Numerical simulation of a self-propelled fish-like swimmer with rigid and flexible caudal fins

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Abstract

Aim: In this paper, numerical simulations were conducted to investigate the swimming performances, hydrodynamics performances and wake structures of a self-propelled swimmer with rigid and flexible caudal fins.

Methodology: The kinematics model of the swimmer was constructed using thunniform swimming. Using computational fluid dynamics (CFD) method, the systematic study of swimmer with rigid and flexible caudal fins was carried out.

Results: The results showed that the caudal fin flexibility is beneficial to the fast-start of fish but not conducive to the fast cruising of fish. The fish with rigid caudal fin has larger cruising velocity in quasi-steady swimming and smaller forward acceleration in fast-start stage. In addition, the caudal fin flexibility is also beneficial to the heading stability of fish's self-propelled swimming. The pressure distribution on the fish surface indicates that most of the thrust is generated by the leading-edge region of the caudal fin. The visualization of wake structures showed the existence of the attached leading-edge vortex (LEV) in thunniform swimming.

Interpretation: Based on the present simulations, the hydrodynamic performance of tuna during self-propelled swimming was analyzed in detail. Researchers can use these findings to design bionic robot fish with rigid and flexible tails.

Key words: Bionic robot fish, Computational model fluid dynamics, Caudal fin, *Fangsheng-I*, Fish Hydrodynamic performances, Numerical simulation, Swimming performance

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Introduction

Fish oscillate their caudal fins to generate force for swimming. In this swimming mode, the caudal fin is the main propulsor to generate thrust (Liu *et al.*, 2017; Krishnadas *et al.*, 2018). Therefore, the investigation on the hydrodynamic performance of caudal fin plays an important role in understanding the swimming mechanism of fish. The hydrodynamics performance and propulsion mechanism of the fish's caudal fin has been widely investigated using rectangular wings and biomimetic fins with prescribed heaving and pitching motions (Read *et al.*, 2003; Yang *et al.*, 2011). Yang *et al.* (2011) studied the hydrodynamic performances and vortex structures of rigid and flexible tuna-tails with heaving and pitching motions using commercial computational fluid dynamics (CFD) software FLUENT. They found that the propulsive efficiency of tuna-tail initially increases as the tail becomes more flexible, and then decreases as the flexibility increases. Further, Li *et al.* (2016) studied hydrodynamic of rigid and flexible pectoral fins.

The experimental and numerical studies on a live fish performed by Wolfgang *et al.* (1999) reported that the wake flow of fish is the result of the interaction of vortex generated by fish body with the vortex generated by the caudal fin. Therefore, it is impossible to truly understand the mechanism of fish swimming by taking the caudal fin as the research object alone, and only by taking the whole fish as the research object can truly understand the mechanism of the thrust generated by the caudal fin. Therefore, researchers have performed the numerical simulations of fish's swimming based on virtual swimmer (Borazjani and Sotiropoulos, 2008; Kern and Koumoutsakos, 2006; Yang and Su, 2011; Zhu *et al.*, 2002). Yang and Su (2011) simulated the straight-line swimming performance of a tuna-like swimmer in the uniform stream, they also found that the body- and tail-generated vortices strengthen each other, resulting in a stronger jet flow. In the above studies on the whole fish, the fish body is fixed in space and immersed in uniform incoming flow for undulating motion. As fish are free-swimmers in water, their motion is controlled in real time by the forces of the fluid. Therefore, it is necessary to simulate the self-propelled swimming of fish in detail. The hydrodynamics of anguilliform swimming was investigated using a self-propelled body by Ken and Koumoutsakos (2006). In the present study, the virtual fish was built with the same geometric shape with the "Fangsheng-I", a laboratory robotic fish imitating the body and motion of the real-life tuna. Based on numerical method, the effects of flexible caudal fin and rigid caudal fin on the swimming performance, hydrodynamic performance and vortex structure of fish during self-propelled swimming were analyzed in detail. This is an issue that has not been studied in previous investigations, and the results can be vital for designing bionic robot fish, as caudal fin is the main propulsor for fish.

