Research Article

Inspired by the Black Ghost Knifefish: Bionic Design of Undulatory Fin with 2-DOF Rays and Its Propulsion Performance

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The demand for high-performance underwater thrusters in marine engineering is increasing. The concealed, mobile, and efficient underwater ability of fish provides many directions for research. The black ghost knifefish uses only wavy ventral fins to swim and can hover and roll in the water. Based on the physiological and morphological characteristics of the black ghost knifefish, we explored the structure and movement mode of the ventral fin, so as to establish a two-degree of freedom (2-DOF) structural model and kinematic model. We reveal the motion mechanism of the undulating fin propulsion through the constructed model and computational fluid dynamics. It is found that when the fin surface fluctuates, a pair of vortices with opposite directions will be formed on the concave side of the fin surface. These vortices will produce a central jet on the fin surface, provide a reverse impulse for the ventral fin, and make the fin obtain power. In addition, we found that the propulsive force of the ribbon fin along the body direction is positively correlated with the swing amplitude and frequency of the fin movement, and the propulsive torque of the ribbon fin to realize the maneuvering movement increases first and then decreases with the increase of the torsion angle. The research on the structure and motion mechanism of the ribbon fin of the black ghost knifefish provides a basis for the development of a bionic prototype of multi-DOF motion and the control strategy of high-mobility motion.

1. Introduction

Unmanned underwater vehicle has bright application prospects and potential in the exploration and exploitation of marine resources and the implementation of seabed reconnaissance, which makes it a hotspot of innovative research by scholars and experts [1, 2]. According to special needs and purposes, focusing on simulating various superior underwater capabilities of fish is one of the basic research methods for developing high-performance underwater thrusters [3, 4]. Most of the existing bionic robotic fish use BCF (body and/or caudal fin) propulsion, which has high-acceleration performance and can realize long-distance high-speed cruise [5, 6]. MPF (median and paired fin) propulsion has the ability of thrust vector [7], which can realize the transformation of heading and posture only through the change of fin fluctuation form, and the fish body does not bend and deform during swimming [8]. This physiological morphological feature is especially suitable for integration into a rigid underwater vehicle.

The low-speed maneuverability and hovering performance of undulatory fin propulsion are very inline with the current needs of ocean engineering for operation in complex environment. Therefore, research institutions such as Northwestern University and Nanyang University of Technology have studied various organisms which swim by means of an undulating fin, such as manta ray [9–11], stingray [12], black ghost knifefish [13, 14], Rhinoptera javanica [15], and seahorse [16]. The various approaches they employed encompass analysis of kinematic data from live swimming fish [17], computational fluid dynamics (CFD) studies [13, 18, 19], and theoretical modeling [4, 20, 21]. Based on the research of undulating fin propulsion, many bionic prototypes of robotic fish have been designed and manufactured.

Curet et al. [22] and Hu et al. [23] have developed a design that emulates the morphological features of the
ventral fin of the black ghost knifefish. Their prototype incorporates numerous self-driven fin rays that are interconnected via flexible materials and affixed to rails for experimental purposes. While the fin motion is restricted by the rails, it nonetheless generates an effective wave pattern, thereby facilitating a dependable approach for evaluating its performance. In contrast, Liu et al. [24] exhibits a pared-down mechanical structure featuring a singular flexible fin surface driven by individually powered fin rays that oscillate, thereby engendering a form of wave propagation that enhances operational stability. However, the existing robotic undulatory fins can only realize the swing motion of one degree of freedom (1-DOF) [25, 26]. The range of fin motion is small, the motion form is more real, and the fish is too simplified.

The black ghost knifefish *Apteronotus albifrons* is one type of South American weakly electric knifefish. Its body is relatively flat, its back is smooth without fins, and its wavy abdominal fins go straight to the tail. The muscles connected with it are broad and developed. The tail fin degenerates like a rod made of white rings, and the whole body of the fish is similar to feathers. It only relies on the wavy swing of its ventral fin to swim freely through water, grass, and rock cracks, realize various maneuverable postures and also has extremely fast speed when hunting [27, 28].

