Fluid Mechanics Analysis of the Sweep Motion of Tuna Median Fins

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Abstract. Study has shown that tuna can improve hydrodynamic performance and turning maneuverability by rapidly and accurately changing the shape of its median fins. In this paper, the shape change of tuna median fins is simplified as the sweep motion. The fluid mechanics analysis of the sweep motion is carried out from the aspects of rectilinear cruise and turning maneuver. The results show that the sweep motion of the median fins plays a different role in rectilinear cruise and turning maneuver. When in a rectilinear cruise, tuna should increase the sweep angle to reduce the drag force. For turning maneuver, a larger sweep angle of the median fins can provide more positive turning torque to assist tuna to steer efficiently in the early and middle stage of turning process, while a smaller sweep angle should be taken in the later turning period.

1. Introduction
Fish swimming gait can be divided into two functional modes: BCF (Body and/or Caudal Fin) and MPF (Median and/or Paired Fin) gait [1]. In BCF swimming, median fins which includes dorsal and anal fin have the balancing action and prevents fish from moving side to side. As the research moves along, scholars realize that median pins also play an important role in turning maneuvers. Among all kinds of fish, the bluegill is the first one to catch scholars’ attention. Jayne [2], Tytell [3], Chadwell [4-5], Borazjani [6] and Flammang [7] indicate that the flexible back part of bluegill’s dorsal fin can accelerate the water around it, enhance hydrodynamic force, and equilibrate overturning moment, thereby the maneuverability can be controlled efficiently.

Researches show that median fins of tuna have the similar function as well. In July 2017, Pavlov [8] indicated in science that the base of the second dorsal and anal fin of bluefin and yellowfin tuna exist specific bio-hydraulic system, which can change the shape of median fins quickly and precisely. Median fins of tunas are analogous to thin, symmetrical hydrofoils generating sideways lift force when the fin plane makes an angle to the fluid flow direction. Movable fins, capable of changing their area and shape, are associated with expanded capabilities for producing hydrodynamic forces. On the one hand, median fins can provide stability to prevent rollover and yaw, and on the other hand, they also can assistant pectoral and tail fins to increase turning maneuverability.

Both bluegill and tuna can change the area and shape of median fins. However, there are many differences between them in morphological structures and swimming modes. Thus, the fluid mechanics theory of bluegill median fins is not fully suitable for tuna. Current research results for tuna median fins mainly focus on physiology, anatomy and morphology, which lack deep fluid mechanics analysis on the relation among bio-morph, motion parameter and flow field structure.
In this paper, the shape change of tuna’s median fins is simplified as the sweep motion. Taking sweep angle as characteristic parameter, the fluid mechanics analysis of tuna median fins is discussed in details from the aspects of rectilinear cruise and turning maneuver.

2. The model of median fins

The front view, the top view and the side view of the tuna are picked out. Taking the mouth of the tuna as the origin, the coordinate system is set up by using the symmetric bisectors of body length, height and thickness as x, y and z axes, respectively. The tuna is scaled down proportionally along the 3D direction until its body length is 320mm. The coordinate values of each point are measured to obtain the data point cloud map of tuna shape. After proper cleaning and scaling of the original data cloud map, the contour curve equations of the fish body, the median fin and the caudal fin are fitted by using the least square method, as shown in figure 1.

![Figure 1. The model of tuna](image1.png)

The fitting curve equations for each segment of tuna are as follows:

Body curve 1: \( f_1(x) = 1.72e^{-8}x^3-3.749e^{-6}x^2-0.002543x^2+0.6424x+0.1274 \) (0≤x≤270)

Body curve 2: \( f_2(x) = -7.862e^{-10}x^5+5.634e^{-7}x^4-0.0001515x^3+0.02072x^2-1.482x-0.2207 \) (0≤x≤270)

Dorsal curve 3: \( f_3(x) = 56.38\sin(0.019x+10.24)+0.1942\sin(0.1741x-5.756) \) (156.5≤x≤198)

Dorsal curve 4: \( f_4(x) = 61.02\sin(0.02666x+39.82) \) (185≤x≤198)

