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Numeric Simulation on the Performance of an Undulating Fin in the Wake of a Periodic Oscillating Plate

Regular Paper

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Abstract A two-dimensional unsteady computational fluid dynamics (CFD) method using an unstructured, grid-based and unsteady Navier-Stokes solver with automatic adaptive re-meshing to compute the unsteady flow was adopted to study the hydrodynamic interaction between a periodic oscillating plate and a rigid undulating fin in tandem arrangement. The user-defined function (UDF) program was compiled to define the undulating and oscillating motion. First, the influence of the distance between the anterior oscillating plate and the posterior undulating fin on the non-dimensional drag coefficient of the fin was investigated. Ten different distances, D=0.2L, 0.4L, 0.6L, 0.8L, 1.0L, 1.2L, 1.4L, 1.6L, 1.8L and 2.0L, were considered. The performance of the fin for different distances (D) is different. Second, the plate oscillating angle (5.7°, 10°, 20°, 30°, 40°, 45°, 50°) and frequency (0.5 Hz, 1.0 Hz, 1.5 Hz, 2.0 Hz, 2.5 Hz, 3.0 Hz, 3.5 Hz, 4.0 Hz) effects on the non-dimensional drag coefficient of the fin were also implemented. The performance of the fin for different oscillation angles (θ) is different. Second, the plate oscillating angle and frequency also make a certain contribution to the performance of the posterior undulating fin. The results are similar to the interaction between two undulating objects in tandem arrangement and they may provide a physical insight into the understanding of fin interaction in fishes or bio-robotic underwater propulsors that are propelled by multi fins.

Keywords Vortex Wakes, CFD, Hydrodynamics, Oscillating Plate, Undulating Fin, Interaction

1. Introduction

Biomimetics takes nature as a model for inspiration to immensely help abstract new principles and ideas to develop various devices for real applications [1-2]. It is very interesting and important to pay attention to aquatic
organisms that take advantage of absorbing energy from their environment. Most aquatic organisms experience a disturbed underwater environment. Fortunately, they have evolved to make full use of the energy from the surrounding environment to conserve their own physical strength so as to achieve long distance cruising, high speeds and efficiency. Fish swimming in groups or in the bow wake of solid structures, and dolphins riding in the bow wake of ships [3-7], are cases in point. Liao and Müller reported that some sea inhabitants use the natural environment (or by themselves) to produce vortex systems to move with higher energetic efficiency. For example, fish living in shoals are studied [8-10]. Wardle and Videler observed that fish are able to exceed a theoretically determined maximum speed under the purposeful use of the flow conditions in their environment [11-12]. Hove and Arreola carried out the theoretical and experimental analysis of the kinetics of a multi-fin system to illustrate the interactions between fins [13-15]. Similar work was also implemented by Lauder and Madden to investigate the hydrodynamic interactions between the dorsal and caudal fins of bluegill sunfish [15]. They suggested that the dorsal and anal fin wake could generate increased thrust at the tail if the tail encounters flow altered to increase leading edge suction by modification of boundary layer flow at the appropriate time [16].

All these remarkable biological studies have inspired researchers to further investigate the internal regulations of the above-mentioned fantastic phenomena. They are usually simplified as research into the interaction of two rigid or flexible bodies in tandem or parallel arrangement for scientific studies. Recently a lot of numerical and experimental methods have been adopted to study the interaction between rigid or flexible bodies. Aktar and colleagues used computational fluid dynamics to study the dorsal fin and tail interaction and found out that the presence of fins in series on the body of fishes could have significant effects on locomotor hydrodynamics and that fishes are very likely to take advantage of this arrangement to increase thrust at the tail [17]. Pan et al. studied the oscillation behaviour of a flexible plate in the wake of a D-section cylinder and found that the incoming vortices make the plate oscillate with large amplitude at the beginning and then slant laterally [18]. Dong [19], Zhang [20] and Wu [21] et al. adopted CFD to illustrate the interactions between fish while cruising in groups and revealed their abilities to control vortices. Wang [22] and Alben [23-25] numerically analysed the influence of phase relationships between the flexible plate and the vortex on its force generation. On the other hand, with the development of experimental methods and equipment, Liao et al. carried out an experiment to investigate a vivid fish swimming in the wake of a D-section cylinder and found that a fish swimming in the bow wake of a bluff body uses less energy than a fish swimming in an otherwise free environment [26]. He also wrote a review on fish swimming mechanics and behaviour in altered flows [27] (Figure 1). Beal et al. put a dead fish in the wake of a D-section cylinder. It was observed that the fish was propelled upstream when its flexible body resonated with oncoming vortices [28]. Jia placed two tandem flexible filaments in a flowing soap film and concluded that the anterior filament modulates the posterior one and that they have the same oscillating frequency. He also implemented an experiment to observe the response modes of a flexible filament in the wake of a cylinder in a flowing soap film and found three oscillating modes of the flexible filament [29-30]. Moreover, Ristroph et al. discovered that there was an increase in drag on the posterior filament while moving in the wake of the anterior filament in a flowing soap film [31].