Taking the black ghost knifefish as the bionic object, this paper mainly studies its ventral ribbon fin, explores its structure and movement mode, so as to establish our bionic model, studies the mechanism of the undulating fin propulsion according to the bionic model, reveals the qualitative relationship between the propulsion parameters of the ribbon fin and the propulsion force and torque, and lays a foundation for the realization of the mobility of the undulatory fin propulsion in various environments.

### 2. Methods

According to the literature, the ventral fin of black ghost knifefish is composed of many fin rays and flexible membranes connected with them, in which the fin rays are connected with the muscles and bones of the abdomen [7, 29]. As shown in Figure 1, the muscle as the driving source can be simplified into transverse muscle and longitudinal muscle. The longitudinal muscle can realize the swinging movement of the fin around the baseline of the ventral fin, the transverse muscle can realize the twisting movement of the fin around its axis, and the cooperative actuation of the muscle can realize the multi-DOF movement of the fin [30], which is the key to the movement of the ventral fin.

#### 2.1. Research on Bionic Characteristics

In order to better understand the ventral fin of black ghost knifefish and establish a bionic model, we carried out two observation experiments. First of all, we observed the dead sample (body length: 98 mm) of a black ghost knifefish. As shown in Figure 2, our investigation revealed that the ventral fin exhibits a ray count of 153 (varying from 140 to 160 in different individuals [31]). Furthermore, we observed significant heterogeneity in the morphological characteristics of the ventral fin length. Based on our analysis of ray length, we partitioned the ventral fin into three distinct regions: the fore fin, mid fin, and rear fin. By accounting for the number of fin rays, as well as considering their respective lengths, our findings are presented in Table 1. Obviously, it can be seen that the fore fin and the rear fin account for a small proportion of the whole abdominal fin, and the average length of the fin is short, while the proportion of the mid fin reaches three-fourth of the whole ventral fin, and its fin length is long and uniform. Fore fin, mid fin, and rear fin.

After obtaining the basic data of each part of the ventral fin, we also need to know the movement form of the ventral fin and fin rays and the role of each part of the fin rays in swimming, so as to provide support for establishing an accurate and simple bionic model. Therefore, we designed and carried out the observation experiment of undulating fin propulsion.

The experiment was carried out in a transparent plastic fish tank (37 × 23 × 40 cm) filled with warm water (15 cm deep), in which there are two black ghost knifefishes (body length about 95 mm) swam freely. The bottom and side of the fish tank use the pasted white paper as the background,
and use the high-speed camera (phantom, the parameters are shown in Table 2) to take continuous photos, and record the fin surface characteristics of black ghost knife fishes when swimming freely.

Figure 3 presents an image sequence depicting the black ghost knife fish in steady forward swimming. It can be directly seen that during the propulsion of the fish body, the ventral ribbon fin produces a sinusoidal traveling wave, in which the transmission direction of the wave is opposite to the movement direction of the fish body. These findings are consistent with those reported by Ruiz-Torres et al. [32]. When we extract the waveform during swimming, we can more clearly see that the whole traveling wave passes from the fin head to the fin tail, as shown by the yellow dotted line, and the wave speed is about 33 cm/s, surpassing the highest recorded swimming speed (0.23 BL/s) of Ruiz-Torres et al. [32] by a slight margin. By observing the waveform located at the same place of the body, we can see that the motion of a single fin is a quasi-harmonic oscillation between the crest and trough, as shown by the green dash, and the oscillation frequency is 3 Hz. Therefore, we can judge that the simple harmonic oscillation of the fin produces traveling waves, which makes the fish obtain propulsion. Youngerman et al. [33] have conducted a meticulous investigation on the peak-shaped wave structure of the ventral fin, postulating that it is caused by the exertion of inclinator muscles. Analogously, upon a scrupulous observation of the waveform of the ventral fin, we can also discern that the wave generated by the fin rays does not exhibit orthogonality with respect to the direction of the body axis, but rather manifests an inclination at certain angles, indicating that the motion of the fin rays occurs with a diverse range of freedom degrees.

