Hydrodynamics of a self-propelled flexible fin in perturbed flows

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Abstract
A self-propelled flexible fin is subjected to perturbed flows produced by inanimate structures or other moving organisms. An optimal flapping motion in unbounded fluids may not be optimal in perturbed flows. The goal of this paper is to review key studies that focused on the hydrodynamics of fish swimming in perturbed flows, and to reveal the mechanisms by which fish can exploit energy from the surrounding fluid by modelling a self-propelled flexible fin. A heaving motion was prescribed on the leading edge of the fin, and other posterior parts passively adapted to the surrounding fluid as a result of the fluid-flexible-body interaction. We consider three flow environments in this paper; i) near the ground, ii) behind a cylinder, and iii) in the wake of another moving fin. The self-propelled fin modeled here can generate more thrust with a smaller penalty of increased power input, leading to increased propulsive efficiency by flapping near the ground. For the same heaving motion, the self-propelled fin near the ground can swim faster than that moving far from the ground. The fins swimming in the wake of a circular cylinder can maintain the relative positions to the upstream cylinder without using any power input by adjusting their heaving frequency as the vortex shedding frequency, and by slaloming between the oncoming vortices. Two tandem self-propelled fins with an identical heaving motion form a stable configuration spontaneously, and the power input is reduced for the following fin by passing through the oncoming vortex centers. A Karman vortex street is generated in the wake of the cylinder, while a reverse Karman vortex street is formed behind a self-propelled fin. The optimal trajectories for the fins swimming in a Karman and reverse Karman vortex streets are observed in the vortex slaloming and interception modes, respectively, where the heaving motion is in-phase with the induced flow direction in the spanwise direction. The synchronization enables the fins to save the energy required in the swimming behaviors.

Keywords: Propulsion, Vortex dynamics, Flow-mediated interaction, Immersed boundary method, Biomimetics

1. Introduction
Many animals have their own propulsion mechanisms, and specific hydrodynamic patterns are generated in the wake of these animals, depending on their flapping behaviors (Park et al. 2014). The hydrodynamic footprints result from interactions between the animal bodies and the surrounding fluid. The animals transfer momentum to the surrounding fluid by the flapping motions, the mechanisms of which affect the propulsion performance and determine the hydrodynamic patterns. Many studies of animal locomotion have focused on moving organisms through unbounded fluids to reveal the relationship between the propulsion and the hydrodynamic patterns. Most fish, however, live in cluttered habitats characterized by structures, and the flapping motions optimal for organisms moving through unbounded fluids may not be optimal for those moving near structures (Webb 1993, 2002). In this paper, we mainly focus on fish swimming in the perturbed flows induced by i) a nearby solid boundary, ii) an upstream bluff body, or iii) another swimming fish.

Swimming near a solid boundary has been observed to enhance propulsion in many animals. The hydrodynamic benefits were found to result from flow-mediated interactions between the propulsors and the substrates (ground effect). Steelhead trout decreased their tail beat amplitude and reduced the rate of work during locomotion near solid walls (Webb 1993). Buoyant mandarin fish spent less power in hovering by a nearby substrate (Blake 1979), and plaice can reduce their cost of transport by swimming near walls (Webb 2002). Motivated by many animals swimming near the ground,
many researchers have performed experimental (Blevins and Lauder 2013; Quinn et al. 2014a, 2014b; Fernandez-prats et al. 2015; Bleishwitz et al. 2016) and numerical (Dai et al. 2016; Ryu et al. 2016; Tang et al. 2016; Park et al. 2017) studies on the ground effect, and observed the hydrodynamic advantages such as increments of cruising speed, thrust and propulsive efficiency depending on the body motion of a swimmer.

Fish can benefit from swimming in the wake of an inanimate structure as well as swimming near the ground. Many studies examined that swimming fish can exploit turbulence formed by physical structures to reduce locomotion costs (Gerstner 1998; Gerstner & Webb 1998; Webb 1998; Liao et al. 2003a, 2003b; Ulrike 2003; Beal et al. 2006; Eldredge and Pisani 2008; Park et al. 2016). A simple approach to describe the perturbed flow generated by a physical structure in nature was to use a bluff cylinder in a uniform flow. Liao et al. (2003a, 2003b) observed that trout swimming in the wake of a D-section cylinder (D-cylinder) modulate their flapping behaviors depending on the vortex shedding wavelength and frequency, and only activate the anterior parts of their swimming muscles, suggesting clear evidence that energy was saved. A dead fish initially placed 4 diameters downstream of a cylinder was propelled toward the cylinder (Beal et al. 2006). Park et al. (2016) numerically found that a self-propelled flexible fin in the wake of a circular cylinder could overcome a net drag and maintain the relative position to the upstream cylinder without using any energy by resonating its body in synchrony with the oncoming vortices.