Figure 1. Schematic summary of key field, laboratory and theoretical studies, which have investigated the effects of biotically and abiotically generated wakes on fish swimming kinematics and behaviour [27]. (a) boulders, (b) log baffles, (c) Plexiglas T-structures, (d) Laboratory manipulations of substratum ripple height and spacing on cod, (e) A schooling fish swimming in the vortex wake of preceding members, (f) Brook trout swimming behind cones, half spheres and spheres, (g(i)) Dorsal and (g(ii)) lateral view of fish entraining on relatively small diameter horizontal cylinders, (h(i)) Dorsal and (h(ii)) lateral view of brook trout, river chub and small mouth bass entraining on relatively small diameter vertical cylinders, (i) Riding in the bow wake, (j) entraining and (k) exploiting vortices behind a relatively large D-section cylinder.

Unlike former studies, the present work is concerned with the performance of an undulating fin in the wake of a periodic oscillating plate. A numerical method is adopted to analyse the motion of the undulating fin and the drag force on both bodies is computed. It is shown that the fin performances largely depend on the gap between the two objects. The plate oscillating angle and frequency also make a certain contribution to the performance of the posterior undulating fin. The rest of the paper is organized as follows. Section 2 describes kinematic equations of both the oscillating plate and
undulating fin. Meanwhile, the computation domain discretization, the computation initial values, as well as the governing equations are introduced. In Section 3, we present detailed numerical results of the fin’s undulating behaviour and a further discussion is carried out in Section 4. Finally, the work is concluded with some remarks.

2. Materials and methods

2.1 Definition of coordinate system

Figure 2. Definition of reference coordinate system

Figure 2 shows the definition of the reference coordinate system. There are three main coordinate systems: the earth coordinate system \(xoy\), the plate coordinate system \(xoscooscyosc\) and the fin coordinate system \(xundoundyund\).

The x-axis of both the plate coordinate system and the fin coordinate system overlap the x-axis of the earth coordinate system. The origin of the plate coordinate system also overlaps the origin of the earth coordinate system. The distance between the origin of fin coordinate system and the earth coordinate is \(\Delta x\), as shown in Figure 2.

2.2 Kinematics modelling

2.2.1 Periodic oscillating motion

Figure 3. Modelling of the anterior periodic disturbance

As mentioned above, the plate is strictly defined as oscillating around its front end point \(O\). Thus, in the plate coordinate system \(xoscooscyosc\), the space coordinate of a point \(P(xosc, yosc)\) can be described as follows:

\[
\begin{align*}
    xosc &= L \cos(\theta(t)) \\
    yosc &= L \sin(\theta(t))
\end{align*}
\]

where \(L\) is the distance from point \(P\) to point \(O\) and \(\theta(t)\) is the angular position of the oscillating plate at time \(t\). If we assume that the plate oscillates under the sinusoidal waveform, \(\theta(t)\) is then given by Equation (2):

\[
\theta(t) = \theta_{osc} \sin(2\pi T - \theta_0)
\]

(2)

where \(\theta_{osc}\) is the oscillating amplitude, \(T\) is the oscillating cycle and \(\theta_0\) is the initial phase \((\theta_0 = 0\) in this paper). We obtain the oscillating angular velocity of the plate \(\omega(t)\) through the first derivation of equation (2):

\[
\omega(t) = \frac{d\theta(t)}{dt} = \frac{2\pi \theta_{osc}}{T} \cos(2\pi / T)
\]

(3)

As is indicated in Equation (3), the maximum oscillating angle \(\theta_{osc}\) is controlled by \(\theta_{osc}\), while the oscillating angular velocity of plate \(\omega_{osc}\) is determined by \(T\).