![Figure 3](image)

**Figure 3:** Outlines of the ventral fin undulations during steady forward swimming.

**Table 2: Parameters of the Phantom V12.1 high-speed camera.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max resolution</td>
<td>1,280 × 800</td>
</tr>
<tr>
<td>Photo frequency</td>
<td>6,242/s</td>
</tr>
<tr>
<td>ISO sensitivity</td>
<td>6,400/1,600</td>
</tr>
<tr>
<td>Communication mode</td>
<td>CBE</td>
</tr>
<tr>
<td>Camera lens</td>
<td>Nikon F-type</td>
</tr>
<tr>
<td>Power</td>
<td>60 W</td>
</tr>
</tbody>
</table>

2.2. Construction of Biomimetic Ribbon Fin Model. Combined with the observation of biological characteristics and the knowledge of literature, the focus of establishing the bionic model is the structure of multi-degree freedom moving fin. To simply and clearly describe the fin structure, each closely connected fin, muscle tissue, and bone in the ventral fin are named as a fin unit. As shown in Figure 4, we propose a fin unit model of 2-DOF RLR mechanism, which can describe the compound motion of torsion and swing of a single fin, and each joint rotates around the same rotation center, which is very close to the actual structure of fin and muscle. From the extracted waveform in Figure 3, it can be seen that the fore fin and the rear fin have small swing amplitude due to the length of the fin, so they play little role in the undulating propulsion process, while the wave amplitude of the mid fin is large, which plays a major role in the propulsion process. Therefore, we mainly use the mid fin to build the model of the bionic ribbon fin.

The mid fin has the following characteristics:

1. Fin rays are equally long and spaced.
2. It can produce 1.5 wavelengths.
3. The total number of fins is 99 and the aspect ratio is 7.64.
4. According to the similarity principle, the biomimetic ribbon fin model is assembled in SolidWorks, as shown in Figure 4.

2.3. Research on Kinematic Model. Next, we further study the 2-DOF motion characteristics of the bionic fin to test whether the traveling wave generated by the bionic model is consistent with reality. According to the fin unit model proposed by the observation experiment, it can be seen that the fin makes a fixed-point motion in space, and the motion characteristics of its 2-DOF can be reflected by the motion trajectory of the central vertex of the tip of the fin. The fixed point connecting the fin and the fish body is set as the base point, and the connecting line of the base point of each fin
forms the ventral fin baseline. In order to describe the movement of a single fin, take the \( N^{th} \) fin as the research object, and establish a reference system to describe the movement of the fin, as shown in Figure 5.

Taking the bionic model as the reference, the fin rays are of equal length (length \( l \)) and equally spaced along the axial direction of the body (spacing \( d \)). If the swing angle of the \( N^{th} \) fin at a certain time is \( \varphi_n \) and the torsion angle is \( \varphi_n \), the pose transformation parameter table of the \( N^{th} \) fin can be established, as shown in Table 3.

According to the chain rule of coordinate system transformation, the transformation matrix from coordinate system \( \{i\} \) to coordinate system \( \{i-1\} \) can be written as:

\[
i^{-1}T = \begin{pmatrix}
\text{Rot}_{\varphi_n} & 0 & 0 & 1 \\
0 & \text{Rot}_{\alpha_{i-1}} & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}.
\]

Substituting the coordinate system transformation parameters into Equation (2):

\[
0^iT = \begin{pmatrix}
\cos\varphi_n & -\sin\varphi_n & 0 & (n-1)d \\
\sin\varphi_n & \cos\varphi_n & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}.
\]

Multiply Equations (3) and (4) to obtain the transformation matrix \( 0^iT \) from the coordinate system \( O_2 - x_2y_2z_2 \) of the fin tip to world coordinate \( O_0 - x_0y_0z_0 \):

\[
0^iT = \begin{pmatrix}
\cos\varphi_n & -\sin\varphi_n\cos\alpha_{i-1} & \sin\varphi_n\sin\alpha_{i-1} & \varphi_n \sin\alpha_{i-1} + (n - 1)d \\
\sin\varphi_n & \cos\varphi_n\cos\alpha_{i-1} & -\cos\varphi_n\sin\alpha_{i-1} & -\varphi_n\sin\alpha_{i-1} \\
0 & \sin\alpha_{i-1} & \cos\alpha_{i-1} & l\cos\alpha_{i-1} \\
0 & 0 & 0 & 1
\end{pmatrix}.
\]

