Hydrodynamical analysis of the effect of fish fins morphology

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Abstract. The previous works on the biomechanics of fishes focuses on the locomotion effect of the fish bodies. However, there is quite a insufficiency in unveiling the respective function of fins when the fishes pose statics and exposed to fluid flow. Accordingly, this paper's focus is to investigate the hydrodynamic effect of the fins configuration to the fluid flow of shark-shaped-inspired structure. The drag and lift coefficient is computed for different cases of fish fins addition and configuration. The k-epsilon turbulence model is deployed using finite volume method with the aid of commercial software ANSYS CFX. The finding will demystify some of the functions of the fish’s fins in term of their contribution to the hydrodynamic flow around the fishes.

1. Introduction
The high manoeuvre and swimming efficiency of the fishes have inspired human to design the unmanned underwater vehicles such as by manipulating the pectoral fins [1]. This is needed as a powerful resolution for the deep sea exploration and survey of offshore industry [2]. In the real nature of fish fins configuration is a consummate association of both types of fins to ensure their ability in swimming due to the evolution of billions of years [3]. Although a variety of researches have been done on the undulation effects and fluid structure interaction of swimming fish, the respective functions of fish fins during static state are remained unclear.

Fins play instrumental roles in the propulsion, stabilization, and manoeuvre of the fishes. In general, the fins could be classified into ceratotrichia and lepidotrichia. Ceratotrichia fins are fairly stiff, unbranched, and unsegmented meanwhile the lepidotrichia fins are flexible, branched and segmented [4]. Specifically in this paper, only the ceratotrichia fins are considered in order to have a clearer insight into the functions of the fins.

From figure 1 as follows, it could be observed that the main fins existed in most of the fishes are caudal fin, dorsal fin and pectoral fins. The pelvic fins and adipose fin or second dorsal fin are the minor fins existed. They play their own roles contributing to the swimming ability of the fishes.
Caudal fin determines the normal swimming speed of the fishes. Caudal fins can be categorized into homocercal tail, or lunate shaped tail, and heterocercal tail. For homocercal tail, the upper lobe has the similar length with the lower lobe of caudal fin, and it normally exists in the structure of fast-swimmer. The heterocercal tail has a longer upper lobe, acting to lift the posterior body of the sharks [4].

Dorsal fin is able to provide the stability to the fishes. Upon folding of the fin by some of the fishes, the surface area of the fished which is exerted by the normal force will be dwindled, and hence reducing the drag coefficient. Yet the method of drag force reduction is not available in sharks [4].

Pectoral fins, which are located symmetrically at the left and right side of the fishes, operate as the stabilizer, and the "diving planes". Thus when the fishes are about to lift, the fins are adjusted to some angle of attack. For fast swimming fins, the pectoral fins are long and pointed while for slow swimmers, the fins are rounded [4].

For the minor fins, pelvic fins act as the steering and braking fins. However the function of adipose fin or second dorsal fin, a tiny fleshy fin, is still a remained mystery [1].

2. Mathematical Model

The simulation is solved by deploying the Reynolds-Averaged Navier-Stokes (RANS) Model, or more specifically the eddy-viscosity models. First and foremost the general Navier-Stokes equations (momentum and continuity equation) for both laminar and turbulent flow is [5-10]:

\[
\rho \left( \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) = -\frac{\partial P}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j^2} \tag{1}
\]

\[
\frac{\partial u_j}{\partial x_j} = 0 \tag{2}
\]

Taking Reynolds averaging in order to decompose the flow fields into the averaged and fluctuated components such that:

\[
u = \bar{u} + u', \quad P = \bar{P} + P' \tag{3}
\]

Upon some modification, the Reynolds stress transport equation can be derived in the following form:
The term \( k = 0.5 \bar{u} \bar{u}' \) is the kinetic energy per unit mass. In equation (4), the first term on the right hand side represents the redistribution of the flow. Meanwhile the second and third term denotes dissipation and turbulent transport respectively. The fourth and fifth terms are the production term [11].

To close the equation (4), the eddy viscosity concept is applied to develop the \( k - \varepsilon \) model. The \( k - \varepsilon \) model yielded after some mathematical derivation would be:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho \bar{u} k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \rho \varepsilon + P_{cb}
\]  

(5)

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \bar{u} \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\varepsilon}{k} \left( C_{e1} P_v - C_{e2} \rho \varepsilon + C_{e3} P_{cb} \right)
\]  

(6)

and the turbulent viscosity, \( \mu_t \) can be linked to the turbulence kinetic energy, \( k \), and dissipation, \( \varepsilon \), with the relationship [12]:

\[
\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}
\]  

(7)

whereby \( C_{e1}, C_{e2}, C_\mu, \sigma_k, \) and \( \sigma_\varepsilon \) are constant.