Materials and Methods

Computational model and kinematics: The "Fangsheng-I" bionic robot fish and computational model are shown in Fig. 1.

The total length of the swimmer was $L=2.4$ m. The caudal fin was crescent-moon shaped, and the chordwise sections were NACA0018 shape. The chord length C of the caudal fin was 0.312 m. In this study, the swimmer swam freely in the X - Y plane of the global frame, and the prescribed undulation motion of the swimmer body was executed in body-fixed frame. In this work, the swimmer body was divided into rigid front body, posterior flexible body and caudal fin. The kinematics of the swimmer was divided into two parts: lateral undulation of flexible body and rigid motion of caudal fin (Yang and Su, 2011; Zhu *et al.*, 2002). Lateral undulation of posterior flexible body is defined as:

$$y(x,t)=A_p[(x-x_i)/L_f]^2 \sin(2\pi ft-kx) \quad (1)$$

where, $y_i(x,t)$ is lateral displacement of the body mid-line, x is the axial position, t is the time, f is the undulating frequency, k is the wave number, A_p is the undulating amplitude of the tail peduncle end, x_i is the beginning of flexible body, L_f is the length of flexible body. In order to match with previous numerical and experimental work in laboratory (Liu *et al.*, 2014; Yang and Su, 2011), the wave number k was set at zero in this work. The effect of k on the swimming will be discussed in future work. In addition, the undulating frequency f was always 1Hz. Inspired by multi-joint vertebrae of fish, the flexible body was divided into several joints, and the movement of flexible body was realized through Eq. (1), previous studies (Feng *et al.* 2019). The caudal fin undergoes a translation motion which follows the peduncle end and a pitching motion around the tail peduncle end (Yang and Su, 2011). The pitching motion of the caudal fin is defined as:

$$\theta_i(t)=\theta_m \sin(2\pi ft-\varphi) \quad (2)$$

where, θ_m is the pitching amplitude of caudal fin, φ is the phase angle between the translation motion and pitching motion, which was set at 90° . For flexible deformation of caudal fin, the same kinematic model of Yang *et al.* (2011) in the study of a tuna-like tail was applied, only deformation in chord wise direction was considered, and defined as follows:

$$y_{if}(x_{ca},t)=-\frac{f_a}{C}(x_{ca}-x_{ca0})^2 \sin(2\pi ft-\varphi) \quad (3)$$

where, $y_{if}(x_{ca},t)$ is the chordwise deformation displacement, f_a represents the ratio of maximum chordwise deformation of caudal fin tip to the chord length C , and is defined as flexure amplitude in this work, x_{ca0} is the starting point of caudal fin. In this work, f_a is defined as 0.0 and 0.5 to investigate the fish's self-propelled swimming with rigid and flexible caudal fins. When f_a is 0.0, the caudal fin is rigid and not deformed. Fig. 2 shows the body shape of swimmer during one swimming period.

Numerical method: In this study, the commercial CFD solver FLUENT was employed in all simulations. The FLUENT has been widely used for numerical simulations of fish-like swimming, and the accuracy of the solver has been validated extensively for flows with rigid/flexible fins or fishes (Hu and Xiao, 2014; Li *et al.*,

2018; Wojciech and Antomio, 2007; Yang and Su, 2011; Yang et al., 2011). The computational domain is discretized by the finite volume method with first-order discretization in time and second-order discretization in space, the SIMPLEC algorithm was applied for pressure-velocity coupling. The SST $k-\omega$ model was applied for the effect of turbulence (Yang and Su, 2011). The computational domain was $8.5L(X) \times 2L(Y) \times L(Z)$ cubic tank, which was discretized with a grid including 3.57 million elements. The computational domain was divided into three domains, one was outer domain (defined as D1) and the other two were inner domains (defined as D2 and D3). The boundary conditions of computational domain were set with: (1) zero velocity and zero gradient of pressure on inlet and far-field boundaries; (2) zero gradient of both velocity and pressure on outlet boundary; (3) no-slip boundary condition on the swimmer surface.