2.2.2 Fin undulating motion

For the present study, we idealize the fin kinematics as a travelling sinusoid (Figure 4).

Therefore, the two-dimensional undulating motion of the fin can be expressed as [32]:

\[
y(x_{und}, t) = A \sin(\omega t - k_{und} x_{und})
\]

(4)

where \(\omega = 2\pi f\) is the angular frequency, \(K\) is the wave number and \(A\) is the wave amplitude. However, in the current condition, a slight modification of Equation (4) should be used on account of the coordinate transformation. Thus, in the earth coordinate system xoy, Equation (4) is rewritten as follows:

\[
y(x - \Delta x, t) = A \sin[2\pi f t - k(x - \Delta x)]
\]

(5)

\(\Delta x\) is depicted in Figure 2. The values of parameters for the fin motion are listed in Table 1:

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Values</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f)</td>
<td>4 Hz</td>
<td>Frequency of the undulating fin.</td>
</tr>
<tr>
<td>(A)</td>
<td>0.005 m</td>
<td>Amplitude of the undulating fin.</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>0.04 m</td>
<td>Wavelength of the undulating fin.</td>
</tr>
</tbody>
</table>

Table 1. Values of parameters for the undulating fin
2.3 Governing equations

The governing equations employed are the incompressible Navier-Stokes equations, which are written as [33]:

\[
\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} + \nabla p = \nu \nabla^2 \vec{v} \tag{6}
\]

where \(\nu\) is the kinematic viscosity, \(p\) indicates the pressure, \(t\) is the time, \(\vec{v}_a = \vec{v} - \vec{U}\) is the advective velocity vector, where \(\vec{v}\) is the flow velocity and \(\vec{U}\) is the mesh velocity and the material derivative is with respect to the mesh velocity \(\vec{U}\). Both the pressure \(p\) and the viscous stress tensor have been normalized by the density \(\rho\) and are discretized in time using an implicit time stepping procedure. The details of the flow solver have already been discussed extensively elsewhere in connection with successfully validated solutions for numerous 2-D and 3-D, laminar and turbulent, steady and unsteady flow problems [33-35].

2.4 The two-dimensional computational domain and its discretization

![Figure 5](image_url)

**Figure 5.** The two-dimensional computational domain for the present study is shown with the direction of uniform flow from left to right.

In order to investigate the issue, we applied a two-dimensional numerical simulation to study the behaviour of an undulating fin in the wake of a rigid oscillating plate. The computational domain is shown in Figure 5. The computational domain is from -1 to six (normalized by the undulating fin length) along the longitudinal (or stream wise) direction (i.e., the x-direction) and -1.5 to 1.5 along the transverse direction (i.e., the y-direction). A rigid oscillating plate with length \(L_{osc}\) is placed upstream of an undulating fin at the centreline. The minimum distance between the two objects is \(D\). The fluid density and viscosity are constant and the flow velocity is \(\vec{v}\). The head of the oscillating plate is fixed when the body is oscillating. Note that the dimensionless parameter, Reynolds number \(Re = Vd / \mu v\) and \(\mu\) are the same as Equation (6), is set to be 200 throughout the study. The other parameters are listed in Table 2.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Nondimensional value*</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>(W_{area})</td>
<td>3</td>
<td>Width of the computational area.</td>
</tr>
<tr>
<td>(L_{area})</td>
<td>7</td>
<td>Length of the computational area.</td>
</tr>
<tr>
<td>(W_1)</td>
<td>1.5</td>
<td>Distance between the oscillating plate and the edge of the computational area.</td>
</tr>
<tr>
<td>(L_1)</td>
<td>1</td>
<td>Distance between the oscillating plate and the inlet.</td>
</tr>
<tr>
<td>(L_2)</td>
<td>3</td>
<td>Distance between the undulating plate and the outlet.</td>
</tr>
<tr>
<td>(L_{osc})</td>
<td>1</td>
<td>Length of the oscillating plate.</td>
</tr>
<tr>
<td>(L_{und})</td>
<td>1</td>
<td>Length of the undulating plate.</td>
</tr>
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</table>

*All the values are normalized by being divided by fin length.