In any case, the relationship between the position of the end point of the \( n^{th} \) fin and the fin length, spacing, swing angle, and torsion angle can be expressed by the following formula:

\[
\begin{cases}
x_n = l\sin\varphi_n\sin\alpha_{i-1} + (n - 1)d \\
y_n = -l\cos\varphi_n\sin\alpha_{i-1} \\
z_n = l\cos\alpha_{i-1}.
\end{cases}
\]

Assuming that the left–right swing of the fin on both sides of the body is an equal amplitude simple harmonic motion with sinusoidal variation, the swing motion function of the fin is:

\[
\varphi_n(t) = \varphi_n(0) + \varphi_{\text{max}}\sin(2\pi f_1 t),
\]

where \( t \) is the time, \( \varphi_n(0) \) and \( \varphi_n(t) \) are the swing angle of the \( N^{th} \) fin at time \( t \) and time 0, \( \varphi_{\text{max}} \) is the maximum swing angle of fin, and the \( f_1 \) is the swing frequency of the fin.
Simulation is carried out in Python to obtain the figure of the biomimetic ribbon fin, as shown in Figures 6(a) and 6(b). Although the number of fins of the bionic model is one-fifth of that of the black ghost knifefish, it can be seen from Figures 6(c) and 6(d) that the waveform of the bionic model is consistent with the fin surface contour of the ventral ribbon fin of the black ghost knifefish, which shows that the kinematic model established for the bionic model is effective, so the bionic model can be used to replace the black ghost knifefish to study the undulating fin propulsion mechanism in the future.

2.4 Computational Fluid Dynamics Simulation. According to the observation of biomorphology, the ventral fin of the black ghost knifefish can be regarded as the combination of rigid fins and a flexible fin surface, so the force of the moving ventral fin underwater is very complex. Because of the flexibility of the ribbon fin, the interaction between the fluid and it belongs to the theoretical model of fluid-structure coupling, that is, the fin surface is deformed due to the pressure field and velocity field of the fluid, which affects the distribution of the flow field and the acting propulsive force at the same time.

Because the calculation of fluid-structure coupling is very complex, we realize the simulation calculation with the help of the ANSYS Workbench coupling platform. Import the bionic fin model established in SolidWorks, add the flexible fin surface in the geometry module. Subsequently, the fin ray must be set as a rigid body, while the fin surface should be designated as a rubber material with an elastic modulus of 0.5 MPa [34]. Then add simple harmonic oscillation to each fin of the bionic model, establish a flow field, and then mesh them. The mesh graph is shown in Figure 7. After meshing, carry out iterative calculations to obtain the flow field data and propulsion load data in the undulating fin propulsion. The specific fluent solver parameters are shown in Table 4.

3. Results and Discussion

3.1 Propulsion Mechanism Analysis. Perform simulations for a single operational condition and analyze the results using
CFD-Post. The computed $y+$ value for the fin surface reveals concentration between 35 and 75, thus implying that the k-epsilon (2 equation) model can yield accurate performance predictions of the fin surface underwater. Subsequently, further investigations into the pressure distribution, flow velocity distribution, and vortex structure distribution within the flow field surrounding the ventral fins are required. Figure 8 is a cloud diagram of the surface pressure of the ribbon fin model: (a) observe from the positive direction of the $Z$-axis; (b) observe from the positive direction of the $Y$-axis.

The change of pressure in the flow field must be accompanied by a change in velocity. A plane close to the end of the ribbon fin model is intercepted, as shown in Figure 9, which is the vector diagram of the fluid velocity field on this plane. By carefully observing the change of velocity vector, it can be found that when the ribbon fin model fluctuates, a pair of vortices with opposite rotation directions will be formed on one side of the fin surface wave depression, while there are residual vortices that have not completely dissipated along the side of the fin surface wave protrusion. It can be seen that with the periodic transmission of traveling waves, these vortices also occur periodically and fall off.