Fish swimming adjacent to another fish can reduce locomotion costs by the flow-mediated interactions. Fish schools have enticed many researchers from biologists to hydrodynamicists, and the hydrodynamic mechanisms at which fish can benefit from swimming in a group have been studied theoretically (Breder 1965; Weihls 1973), experimentally (Abrahams and Colgan 1985; Pitcher 1986; Abrahams and Colgan 1987; Killen et al. 2012; Marras et al. 2015), and numerically (Zhu & Peskin 2003; Deng & Shao 2006; Deng et al. 2007; Dong & Lu 2007; Huang et al. 2007; Alben 2009; Zhu 2009; Kim et al. 2010; Gazzola et al. 2011; Uddin et al. 2013; Zhu et al. 2014; Daghooghi & Borazjani 2015; Hemelrijk et al. 2015; Uddin et al. 2015; Tian et al. 2016; Lin et al. 2017; Maertens et al. 2017). According to the early inviscid theoretical model proposed by Weihls (1973), fish positioned laterally midway between two upstream fish can benefit from enhanced flows induced by oncoming vortices, which is referred to as the vortex hypothesis. Swimming fish were modeled by using traveling wavy foils in a tandem configuration, where the downstream fish can obtain a hydrodynamic advantage by appropriately modulating its body motion and interacting accordingly with oncoming vortices (Deng et al. 2007; Maertens et al. 2017). Infinite fish schools of in-line, side-by-side, diamond, and rectangular configurations were modelled by using periodic boundary conditions, and global energy savings were achieved (Daghooghi and Borazjani 2015; Hemelrijk et al. 2015).

Recently, many numerical and experimental studies have been performed on swimming fish in various fluid environments, but little synthesis has been attempted from a hydrodynamic point of view. The goals of this paper are to review some of recent studies that focus on fish swimming i) near the ground, ii) in the wake of a cylinder, and iii) behind another swimming fish, and to summarize their energy saving mechanisms through vortex-vortex and vortex-body interactions. After a brief introduction of previous findings, we discuss the hydrodynamics of fish by modelling a self-propelled flexible fin in the three fluid environments. The interaction between the self-propelled fin and the surrounding fluid was implemented on the framework of an immersed boundary method. This paper is organized into four sections. Section 2 describes the numerical method, and section 3 includes the results obtained from the previous studies. The manuscript is wrapped up by a summary and conclusion in section 4.

2. Problem formulation

Figure 1 shows a schematic diagram of the self-propelled flexible fins in perturbed flows induced by (a) the nearby ground, (b) upstream circular cylinder, and (c) another upstream self-propelled fin. A harmonically plunging motion was imposed at the fin leading edge with a heaving amplitude $A_f$ and frequency $f_f$. The posterior part of the fin was passively fluttered and influenced by the surrounding fluid or nearby structures due to its flexible properties. The fin moved freely in the streamwise direction, and the swimming speed was dynamically determined by the fin-fluid interaction. The fin and fluid motions were solved independently in each grid system. The flexible fin was defined on a moving Lagrangian grid system and the fluid on a fixed Eulerian grid system. The fin-fluid interaction was implemented by coupling their motions on the framework of an immersed boundary method (Huang et al. 2007).
The fluid motion was governed by the incompressible Navier–Stokes equations, which were non-dimensionalized using the following characteristic scales: the flapping velocity \( U_{ref} = 2\pi f A_f \) (Figs. 1(a) and (c)) or free-stream velocity \( U_\infty \) (Fig. 1(b)) for the velocity, the fin length \( L \) for the length, the fluid density \( \rho_0 \) for the density, \( L/U_{ref} \) for time \( t \), \( \rho_0 U_{ref}^2 \) for the pressure \( p \), and \( \rho_0 U_{ref}^2/L \) for the Eulerian momentum force \( f \), which represents the interaction force between the fin and the surrounding fluid. The non-dimensional governing equations were

\[
\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{\text{Re}} \nabla^2 \mathbf{u} + \mathbf{f},
\]

(1)

\[
\nabla \cdot \mathbf{u} = 0,
\]

(2)

where \( \text{Re} \) is the flapping Reynolds number, \( \text{Re} = \rho_0 U_{ref} L/\mu \), and \( \mu \) is the dynamic viscosity. The motion of the flexible fin was governed by the nonlinear structural equation under the inextensibility condition, and non-dimensionalized by the characteristic scales: \( \rho_1 U_{ref}^2 \) defined the unit for the tension force \( \phi \), \( \rho_1 U_{ref}^2 L^2 \) for the bending rigidity \( \gamma \), and \( \rho_1 U_{ref}^2/L \) for the Lagrangian momentum force \( F \), where \( \rho_1 \) is the density difference between the fin and fluid and set to 1. The dimensionless governing equation was expressed by

\[
\frac{\partial^2 \mathbf{X}}{\partial t^2} = \frac{\partial}{\partial s} \left( \phi \frac{\partial \mathbf{X}}{\partial s} \right) - \frac{\partial^2}{\partial s^2} \left( \gamma \frac{\partial^2 \mathbf{X}}{\partial s^2} \right) - \mathbf{F},
\]