The rigid front body was placed in D2 and the posterior flexible body was placed in D3. The unstructured tetrahedral meshes were generated within D2 and D3 using Delaunay triangulation based on ICEM software. The meshes were locally refined and concentrated near the surface of swimmer with an element spacing size of $0.0005L$ to ensure sufficient resolution of the boundary layer, which was similar to the approach used by Xia et al. (2015). In D1, the meshes were unstructured in the regions adjacent to D2 and D3, and the other regions were discretized with hexahedral meshes. In addition, the mesh was rapidly stretched in directions of

swimmer height and width. In the longitudinal direction, the grid stretching was rapid in the upstream region of the swimmer, while in the near wake region the stretching ratio of mesh was kept below 2% (approximately equal to 1.7%) so as to keep relatively high stream-wise resolution. The dynamic mesh technology was employed in D3 with smoothing and remeshing methods provided by FLUENT to update the meshes caused by lateral undulation of posterior flexible body and flexible deformation of caudal fin. The parameters of smoothing and remeshing methods were selected reasonably to ensure the quality of meshes. The surface meshes of the swimmer, meshes of computational domain are illustrated in Fig. 3. The coupled of the swimmer with the fluid is realized though the no-slip boundary condition on the swimmer surface, enforcing the swimmer body velocity (U_s) to be the same as the fluid (UF) through $U_s = U_F$. For self-propelled swimming, the swimmer body velocity U_s can be decomposed into three terms (Gazzola et al., 2014), i.e., its rigid translation velocity U_c of the center of mass (COM), rigid rotational velocity $U_r = \omega_z \times r$ and its prescribed deformation velocity U_d , where r is the position vector from COM, ω_z is the yawing angular velocity. The velocities U_c and U_r are not prescribed first and are computed based on the hydrodynamic forces and moment exerted by fluid on the swimmer. The feedback of fluid to the swimmer is in turn described by the Newton's motion (momentum) equations.

$$\begin{cases} m \frac{dU_c}{dt} = F \\ \frac{d(\omega_z I_z)}{dt} = I_z \frac{d\omega_z}{dt} + \omega_z \frac{dI_z}{dt} = M_z \end{cases} \quad (4)$$

where, m is the swimmer mass, I_z is the yawing moment of inertia, F is the hydrodynamic force vector exerted by the fluid on COM and M_z is the yaw moment. As the swimmer swims freely in the X - Y plane, the hydrodynamics force vector F only has two components F_x and F_y , which can be computed by an integral local pressure and viscous forces acting on the swimmer surface (Borazjani and Sotiropoulos, 2008). The instantaneous power consumption P_{hydro} due to undulation of fish body was calculated by the following formula (Borazjani and Sotiropoulos, 2008):

$$P_{hydro} = \sum_{j=1}^2 \left(\int_S (-pn_j \dot{y}_j) dS + \int_S (\tau_j n_j \dot{y}_j) dS \right) \quad (5)$$

As the swimmer swims along negative x_b -direction, for the convenience of analyzing, the forward velocity U_f of the swimmer is defined as negative swimming velocity in the x_b -direction. The asymptotic constant speed in quasi-steady swimming is defined as U_{cr} , which is called the cruising velocity. U_{cy} and ω_z are the lateral velocity and yawing angular velocity of the swimmer, respectively. The Reynolds number $Re = \rho U_{cr} L / \mu$, and Strouhal number $St = 2A_p f / U_{cr}$, two non-dimensional parameters characterizing the swimming performance of fish's self-propelled swimming can be obtained. In this work, the A_p chosen as $0.3C$

Fig. 1: Computational model and real-life tuna: (a) "FangSheng-I" bionic robot fish; (b) Computational model.

Fig. 2: Body shape of swimmer with rigid caudal fin and flexible caudal fin during one swimming period under the prescribed kinematics model: (a) rigid caudal fin and (b) flexible caudal fin.

(0.039L), 0.5C (0.065L) and 0.7C (0.091L), covered the range of 0.052L-0.082L as reported by Donley and Dickson (2000) in the experimental study on the real-life tuna. The selected θ_m were 20°, 25° and 30°, and as a comparison, Yang *et al.* (2011) used θ_m of 5°-30° to investigate the propulsion mechanism for tuna-like tail.