Figure 10 shows the distribution of vortex structure falling off the surface of the ribbon fin model in different periods. Connecting the pressure and vortex, it can be seen that the place where the pressure difference between the positive

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**Table 4**: Solver parameters for Fluent.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prevalue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solver</td>
<td>Pressure based</td>
</tr>
<tr>
<td>Time</td>
<td>Transient</td>
</tr>
<tr>
<td>Viscous model</td>
<td>k-epsilon (2 equation)</td>
</tr>
<tr>
<td>Materials</td>
<td>Water liquid</td>
</tr>
<tr>
<td>Inlet</td>
<td>Velocity inlet (0 m/s)</td>
</tr>
<tr>
<td>Outlet</td>
<td>Pressure outlet</td>
</tr>
<tr>
<td>Dynamic Mmesh</td>
<td>Smoothing and remeshing</td>
</tr>
<tr>
<td>Computational domain</td>
<td>$20 \times 15 \times 15$ mm</td>
</tr>
<tr>
<td>Number of grid</td>
<td>1,468,85</td>
</tr>
<tr>
<td>Number of time steps</td>
<td>200</td>
</tr>
<tr>
<td>Time step size</td>
<td>0.01 s</td>
</tr>
</tbody>
</table>

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and negative sides on the fin surface is significant is the place where the vortex appears. This shows that it is the periodic change of vortices’ current that leads to the change in pressure. These vortices in opposite directions will produce a central jet on the fin surface [35]. According to the momentum principle, it can be seen that the jet provides a reverse impulse for the fin surface, which is the essential reason for the ribbon fin to obtain power.

3.2. Multi-Parameter Impact Analysis. Through bionic experiments and simulation studies, we have known that the reason why the fin surface obtains power is that the fin surface generates traveling waves due to the movement of the fin. Then studying the relationship between several key parameters of the fin movement and the propulsion force and propulsion torque will help to control the movement for the undulatory propulsion of the ribbon fin.

Swing amplitude and swing frequency are two important parameters in the motion equation of fin swing. By using the method of control variables, when the torsion angle of the fin is 0, the forces of the ribbon fin model are obtained through simulation, as shown in Figure 11. It can be seen that the larger the amplitude and the faster the frequency of the fin swing, the greater the propulsive force on the fin surface in the X and Y directions; among them, the X-direction force is a positive value, indicating that the ribbon fin receives the thrust in X-positive direction, and the Y-direction force is a negative value, indicating that the ribbon fin receives the thrust in Y-negative direction, that is, the lifting direction to overcome gravity. Figures 11(c) and 11(f) are the Z-direction force of the ribbon fin, it can be seen that the force on the fin surface fluctuates sinusoidally with 0 as the baseline, with positive and negative phases.

Since the forces on the fin surface at each simulation calculation time are recorded in Fluent and are discrete, the impulse of the fluid to the fin surface can be obtained by integrating these forces, so as to obtain the change in momentum of the ribbon fin. The impulse of the fin surface at different swing amplitudes and different swing frequencies is shown in Figure 12, it can be seen that the X- and Y-directions impulse of the fin surface gradually increases with the increase of amplitude or frequency, while the Z-direction impulse is always close to 0. It can be concluded that at the sinusoidal swing without torsion angle, the ribbon fin has almost no momentum change in the Z direction.

In addition to the swinging motion, the torsional motion of the fin is also important in undulating fin propulsion. The torsional angle directly affects the steering, rolling, and other maneuvers of the ribbon fin. Therefore, taking the torsion angle as the variable, we also did the control simulation, the forces and moments of the fin surface at different torques are obtained through simulation, as shown in Figure 13.

In Figures 13(a) and 13(b), it can be clearly seen that with the increase of torsion angle, the variation range of the force on the fin surface gradually decreases, and the propulsive force on the fin surface in the X and Y directions gradually decreases; among them, the X-direction force is a positive value, indicating that the ribbon fin receives the thrust in X-positive direction, and the Y-direction force is a negative value, indicating that the ribbon fin receives the thrust in Y-negative direction, that is, the lifting direction to overcome gravity. It can be found from Figure 13(c) that the Z-direction force on the fin surface fluctuates sinusoidally with 0 as the baseline, with positive and negative phases, and the fluctuation amplitude and torsion angle show a relationship of first increasing and then decreasing.

