the lift force of the median fins rise obviously during yaw motion, which is beneficial to the tuna’s yaw mobility.

The functional mechanism of the morphing median fins can be described as follow. In the process of searching and feeding, tuna needs to change the motion direction frequently. At this time, the erected median fins provides additional lift forces, which improves the yaw mobility of tuna. When the yaw angle is about 4°~8°, the median fins have the largest L/D ratio, and they have the best effect on improving the swimming performance of tuna. Moreover, the lift and L/D ratio of the tuna’s body also increase when all the median fins erect, which further enhances the swimming performance of tuna, making it more maneuverable in the wake of a school of fish. In a word, the erected median fins improve the performance of tuna’s yaw motion.

Figure 8. The average values of the L/D ratio and lift increment of the AF, Body, SDF, and FDF within a range of yaw angles from 1° to 14°. (a) the mean L/D ratio; (b) The mean lift increment.
5. Conclusion
Tuna keeps its median fins erect in searching and feeding behaviors. During the process of these behaviors, tuna probably needs to yaw frequently in the wake of a shoal of small fish. This paper aims to clarify the functional mechanism of the erected median fins on yaw mobility in unsteady flow. Though numerical simulation, the results show that the hydrodynamics of the median fins and the body is increased in the erection state, which is very helpful to the yaw mobility of the tuna in unsteady flow. Based on this bionic principle, the morphing median fins can be designed for robotic fish to facilitate the control of their yaw maneuverability and stability. In future studies, we will apply this mechanism to AUVs.

Acknowledgement
This research was supported by National Natural Science Foundation of China (No.51805512).

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