**Table 2.** The values of the computational domain

Here, our investigation focuses on the effect of the distance between the oscillating plate and the undulating fin as well as the angular velocity and the maximal angle of the periodic oscillating plate on this dynamical system. All these values are listed in Table 3.

![Figure 6](image_url)

**Figure 6.** Mesh scheme

To reach an accurate calculation of the forces acting on the fin surface and reduce the number of meshes, a boundary schema with a growing rate of 1:1 ratio is applied for meshing the hydrodynamic boundary of the two objects. For the fluid domain, the total number of triangle cells is 342,504. Figure 6 shows the mesh distribution in the fluid region and a close view around the two objects.
Table 3. Parameters for effect study

Symbol | values | Description
-------|--------|----------------------
$\omega_{osc}$ | 0.5 Hz, 1.0 Hz, 1.5 Hz, 2.0 Hz, 2.5 Hz, 3.0 Hz, 3.5 Hz, 4.0 Hz | Oscillating angular velocity of the periodic oscillating plate.
$\theta_{osc}$ | 5.7°, 10°, 20°, 30°, 40°, 45°, 50° | Maximal angle of the periodic oscillating plate.
D | 2, 1.8, 1.6, 1.4, 1.2, 1, 0.8, 0.6, 0.4, 0.2 | The normalized distance between the oscillating plate and the undulating fin.

Table 4. Parameters for dynamic mesh

Symbol | values
-------|--------
Solver | Pressure based, implicit, unsteady
Mesh methods | Smoothing and remeshing
Pressure-velocity coupling | SIMPLE algorithm
Pressure discretization | Second order accurate scheme
Momentum discretization | Second order upwind
Size remesh interval | 1
Number of time steps | 1000
Time step size | 0.005 s
Max interactions per time step | 50
Number of triangle cells | 342,504

A User Defined Function (UDF) is used to define the movement of the undulating and oscillating motion. As the oscillation of the anterior plate and the undulation of the posterior fin are complex, we choose the DEFINE macro DEFINE_CG_MOTION and DEFINE_GRID_MOTION to describe the movement of the two objects respectively.

2.6 Wake analysis

Wakes were only analysed when the kinematics remained steady. The vorticity vector ($\vec{\omega}$) is a measure of the rotation of the flow field and is equal to the curl of the velocity vector, which for two-dimensional flow reduces to Equation (7) [32]:

$$\vec{\omega} = \frac{\partial \vec{v}}{\partial x} - \frac{\partial \vec{u}}{\partial y}$$

$\vec{u}$ and $\vec{v}$ are the particle velocity components in the respective x and y directions. $\vec{\omega}$ has the unit of $s^{-1}$. Positive vorticity represents rotation in the counter clockwise direction, while negative vorticity represents rotation in the clockwise direction.

2.7 Non-dimensional drag coefficient and lift coefficient

The total force acting on the undulating fin is defined as follows:

$$\vec{F} = -\frac{1}{2} \rho C S \vec{V}$$

$\rho$ is the fluid density, $C$ is a nondimensional constant that relates to fin shape and $S_{fin}$ is the upwind surface. In order to make general comparisons, the thrust and drag forces are normally nondimensionalized into the following coefficients:

$$C_L = \frac{\bar{F}_{lift} \times 2}{\rho \bar{V}^2 S_{fin}}$$
$$C_d = \frac{\bar{F}_{drag} \times 2}{\rho \bar{V}^2 S_{fin}}$$

where $C_d$ and $C_l$ are the non-dimensional drag coefficient and lift coefficient, respectively.

3. Results

In this section, some numerical results of the present topic will be presented and discussed. In the following subsections, the comparisons with or without anterior periodic disturbance are first demonstrated. We then mainly investigate the effect of distance between the
anterior oscillating plate and the posterior undulating fin on the undulation of the fin. The amplitudes effect of plate oscillation and the frequency effect of plate oscillation on the non-dimensional drag coefficient of the fin are also presented.