Anal curve 5: \( f_5(x) = -51.28\sin(0.02059x+9.783) \) (175≤x≤218)

Anal curve 6: \( f_6(x) = -57.67\sin(0.01923x+40.83) \) (202≤x≤218)

Caudal curve 7: \( f_7(x) = 54.78\sin(0.02282x+12.78) \) (270≤x≤320)

Caudal curve 8: \( f_8(x) = 1.709x-497.2 \) (297≤x≤320)

The dorsal and anal fins with 5 different sweep angles \( \chi \) are obtained by rotate their fitting curves about point \( O_d \) and \( O_a \), respectively, as shown in figure 2. The 3D models of median fins are draw using NACA0012 airfoil as cross section, and the parameters are shown in table 1.

![Figure 2. The model of the median (dorsal and anal) fins](image2.png)

| Dorsal fin \( (\chi^\circ) \) | 10° | 20° | 30° | 40° | 50° | 14° | 24° | 34° | 44° | 54° |
|-------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| SA (\( \chi^\circ \))         | 553 | 532 | 501 | 457 | 403 | 549 | 524 | 489 | 445 | 396 |
| FA (mm²)                      | 167.4 | 169.2 | 170.9 | 172.3 | 173.8 | 187.0 | 188.7 | 190.2 | 191.5 | 192.8 |
| CG (x y) mm                   | 43.8 | 43.0 | 41.9 | 40.4 | 39.1 | -46.3 | -45.1 | -43.8 | -42.2 | -40.51 |

Note: SA-sweep angle; FA-fin area; CG-center of gravity
3. Fluid mechanics analysis of median fins during rectilinear cruise
Tuna is one of the large fish who is capable of cruising over long distances and with fast speed. Its average speed is 60~80km/h and the highest speed can reach 120km/h. During rectilinear cruise, the exposed median fins can generate drag force and the variation of the sweep angle could directly affect the drag value, thereby changing the cruising performance of tuna.

With the k-omega turbulence model, the drag force of the median fins and body of tuna is shown in table 2 at a cruising speed of 72km/s (20m/s). It can be seen that the drag is 3.66N and 2.02 when the sweep angle of dorsal fin is 10° and 50°, respectively; The drag is 3.56N and 2.11N when the sweep angle of anal fin is 14°and 54°, respectively. On overall trend, no matter dorsal fin or anal fin, the drag force decreases with the increase of sweep angle.

| Body drag (N) | 10° | 20° | 30° | 40° | 50° | 14° | 24° | 34° | 44° | 54° |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 48.98        | 3.66| 3.54| 3.16| 2.47| 2.02| 3.56| 3.16| 2.92| 2.55| 2.11|

As we know, the drag force is proportional to the square of the cruising velocity. According to computational fluid dynamics (CFD) analysis, the drag force curve of the median fins with the cruising velocity is shown in figure 3. Without considering the pectoral fin, the fin-to-body drag ratio is defined as the ratio of the drag force of the median fin to the body. After conversion, the fin-to-body ratio is obtained as shown in figure 4. It can be seen that with the increase of cruising speed, the fin-to-body ratio also increases gradually. When the cruising speed is 2~10m/s, the ratio increases rapidly. When the cruising speed exceeds 10m/s, the ratio tends to be flat. The sweep angle of the median fins has an important influence on the drag force. When the sweep angle of the dorsal and anal fin is 50° and 54°, the total drag ratio is about 5.48%~8.51%; and when that of the dorsal and anal fin is 10° and 14°, the total drag ratio is 9.32%~15.04%. Therefore, during rectilinear cruising, especially at high speed, the tuna should increase the sweep angle of the median fins to reduce the drag force.
4. Fluid mechanics analysis of median fins during turning maneuver

When a tuna is in a rectilinear cruise, its median fins tend to contract to reduce drag force. During high speed turn maneuver, the median fin gradually erects and the sweep angle decreases to improve hydrodynamic performance. The tuna obtains excellent turn maneuverability by controlling the sweep angle of median fin efficiently.