Results and Discussion

The mesh dependence test was conducted using three meshes including 2.54 (coarse), 3.57 (medium) and 6.79 (fine) million elements with time step $\Delta t = T/200$. The U_{cf} with coarse, medium and fine meshes were 0.900, 0.920 and 0.927 m sec⁻¹, respectively. It was observed that the U_{cf} of fine mesh was only 0.76% larger than that of medium mesh whereas the U_{cf} of medium mesh was 2.2% larger than that of coarse mesh. A sensitivity study on time-step was also carried out, $\Delta t = \{T/400, T/200, T/100\}$ was used for sensitive study on time-step with the medium mesh. U_{cf} with $T/400$, $T/200$ and $T/100$ were 0.915, 0.920 and 0.932 m sec⁻¹, respectively.

U_{cf} of $T/200$ was only 0.55% larger than that of $T/400$ whereas the U_{cf} of $T/100$ was 1.3% larger than $T/200$. Hence, the medium mesh and $\Delta t = T/200$ were selected for all simulations in this work. Furthermore, based on previous experiments on “FangSheng-I” (Liu *et al.*, 2014) and numerical simulation of one degree of freedom (1-DoF) self-propelled swimming (Liu *et al.*, 2014), the ability of present numerical method to simulate the fish's three degree of freedom (3-DoF) self-propelled swimming was validated. The $A_p = 0.3C$, $\theta_m = 25^\circ$ and $f_a = 0.0$ were used, then the calculated U_{cf} of swimmer with various f was obtained and compared with previous experimental and numerical results, as show in Fig. 4. The solid lines in Fig. 4 are quadratic fitting curves, revealing that the results obtained by present numerical method are better than those of Liu *et al.* (2014) and are in good

agreement with the experimental values. A maximum error of 20.48% occurred at f value of 0.8, and the errors at the other values were between 6% and 16%. Implementation of fluid-body coupling framework was also validated by the test case of an anguilliform fish undergoing a self-propelled swimming (Kern and Koumoutsakos, 2006). The length of the fish body was $L = 1$ m. In this validation, the mesh generation scheme presented in Section 2.2 was used to generate the numerical grid and the numerical approach presented in Section Numerical method was used to simulate the flow. Fig. 5 shows the time history of forward velocity U_i of the anguilliform fish. The fish reached a cruising velocity of $U_{cf} = 0.381$ L/s, which matches well with numerical results reported by Kern and Koumoutsakos (2006) and Zhou and Shu (2012)

Fig. 3: Schematic of computational mesh: (a) Surface meshes of swimmer; (b) Meshes of computational domain.

Fig. 4: Comparison of present results with previous results.

Fig. 5: Time history of forward velocity U_f of the anguilliform fish.

Fig. 6: Comparison of time history of forward velocity U_f , lateral velocity U_y and yawing angular velocity ω_z for $f_a=0.0$ and $f_a=0.5$ cases.

Fig. 7: Time histories of longitudinal force F_x , lateral force F_y and yaw moment M_z .

where cruising velocity was $0.40 L \text{ sec}^{-1}$ and $0.451 L \text{ sec}^{-1}$, respectively. To study the variations of the swimming performance, hydrodynamics performance and power consumption during the process where the fish accelerates from rest to steady swimming, the swimming parameters were set as $A_p=0.5C$ and $\theta_m=25^\circ$.

The time histories of forward velocity U_f , lateral velocity U_y and yawing angular velocity ω_z for $f_a=0.0$ and $f_a=0.5$ cases are illustrated in Fig. 6. During swimming, two swimmers swam from rest to reach the quasi-steady swimming with asymptotic constant speed when the cycle-averaged value of hydrodynamic forces and moment exerted by the fluid on swimmer were equal to zero.

It can be observed that during the initial fast-start stage, the swimmer with flexible caudal fin was seen to accelerate fast. It was also observed that the cruising velocity U_d of the swimmer with flexible caudal fin were reduced. Interestingly, the swimmer with flexible caudal fin had smaller fluctuation amplitudes of U_y and ω_z than the swimmer with rigid caudal fin, indicating that deformation of the caudal fin has a beneficial contribution to the heading stability of the fish's self-propelled swimming.