3.1 Comparisons with and without anterior periodic disturbance

The pressure comparisons with and without anterior periodic disturbance are shown in Figure 7. As the effect of the surface normal pressure gradient, the larger pressure distributions over the trough region occur, as shown in Figure 7. The thrust and the lateral force are mainly contributed by the pressure and are closely related to the pressure distributions over both the sides of the fin. Pressure contours (Pa) of the flow field at $t = T$ ($T$: undulation period of the fin) instances reveal that negative pressure regions are more intense than positive pressure regions in both cases. At $t = T$, the negative pressure region is the largest and acts to pull the fin upstream, thus generating the maximum thrust. Followed by the decrease of the thrust as the pressure regions are declining, the minimum thrust occurs when the pressure regions are very small. However, the presence of anterior oscillating disturbance will obviously increase the strength of the pressure, as demonstrated in Figure 7.

Figure 7. Pressure contours (Pa) of the flow field at $t=T$ (a) without anterior disturbance, (b) with anterior oscillating disturbance at the distance(D)=50mm, oscillating amplitude($\theta_{osc}$) = $\pi$/4, oscillating frequency($\omega_{osc}$)=1 Hz.

The corresponding instantaneous streamline patterns are shown in Figure 8. The fin boundary is no longer a streamline and there are streamlines that emanate from the fin and end on the fin. Lu and Tokumaru have verified that the travelling wave motion of the fin tends to suppress flow separation along the fin surface by both numerical and experimental methods respectively [36-37].

In the present case, the appearance of the anterior oscillating plate causes the disturbance in the wake, which is then immersed into the incoming flow of the fin and makes the flow rather tangled. The posterior fin undulates in the tangled flow and may extract extra energy from it.

We then focused on the generation, shedding and interaction process of the leading edge vortex and the trailing edge vortex and revealed the influence of the anterior periodic disturbance on the fin undulating propulsion performance. Figure 9 illustrates the time averaged non-dimensional drag coefficient (left column) and the change of vorticity contours in the wake during one cycle (right column). Therefore, Figure 9(a) is the condition without anterior disturbance and Figure 9(b) has anterior oscillating disturbance. It can be seen from Figure 9 that the time averaged non-dimensional drag without anterior disturbance is -0.1, while it is -0.14 with anterior oscillating disturbance at the distance(D)=50mm, oscillating amplitude($\theta_{osc}$) = $\pi$/4 and oscillating frequency($\omega_{osc}$)=1 Hz, indicating that the fin enjoys a drag reduction from the contribution of oscillating plate.

Figure 9(a) shows that the shear layer is generated along the fin and rolls up to form concentrated vortices behind the crest. Then, the vortices gradually shed into the wake to form vortices arrays, similar to classic Karman vortex-streets in the near wake of the travelling wavy plat. It is noted that two vortices with opposite signs shed downstream during one cycle.

As to Figure 9(b), body-bound vorticity develops along the entire length of the plate and is shed into the wake at the distal end. This vorticity has opposite rotation on each side of the plate due to the boundary layer. The vorticity bound originally to the right side of the body is shed to the left side of the wake and vice versa (Figure 9(b)). Moreover,
we may observe that vorticity also develops at the leading end of the plate. This increased vorticity region is then carried downstream along the plate. The vorticity is gradually dissipated and appears to be thinner near the posterior of the plate as the oscillating amplitude of the plate increases and finally immerses into the wake at the distal end. The vortices shed from the oscillating plate merge into the two vortex sheets in front of the fin. The reversed Kaman vortex street in the wake produced by the anterior periodic disturbance is then immersed into the vorticity that is produced near the head of the fin at the trough stage when the head was at maximum amplitude to the opposite side. It is re-adjusted by the fin motion.

3.2 Effect of distance between anterior plate and posterior fin on propulsion force generation of the fin

In this subsection, the effect of the distance between the anterior plate and the posterior fin on the forces and flow structures is studied. Ten different distances, $D = 0.2 \ L$, $0.4 \ L$, $0.6 \ L$, $0.8 \ L$, $1.0 \ L$, $1.2 \ L$, $1.4 \ L$, $1.6 \ L$, $1.8 \ L$ and $2.0 \ L$, are considered ($L$: the length of the fin).