As shown in figure 5, the turning motion of tuna is simplified to uniform circular rotation. The CFD analysis of the turning process is carried out by means of sliding mesh method. The whole flow field is divided into inner and outer domains, and the median fin rotates with the inner flow field around the central point \( O \). When the fin plane makes an yaw angle to the fluid flow direction, median fins can generate sideways force \( F_x \) and \( F_y \). The two sideways forces of the median fins are adjusted with the change of sweep angle \( \chi \) and yaw angle \( \theta \), which affect the turning maneuver of tuna. The parameter settings of CFD analysis are shown in table 3. The flow field and median fin mesh is shown in figure 6.

![Figure 5. The turning motion of tuna](image)

![Figure 6. The flow field and median fin mesh](image)

| Parameter setting        | Value       |
|--------------------------|-------------|
| Outer domain             | 1.8\times1.6\times0.8m |
| Inner domain             | \phi0.8\times0.3m |
| Turbulence model         | k-omega SST |
| Turning angular velocity | \omega=2\text{rad/s} |
| Inlet velocity           | \nu=2\text{m/s} |
| Turning radius           | \rho=0.4m |
| Time step                | \Delta t=5\times10^{-4} |
| Max number of iterations | 16          |
| Total number of cells    | 598234–602406 |

Through CFD analysis, the sideways force of dorsal fin \( F_{xd} \) and \( F_{yd} \) with different sweep angles \( \chi_d \) during turning maneuver are obtained as shown in figure 7. The characteristics of \( F_{xd} \) and \( F_{yd} \) are as follows:

1. During 180° turning process, the \( F_{xd} \) curve of dorsal fin presents an inverted V-shaped trend, while \( F_y \) is an approximate negative cos-type trend.

2. Most of the time, the force \( F_{xd} \) of the dorsal fin decreases with the increase of the sweep angle \( \chi_d \), but when the yaw angle \( \theta \) is about 34–60°, the \( F_{xd} \) curves intersect with each other.

3. When the yaw angle \( \theta \) is less than 27°, the force \( F_{yd} \) increases with the increase of sweep angle \( \chi_d \); when \( \theta \) is about 27–62°, the \( F_{yd} \) curves with different sweep angles intersect with each other; and when \( \theta \) is greater than 62°, the \( F_{yd} \) decreases with the increase of sweep angle.

4. When the sweep angle \( \chi_d \) of the dorsal fin is 10°, 20°, 30°, 40° and 50°, the corresponding maximum force \( F_{xd} \) is 1.53N, 1.59N, 1.64N, 1.71N and 1.75N respectively, and the minimum \( F_{yd} \) is...
-1.23N, -1.38N, -1.40N, -1.41N and -1.39N respectively.

(5) Under different sweep angles, the extreme values of the \( F_{xd} \) and \( F_{yd} \) curves appear at different positions (yaw angles).

![Graph of \( F_{xd} \) vs \( \theta \) for different sweep angles](image1)

![Graph of \( F_{yd} \) vs \( \theta \) for different sweep angles](image2)

Figure 7. The sideways force of dorsal fin \( F_{xd} \) and \( F_{yd} \) with different sweep angles

The sideways force \( F_{xa} \) and \( F_{ya} \) of anal fin with different sweep angles \( \chi_a \) during turning maneuver are shown in figure 8. Similar to the dorsal fin, the \( F_{xa} \) curve of anal fin is an inverted V-shaped trend and \( F_{ya} \) is an approximate negative cos-type trend as well. When the sweep angle \( \chi_a \) is 14°, 24°, 34°, 44° and 54°, the corresponding maximum force \( F_{xa} \) is 1.52N, 1.67N, 1.68N, 1.76N and 1.83N respectively, and the minimum \( F_{ya} \) is -1.24N, -1.43N, -1.52N, -1.54N and -1.54N respectively. The extreme values of the \( F_{xa} \) and \( F_{ya} \) with different sweep angles appear at different positions.