All the above equations are solved using software ANSYS CFX. First, the domains are set with eight cases with different configuration of fish morphology. The meshing is then made using tetrahedron patch independent meshing with high smoothing and fine relevance centre. The outer wall of the cylinder enclosure is set to be in free slip condition while the structure wall is set to be in non-slip boundary condition. The inlet of the flow will be at 5m/s. The convergence criterion is \( 1 \times 10^{-6} \).

To examine the effect of fish morphology to the hydrodynamic features of the water flow, the data generated from the CFX solver will be applied to calculate the drag and lift coefficients of the fishes with the equations [13]:

\[
C_D = \frac{F_x}{\frac{1}{2} \rho S U^2}
\]  

(8)

\[
C_L = \frac{F_y}{\frac{1}{2} \rho S U^2}
\]  

(9)

where \( F_x \) and \( F_y \) are the force exerted on the examined structure in X- and Y- direction respectively, \( \rho \) is the water density with value 1000kg/m3, \( S \) is length of the overall fish, and \( U \) is the characteristics velocity.

The Caudal Fin Ratio, CFR can be defined as the ration of the length of lower lobe to the upper lobe of caudal fin, for instance, CFR is less than 1 if its tail is heterocercal.

\[
CFR = \frac{\text{Horizontal length of lower caudin fin lobe}}{\text{Horizontal length of upper caudin fin lobe}}
\]  

(10)
3. Results and Discussions
From the simulation done upon eight cases, the corresponding drag and lift coefficients of the shark-inspired fish structure is shown in Table 1 and Figure 2 and Figure 3.

| Case | Description                              | Drag Coefficient | Lift Coefficient |
|------|------------------------------------------|-------------------|------------------|
| 1    | Simple ellipse                           | 2.44641 × 10^{-7} | 2.10128 × 10^{-7} |
| 2    | Addition of caudal fin with CFR 1.0      | 0.000898034       | -6.60256 × 10^{-7} |
| 3    | Addition of dorsal fin with CFR 1.0      | 0.00098859        | 1.52949 × 10^{-5} |
| 4    | Addition of pectoral fin with CFR 1.0    | 0.001786795       | -1.8391 × 10^{-5} |
| 5    | Addition of pelvic fin with CFR 1.0      | 0.002003269       | -1.12607 × 10^{-5} |
| 6    | Addition of adipose fin with CFR 1.0     | 0.001901752       | -1.93141 × 10^{-5} |
| 7    | Deployment of caudal fin with CFR 0.5    | 0.001741282       | -1.1967 × 10^{-5} |
| 8    | Deployment of caudal fin with CFR 0.25   | 0.001608365       | -8.88942 × 10^{-5} |

Figure 2. The corresponding plot of drag coefficient with different morphological structures.

Figure 3. The corresponding plot of lift coefficient with different morphological structures.

The velocity streamlines profiles of all the eight cases above have been illustrated in Figure 4. From the simple ellipse, upon addition of caudal fin, the drag coefficients increases and lift coefficient decreases. This addition is a burden for the structure to thrust and lift, and thus in the nature the undulation of caudal fin is required to counter the effect and generate forces for propulsion and lifting. This could explain the phenomenon that a reverse Bernoulli von Karman Vortex sheet is required to be produced in order to produce the thrust and significantly reduce the drag force [14].

Pectoral fins increase the drag coefficient and decrease lift coefficient to drag down and slow down the structure. Pectoral fins require further morphological adaptation to decrease the drag [15]. In a case of normal pectoral fin without undulation, Emily and Timothy suggest that it would generate a significant negative lift for the purpose of gripping [16] and this has met with the negative lift generation as shown in Table 1.
The addition of dorsal fin increases the drag coefficient but increases the lift coefficient as well. This finding is in coherence with the natural function of dorsal fin to stabilize the flow and provide lift for fishes\(^1\). This reaches an agreement as well with the Anabela and Cheryl's perception that the first dorsal fin contributes to stability \([17]\).

When the minor fins are configured, it could be observed that pelvic fins are able to further stabilize the structure but they could enhance its lifting ability. The adipose fins function which was remains unknown before, when it is analysed by static hydrodynamic point of view, it decreases the lift and drag coefficient at the same time. The reduction of CFR shows unstable lift coefficient.
fluctuation, and it keeps decreasing the drag coefficient of the structure. In can be seen the extending upper lobe of the caudal fin would enhance the thrusting ability of the structure. Anyhow, from a general view point, when the structure remained static without any locomotion and adjustment of angle of attack of the fins, it tends to dive and slow down. Fish locomotion and swimming kinematics are required to be connoted to ensure an effective trusting and lifting.

4. Conclusion
As a conclusion, during static and stiff condition, the dorsal fin and pelvic fins provides lift to the structure while the other tends to dive down the structure. The entire caudal fin, except the adipose fin, the dorsal fin, pectoral fins and pelvic fins tend to drag and slow down the structure. When the Caudal Fin Ratio (CFR) keeps decreasing, it shows a drag reduction which would enhance the thrusting ability, but it shall be highlighted that it has unstable performance on the lift coefficient. More morphological configuration studies are recommended for deeper understanding of fins functions in the future.

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