Figure 14(a) shows the impulse and impulse moment of the fin surface at different torques. From Figure 14(a), it can be seen that with the increase of torsion angle, the X- and Y-directions impulse of the fin surface gradually decreases, while Z-direction the impulse gradually increases. It can be concluded that under the sinusoidal swing with the same torsion angle of all fins, the ribbon fin receives a lateral Z-direction force, which increases with the increase of torsion angle, momentum changes, and the travel direction also changes.

However, it is difficult to see the mobility of the ribbon fin with the influence of force and momentum, while the moment and momentum can well indicate the change of the motion state of the fin. In Figures 13(a)–13(c), it can be seen that with the increase in torsion angle, the torque around the X and Y axes of the ribbon fin fluctuates sinusoidally with 0 as the baseline, with positive and negative phases, and only the change amplitude and wave phase change; The torque around the Z-axis increases first and then decreases, reaching the peak at 20°.

It can be seen from Figure 14(b) that with the increase of torsion angle, the momentum moment of the ribbon fin around the X, Y, and Z axes first increases and then
FIGURE 11: Continued.
decreases. When the torsion angle is around 20°, the impulse moment generated by the undulatory ribbon fin is the largest, and the momentum moment that overturns the ribbon fin is the largest.

Due to the downscaling of the model utilized in the simulation, its dimensions amount to approximately one-fourth of those of the observed black manta ray. The individual fin ray within the model exhibits a mass of roughly 1.85 E-6 kg.
FIGURE 13: Continued.
with a propulsive force exerted on the fin surface that registers in the order of $1 \times 10^{-5}$ N per temporal unit. Given the weight of the model, the resultant propulsion force is deemed rather substantial.

4. Conclusion

In this paper, the morphological characteristics and motion form of the ventral fin of the black ghost knifefish are studied.
by biomimetic observation. It is found that the ventral fin relies on the 2-DOF motion of the fin to produce sinusoidal traveling waves to obtain power. The middle ventral fin with an aspect ratio of 7.64 is the main part, which can produce 1.5 wavelengths, the traveling wave velocity is about 33 cm/s, and the fin swing frequency is 3 Hz. Based on the data of the middle ventral fin obtained from the observation experiment, the model of the biomimetic ribbon fin is constructed. After analyzing the 2-DOF motion of the fin in the model, the fin surface contour obtained by the simulation is consistent with reality, which proves the reliability of the biomimetic ribbon fin. Using the ANSYS Workbench simulation platform, we found that the high- and low-pressure areas on the fin surface will move in a directional direction with the fluctuation of the fin surface. The pressure difference on both sides of the fin surface is the direct cause of the undulating propulsion. The change of the high- and low-pressure area on the fin surface is due to the formation of a pair of vortices with opposite rotation on the concave side when the fin surface fluctuates, which will produce a central jet on the fin surface and provide a reverse impulse for the fin surface. In addition, we carry out multigroup simulation by controlling variables. It is found that the propulsion force and impulse of the fin surface with only sinusoidal fluctuation in a certain range increase with the increase of swing frequency and swing amplitude; the lateral force, lateral impulse, yaw, and overturning and impulse moment produced by the ribbon fin are related to the torsional angle of the fin, and show a trend of first increasing and then decreasing, with a peak between 20° and 30°.

In future research, we plan to investigate the impact of varying swing frequencies and amplitudes on the front and back of the same ribbon fin, and analyze their effects on the forces and moments acting on the fin surface. Moreover, we will explore the impact of different torsion angles applied before and after the same ribbon fin, and evaluate their influence on the forces and moments on the fin surface. Our study on the structure and motion mechanism of the ventral ribbon fin of the black ghost knifefish could serve as a foundation for developing a bionic prototype with multi-DOF motion and devising strategies for controlling highmobility motion.

Data Availability

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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