In this study, the swimmer swam in the negative x_b -direction, therefore, the longitudinal force F_x is defined as the negative force in the x_b -direction. Fig. 7 illustrates the time histories of the longitudinal force F_x , lateral force F_y and yawing

Fig. 8: Time history of power consumption.

angular velocity ω_z of the swimmer. It can be observed that the F_i of two swimmers converge to fluctuating modes with zero mean value at the quasi-steady swimming from the thrust-type force at the fast-start and acceleration stages. Fig. 8 shows the time variations of the instantaneous power consumption P_{hydro} and the cycle-averaged value of P_{hydro} as a function of f_a . It can be seen that for two fishes, the cycle-averaged value of P_{hydro} decreased till it reached a steady state. In other words, it took more energy for the fish to break out of its initial resting state. As the fish moved

forward, it required less energy. To further examine the propulsive efficiency, the miles per gallon fuel (MPG) efficiency $\eta_m = U_{cf} / P_{hydro}$ was calculated (Schultz and Webb, 2002). It was found that during the quasi-steady swimming, the η_m of swimmer with rigid caudal fin and the flexible caudal fin was 45.76 and 38.57 m kJ^{-1} , respectively. In addition, Triantafyllou *et al.* (1993) found that when the St lie between 0.25 and 0.35, many species of fish can get relatively higher efficiency. In this work, the St of fish with rigid caudal fin was 0.34 whereas 0.40 of fish with flexible caudal fin in quasi-steady swimming indicates that the rigid caudal fin was beneficial to the efficient cruising of fish.

Fig. 9 and 10 shows the pressure distribution on the swimmer surface for $f_a = 0.0$ case and $f_a = 0.5$ case during quasi-steady swimming. According to these figures, the rigid anterior bodies in both cases exhibited nearly the same pressure distribution on the right and left sides. In addition, a significant pressure difference between the right and left sides of the caudal fin was found. The low and high pressure acting on the two sides of the caudal fin resulted in suction and pushing forces. The pressure distribution on the fish surface indicated that most of the thrust was generated by the leading-edge region of the caudal fin.

The time history of U_i for different lateral translation amplitudes A_p is plotted in Fig. 11. For this analysis, A_p was adjusted from $0.3C$ to $0.7C$, while fixing the pitching amplitude at $\theta_{in} = 25^\circ$. It is clear from Fig. 11 that the U_{cf} increased with the increase of A_p for fish neither with flexible caudal fin nor with rigid caudal fin. Comparing fishes with the same A_p , those with rigid caudal fin always reached U_{cf} higher than those with flexible

Fig. 9: Pressure distribution on the swimmer surface for $f_a = 0.0$ case during quasi-steady swimming: (a) beginning of the cycle and (b) one quarter of the cycle.

Fig. 10: Pressure distribution on the swimmer surface for $f_a=0.5$ case during quasi-steady swimming: (a) beginning of the cycle and (b) one quarter of the cycle.

caudal fin, and those with flexible caudal fin always had larger starting speed than those with rigid caudal fin. During the quasi-steady swimming, when A_p changed from $0.3C$ to $0.7C$, the power consumption P_{hydro} of fish with rigid caudal fin and flexible caudal fin was $\{7.2 \text{ W}, 20.11 \text{ W}, 46.92 \text{ W}\}$ and $\{18.3 \text{ W}, 20.17 \text{ W}, 28.12 \text{ W}\}$, respectively. The MPG efficiency η_m of swimmer with rigid caudal fin and flexible caudal fin was $\{80.77, 45.76, 25.5\}$ and $\{32.48, 38.57, 34.5\}$. It is important to note that the increase in cruising velocity of thunniform fish at larger A_p was not for free, since the fish has to beat its tail with larger lateral excursion at the expense of consuming more power. This finding helps to explain previous experimental observation, where kawakawa tunas prefer to increase their tail-beat frequency other than tail undulating amplitude accompanying with the increase of their swimming speed (Donley and Dickson, 2000). The fish with flexible caudal fin had larger P_{hydro} at $A_p=0.3C$ whereas the fish with rigid caudal fin had larger P_{hydro} at $A_p=0.7C$. It was found that the η_m of fish with flexible caudal fin increased firstly as A_p increased from $0.3C$ to $0.5C$ with a turning point of $0.5C$ and then decreased as A_p further increased. On the other hand, the η_m of fish with rigid caudal fin decreased monotonously with increasing A_p . The time history of U_i for different pitching amplitudes θ_m is plotted in Fig. 12. For this analysis, θ_m was adjusted from 20° to 30° , while fixing the lateral translation amplitude at $A_p=0.5C$.