To elucidate the behaviour of time-dependent drag forces generated by the undulation fin, the non-dimensional time-averaged drag force at ten different distances that are between the anterior plate and the posterior fin at the oscillating amplitude ($\theta_{osc} = \pi / 4$, oscillating frequency ($\omega_{osc}$)=1 Hz is shown in Figure 10. It is important to indicate that, based on our calculated results, periodic results are obtained for all the cases considered here. Thus, to clearly exhibit time-dependent drag forces, the results during one cycle are shown in Figure 10(a). When the drag becomes negative, it acts as a thrust force. There are three peaks of time-dependent drag force generated during one cycle. It may be because of the influence of the wake produced by the oscillating plate. Figure 10(b) shows the average non-dimensional drag at ten different distances. The maximal thrust generates at distance=20mm, i.e., 0.4 L, then the thrust decreases with the increase of...
distance and reaches the minimal value at the distance=50mm, i.e., 1 L. Later on, the thrust increases again and fluctuates with the distance. We will further discuss this in Section 4.1.

Figure 10. Effect of distance on forces generation of the fin at the oscillating amplitude ($\theta_{osc}$) = $\pi$/4, oscillating frequency ($\omega_{osc}$)=1 Hz. (a) the non-dimensional time-dependent drag forces during one cycle, (b) the average non-dimensional drag at ten different distances.

3.3 Effect of plate oscillating frequency on propulsion force generation of the fin

Figure 11 shows the effect of plate oscillating frequency on forces generation of the fin at the distance (D)=20mm and oscillating amplitude ($\theta_{osc}$) = $\pi$/6. The plate oscillating frequency mainly affects the intensity and transverse spacing distance of vorticity that is shed upstream of the fin. Figure 11(a) shows the non-dimensional time-dependent drag forces during one cycle and Figure 11(b) shows the average non-dimensional drag at eight different frequencies (0.5 Hz, 1.0 Hz, 1.5 Hz, 2.0 Hz, 2.5 Hz, 3.0 Hz, 3.5 Hz, 4.0 Hz). It can be seen from Figure 11(b) that the average non-dimensional drag of the fin is almost directly proportional to the oscillating frequency of the anterior plate except for the frequency at 3.5Hz. With the increase of the oscillating frequency of the plate, the generated thrust of the fin is decreased. A further comparative analysis is carried out later.

Figure 11. Effect of plate oscillating frequency on forces generation of the fin at the distance (D)=20mm, oscillating amplitude($\theta_{osc}$) = $\pi$/6. (a) the non-dimensional time-dependent drag forces during one cycle, (b) the average non-dimensional drag at eight different frequency.

3.4 Effect of plate oscillating amplitude on propulsion force generation of the fin

In this subsection, the effect of plate oscillating amplitude on propulsion force generation of the fin at the distance (D)=20mm and oscillating frequency ($\omega_{osc}$)=1 Hz is studied. Seven different oscillating angles (5.7°, 10°, 20°, 30°, 40°, 45°, 50°) are considered.

Figure 12(a) shows the non-dimensional time-dependent drag forces during one cycle and Figure 12(b) shows the average non-dimensional drag at the above seven different amplitudes. The results illustrate that the generated thrust of the fin is increased with the oscillating amplitude except for the amplitude at 10°. The thrust dramatically increases at this oscillating amplitude and the non-dimensional drag coefficient is about -0.112,
while the adjacent values are -0.097 at 5.7° and -0.104 at 20° respectively. The oscillating angle of 5.7° is considered here because the amplitude of the distal end of the plate at this angle equals to the undulating amplitude of the fin.

4. Discussion

A further discussion is implemented in this section to depict some extraordinary phenomena that are pointed out in Section 3.

4.1 Distance between the two objects

The pressure contours, vorticity distribution and instantaneous streamlines at four different distances (D = 20 mm, 30 mm, 50 mm and 70 mm respectively) at t = 4/5 T are shown in Figure 13. These four distances are selected because both the maximal and the minimal thrust happened at these distances in our simulation. The t = 4/5 T is selected because the pressure at this moment approximates the average value. The negative and positive pressure regions are greatly developed through the undulating motion of the fin. Thus this pressure differences result in the generation of propulsion force. The intensity of the pressure and vortex at distance = 20 mm is larger than the values at other distances and the thrust of the fin is also greater than in any other cases. Similarly, the intensity of the pressure and the vortex at distance = 50 mm is the smallest and the thrust of the fin at this distance is also the smallest. The change in distance may affect the locomotion phase between the two objects, which indicates that the fin can extensively obtain the energy from the upstream wake in certain phase differences. Zhang et al. has carried out a detailed numerical investigation on them [38].