![Graph of \( F_{xa} \) vs \( \theta \) for different sweep angles](image3)

![Graph of \( F_{ya} \) vs \( \theta \) for different sweep angles](image4)

Figure 8. The sideways force of anal fin \( F_{xa} \) and \( F_{ya} \) with different sweep angles

5. Turning torque analysis of median fins

In the turning process, turning torque generated by sideways force \( F_x \) and \( F_y \) of the median fins can affect maneuverability and stability of tuna. Resultant turning torque \( T \) is shown in formula (1).

\[
T = -F_x r \sin \theta - F_y r \cos \theta \tag{1}
\]

Turning torque curves of the dorsal fin and anal fin can be obtained by taking each parameter into the formula (1), which is shown in figure 9. It can be concluded as follows.

1) When \( \theta = 0 \sim 90^\circ \), \( F_x \) is inclined to block turning motion, and \( F_y \) is inclined to promote turning motion. However, when \( \theta = 90 \sim 180^\circ \), the effect of these two forces is reversed.

2) In the initial stage of turning process, both anal fin and dorsal fin have the tendency to block turning motion because the turning torque \( T_a \) and \( T_b \) is negative. Then due to \( T_a \) and \( T_b \) change from negative to positive, extra turning torque is provided by median fins which can assist tuna to turn quickly.
(3) With different sweep angles, the yaw angle position where positive torque occurs is different. For the dorsal fin with sweep angle of 50°, it provides negative torque $T_d$ when yaw angle $\theta < 24.9°$, while it provides positive torque $T_d$ when yaw angle $\theta > 24.9°$. When the sweep angles of the dorsal fin are 40°, 30°, 20° and 10°, the corresponding yaw angles where positive torque occur are 25.1°, 55.9°, 70.7° and 84.9°, respectively.

(4) Similar to the dorsal fin, when the sweep angles of the anal fin are 54°, 44°, 34°, 24° and 14°, the corresponding yaw angles where positive torque $T_a$ occur are 27.8°, 25.7°, 25.8°, 59.6° and 70.8°, respectively.

(5) When the yaw angle $\theta < 24.9°$, the dorsal fin with sweep angle of 50° has minimum negative torque; When $\theta$ is 24.9°~116.5°, the dorsal fin with sweep angle of 50° has maximum positive torque; When $\theta$ is 116.5°~135.5°, the torque curves of the dorsal fin with different sweep angles are cohered with each other. When $\theta$ is 135.5°~180°, the dorsal fin with sweep angle of 10° has maximum positive torque.

(6) The anal fin with sweep angle of 54° has minimum negative torque when the yaw angle $\theta < 18°$; The anal fin with sweep angle of 44° has maximum positive torque when the yaw angle $\theta$ is 18°~43.5°; The anal fin with sweep angle of 54° has maximum positive torque when the yaw angle $\theta$ is 43.5°~105°; the torque curves of the anal fin with different sweep angles are cohered with each other when the yaw angle $\theta$ is 105°~136°; The anal fin with sweep angle of 14° has maximum positive torque when the yaw angle $\theta$ is 136°~180°.

![Figure 9. The turning torque curves of the dorsal and anal fin during turn maneuver](image)

In order to obtain the maximum turning torque, a larger sweep angle should be adopted in the early and middle stage of turning process, while a smaller sweep angle should be taken in the later turning period. For the dorsal fin, the sweep angle is 50° when the yaw angle is less than 116.5°, and then its sweep angle is gradually reduced to 10°. The sweep angle of the anal fin is 54° or 44° when the yaw angle is less than 105°, and then reduces to 14° step by step.

6. Conclusion
In this paper, the shape change of tuna’s median fins is simplified as the sweep motion. The fluid mechanics analysis of the sweep motion is carried out from the aspects of rectilinear cruise and turning maneuver. The results show that the sweep motion of the median fins plays a different role in rectilinear cruise and turning maneuver. When in a rectilinear cruise, tuna should increase the sweep angle to reduce the drag force. During the turning motion, a larger sweep angle of the median fins can provide more positive turning torque to assist tuna to steer efficiently in the early and middle stage of turning process, while a smaller sweep angle should be taken in the later turning period.
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