It is clear from Fig.12 that the U_{cr} increased with the increase of θ_m for fish with rigid caudal fin whereas the U_i of fish with flexible caudal fin became smaller with the increase of θ_m .

Comparing fishes with the same θ_m , those with rigid caudal fin always reached U_{cr} higher than those with flexible caudal fin. In addition, during the fast-start stage (first five cycles), the forward acceleration of fish with rigid caudal fin increased obviously with the augmentation of θ_m . However, the effect of θ_m on the forward acceleration of fish with flexible caudal fin was negligible.

During the quasi-steady swimming, when θ_m changed from 20° to 30° , the power consumption P_{hydro} of fish with rigid and flexible caudal fin was $\{7.2 \text{ W}, 20.11 \text{ W}, 46.92 \text{ W}\}$ and $\{18.3 \text{ W}, 20.17 \text{ W}, 28.12 \text{ W}\}$, respectively. The MPG efficiency η_m of the swimmer with rigid caudal fin and flexible caudal fin was $\{80.77, 45.76, 25.5\}$ and $\{32.48, 38.57, 34.5\}$. It was interesting to note that the P_{hydro} of fish with flexible caudal fin increased with increasing θ_m , and the P_{hydro} of fish with rigid caudal fin decreased with increasing θ_m . It was found that, the η_m of fish with flexible caudal fin decreased monotonously as θ_m increased from 20° to 30° . On the other hand, the η_m of fish with rigid caudal fin increased monotonously with increasing θ_m . It should be noted that the St of fish with rigid caudal fin is a decreasing function of θ_m , and approaches the universal optimal value of 0.3 identified for efficient swimming of fish (Triantafyllou et al., 1993) as the θ_m reached 30° .

In the following, the flow structures using streamlines similar to previous numerical simulations of insect flight (Liu et al., 1998) and mackerel fish swimming (Borazjani and Daghooghi, 2013) were visualized. The caudal fin behavior was fixed at

Fig. 11: Time history of forward velocity U_f for different tail undulating amplitudes.

Fig. 12: Time history of forward velocity U_f for different pitching amplitude of caudal fin.

Fig. 13: Three-dimensional flow structures visualized by streamlines colored by vorticity magnitude during one cycle in quasi-steady swimming: (a) $f_a=0.0$ case; (b) $f_a=0.5$ case.

$A_p=0.5C$ and $\theta_m=25^\circ$. Fig. 13 shows the wake structures generated by the caudal fin of $f_a=0.0$ case and $f_a=0.5$ case, respectively. For $f_a=0.0$ case (rigid caudal fin), at the beginning of the swimming cycle (Fig. 13 (a), $t/T=0.0$), both the left side of upper and lower halves of the leading edge of the caudal fin generated a LEV, defined as LEV^u-1 and LEV^l-1 , respectively. The superscripts 'u' and 'l' represent the vortices generated by the

upper and lower halves of the caudal fin. There were two tip vortices (TVs) generated by the upper and lower tips of the caudal fin, denoted by TV^u-1 and TV^l-1 , respectively. These two TVs were largest in the cycle and about to move downstream at this time instant. In addition, there was a large trailing-edge vortex (TEV), denoted by $TEV-1$, connected to the trailing edge of the caudal fin, which was shed into the wake. During flapping of the caudal fin,