Figure 12. Effect of plate oscillating amplitude on forces generation of the fin at the distance(D)=20 mm, oscillating frequency(ωosc)=1 Hz. (a) the non-dimensional time-dependent drag forces during one cycle, (b) the average non-dimensional drag at seven different amplitudes.

Figure 13. Comparisons of pressure contours, vorticity distribution and instantaneous streamlines among four different distances at oscillating frequency = 1.0 Hz, oscillating amplitude = 30°; t = 4/5 T (D: 20 mm, 30 mm, 50 mm and 70 mm; T: cycle).
Furthermore, attention should be paid to Figure 9(a) and Figure 10(b) again. The anterior disturbance on the impact of the fin thrust generation is weakened with the increase in distance, but the thrust produced by the fin is always greater than the case without disturbance, which implies that the fin can take advantage of the energy from the anterior vortices to enhance its thrust.

4.2 The oscillating frequency of the plate

Figure 14 shows the comparisons of pressure contours, vorticity distribution and instantaneous streamlines between two oscillating frequencies at $t = \frac{4}{5} T$. With the increase of the oscillating frequency of the plate, the intensity of the pressure and the vortex is also increased. As depicted in Figure 14, the disturbance to the fluid is rather drastic. This drastic disturbance may have a negative effect on the thrust generation of the fin. However, we are still confused about the reason why the thrust is so large at frequency $= 3.5$ Hz. Our future work will focus on this.

4.3 The oscillating amplitude of the plate

Figure 15 shows the comparisons of pressure contours, vorticity distribution and instantaneous streamlines between two oscillating amplitudes at distance $= 30\text{mm}$, oscillating frequency $= 1.0$ Hz and $t = \frac{4}{5} T$. We found two obvious differences between them, one is the intensity of the pressure and vorticity. With the increase in oscillating amplitude, the intensity of the pressure, as well as the vorticity in the wake of the fin, is increased, which may be concerned with the increase in propulsion thrust generated by the fin. The other difference is that the width of the vortexes in the wake of the plate is enlarged when the oscillating amplitude changes from $10^5$ to $50^5$. At oscillating amplitude $= 10^5$, the vortexes concentrate around the centreline of the two objects. The fin undulates through the vortex array produced by the plate. At oscillating amplitude $= 50^5$, the vortexes are much more dispersive. These dispersive vortexes are then immersed into the vortex that is produced near the head of the fin at the trough stage when the head was at maximum amplitude to the opposite side, which may cause the increase of the thrust generated by the fin. Similarly, we have difficulty in explaining the reason why the thrust is so large at amplitude $= 10^5$.

![Figure 14](image1.png)

**Figure 14.** Comparisons of pressure contours, vorticity distribution and instantaneous streamlines between two oscillating frequencies at distance $= 30\text{mm}$, oscillating amplitude $= 30^5$, $t = \frac{4}{5} T$ (frequency $= 3.0$ Hz and $3.5$ Hz; $T$: cycle).
5. Conclusion

In this paper, by using a two-dimensional unsteady CFD method combined with a UDF program, the influence of the distance between an anterior oscillating plate and a posterior undulating fin on the non-dimensional drag of the fin is investigated. The plate oscillating angle and frequency effects on the non-dimensional drag of the fin are also implemented. In summary, we conclude that:

1) The existence of the upstream disturbance does contribute to the undulating performance of the downstream fin.
2) The upstream disturbance of the effect of the fin thrust generation is weakened with the increase of the distance, but the thrust produced by the fin is always greater than the case without disturbance. It implies that the fin can obtain extra energy from the upstream vortices to optimize its performance.
3) With the increase of the oscillating frequency of the plate, the generated thrust of the fin is decreased except in specific cases.
4) The generated thrust of the fin is also increased with the oscillating amplitude of the plate, except for specific cases in our simulation.

Our future work will focus on the following four aspects. First, a further investigation should be undertaken to explain the reason why the thrust is so large in a certain specific case in the simulation. Second, an experiment should be carried out to verify the simulation results. Third, the effect of other parameters, such as the horizontal position, on the performance of the undulating motion of the fin will be implemented. Moreover, the change of the undulating motion of the fin will be considered in the future.

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7. References