the TV^{u-1} , TV^{l-1} and $TEV-1$ separated from the caudal fin and moved downstream. At a quarter of the cycle (Fig. 13 (a), $t/T=0.25$), there were two new TVs generated by the upper and lower tips of the caudal fin, denoted by TV^{u-2} and TV^{l-2} , respectively. At this time instant, the LEV^{u-1} and LEV^{l-1} became larger and were about to separate from the leading edge of the caudal fin. As caudal fin continued to flap, the LEV^{u-1} and LEV^{l-1} moved downstream along the surface of the caudal fin and eventually merged with the vortex generated by the trailing edge of the caudal fin and formed a large TEV (denoted by $TEV-2$) at the time instant of half a cycle (Fig. 13 (a), $t/T=0.5$). Similar to TV^{u-1} and TV^{l-1} , TV^{u-2} and TV^{l-2} were larger than those of a quarter of the cycle and were about to shed. In addition, there were two new TEVs (denoted by LEV^{u-2} and LEV^{l-2}) generated by right side of caudal fin. At three-quarters of a cycle (Fig. 13 (a), $t/T=0.75$), the $TEV-2$ had already shed into the flow, the LEV^{u-2} and LEV^{l-2} became larger and were about to separate from the caudal fin, and there were two new TVs (denoted by TV^{u-3} and TV^{l-3}) generated by two tips of caudal fin.

For $f_a=0.5$ case (flexible caudal fin), at the beginning of the swimming cycle (Fig. 13(b), $t/T=0.0$), there were two LEVs (denoted by LEV^{u-1} and LEV^{l-1}) generated by the left side of upper and lower halves of caudal fin's leading edge, and there was a TEV (denoted by $TEV-1$) formed on the trailing edge region of caudal fin. In addition, there were two TVs (denoted by TV^{u-1} and TV^{l-1}) connected to the upper and lower tips of caudal fin. In contrast to $f_a=0.0$ case, the strength of LEV^{u-1} , LEV^{l-1} and $TEV-1$ were smaller whereas the strength of TV^{u-1} and TV^{l-1} were larger. In addition, it should be noted that the LEV^{u-1} , LEV^{l-1} and $TEV-1$ started forming the leading edge and trailing edge regions of caudal fin. During flapping of caudal fin, the TV^{u-1} and TV^{l-1} separated from the caudal fin and moved downstream whereas the LEV^{u-1} , LEV^{l-1} and $TEV-1$ became larger. At a quarter of the cycle (Fig. 13 (b), $t/T=0.25$), there are two new TVs (denoted by TV^{u-2} and TV^{l-2}) generated by the upper and lower tips of caudal fin. In contrast to $f_a=0.0$ case, $TEV-1$ just sheds from the caudal fin and moved downstream slightly. Compared with $f_a=0.0$ case, the LEV^{u-1} and LEV^{l-1} were larger and the strength of these two LEVs were stronger.

As the caudal fin continued to flap, the LEV^{u-1} and LEV^{l-1} moved downstream along the surface of the caudal fin and eventually merged with the vortex generated by the trailing edge of the caudal fin and formed a TEV (denoted by $TEV-2$) at the time instant of half a cycle (Fig. 13(b), $t/T=0.5$). It was also observed that the strength of TV^{u-2} and TV^{l-2} were stronger and were about to shed. In contrast to $f_a=0.0$ case, the $TEV-2$ was much smaller than that formed in $f_a=0.0$ case and was still growing. At three-quarters of a cycle (Fig. 13(b), $t/T=0.75$), the $TEV-2$ just shed from the caudal fin and moved downstream slightly, the LEV^{u-2} and LEV^{l-2} became larger and there were two new TVs (denoted by TV^{u-3} and TV^{l-3}) generated by the two tips of the caudal fin. Based on the numerical simulation method, the swimming performances, hydrodynamics performances and wake

structures of tuna-like fish with rigid caudal fin and flexible caudal fin were studied. The results provide an important reference for designing bionic robotic fish. Researchers can use these findings to control rigidity and flexibility of caudal fin to allow the bionic fish to start-up or cruise quickly.

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