(3)

\[
\frac{\partial \mathbf{X}}{\partial s} \cdot \frac{\partial \mathbf{X}}{\partial s} = 1,
\]

(4)

where \( s \) is the Lagrangian variable defined along the fin \( (0 \leq s \leq 1) \), and \( \mathbf{X} = (X(s, t), Y(s, t)) \) is the position vector. The boundary conditions applied on the flexible fin were

\[
Y(t) = A_f \cos(2\pi f \tau), \quad \frac{\partial \mathbf{X}}{\partial s} = (1, 0), \quad \frac{\partial^3 \mathbf{X}}{\partial s^3} = 0 \quad \text{at} \quad s = 0,
\]

(5)

\[
\frac{\partial^3 \mathbf{X}}{\partial s^3} = (0, 0), \quad \frac{\partial^3 \mathbf{X}}{\partial s^3} = (0, 0) \quad \text{at} \quad s = 1.
\]

(6)

The boundary condition of the leading edge combined the vertical heaving motion, clamped condition, and horizontally unconstrained condition, in Eq. (5). A free-end condition was applied at the trailing edge, in Eq. (6).

The fin-fluid interaction force was derived by using a feedback force law (Peskin 2002; Huang & Sung 2010), and the Lagrangian momentum force \( \mathbf{F} \) was expressed by

\[
\mathbf{F}(s, t) = -\kappa \left[ (\mathbf{X}_{ib} - \mathbf{X}) + \Delta t (\mathbf{U}_{ib} - \mathbf{U}) \right],
\]

(7)

where \( \kappa = -2 \times 10^6 \) is a user-defined constant (Shin et al. 2008), \( \mathbf{X}_{ib} \) and \( \mathbf{U}_{ib} \) are the position and velocity of the immersed boundary (IB), respectively, and \( \mathbf{U} \) is the fin velocity expressed by \( \mathbf{U} = d\mathbf{X}/dt \). The IB moved with the surrounding
fluid and \( U_{ib} \) was calculated by the fluid velocity interpolated at the IB,

\[
U_{ib}(s,t) = \int_{\Omega} u(x,t) \delta(X(s,t) - x) dx,
\]

where the transformation between the Eulerian and Lagrangian variables was realized by using the smoothed Dirac delta function (Peskin 2002). The position of the IB, \( X_0 \), was obtained by

\[
X_0 = X_0^0 + \int_0^t U_{ib} dt,
\]

where \( X_0^0 \) is the initial position of the IB. Equation (7) indicates that the IB moving along the surrounding fluid was connected to the Lagrangian points by a set of identical stiff springs with damping. The Eulerian momentum force \( f \) was calculated by spreading the Lagrangian force \( F \) to the nearby Eulerian grids by using the smoothed Dirac delta function, as described by

\[
f(x,t) = \frac{\rho_1}{\rho_0 L} \int_x F(s,t) \delta(x - X(s,t)) ds,
\]

where \( \rho_1/\rho_0 L \) is derived from the non-dimensionalization process (Huang et al. 2007). The combination of Eqs. (7) – (10) implied that the fluid velocities at the nearby Eulerian grids were enforced to move with those of the Lagrangian points, enforcing the no-slip boundary condition of the fluid on the fin. The fluid motion equations (1) and (2) were solved by using the fractional step method on a staggered Cartesian grid system (Park and Sung 1995; Park and Sung 2001; Kim et al. 2002), and the finite difference method was used to solve the fin motion equations (3) and (4). More details of the numerical procedures are presented in Huang et al. (2007).

3. Results and discussion

3.1. Fish swimming near the ground

In the classical sense, the term ‘ground effect’ was applied to three-dimensional (3D) wings operating near the ground, and referred to the inviscid phenomena of the decreased induced drag and the increased lift. The increased lift-to-drag ratio near the ground was resulted from the increased hydrodynamic pressure beneath the wing and the decreased wing-tip vortices (Armed and Sharma 2005; Han and Cho 2005). In this paper, the term ‘ground effect’ was used to refer to the hydrodynamic changes as a wing or a propulsor approached the ground. The ground effect has been widely studied for rigid oscillating wings (Tanida 2001; Su et al. 2013; Quinn et al. 2014a), as well as rigid static wings (Armed and Sharma 2005; Han and Cho 2005). For the pitching rigid wing near a solid boundary, both the thrust and power input increased, and the propulsive efficiency was comparable to that without the solid boundary (Quinn et al. 2014a). Morossef and Levy (2004) revealed that a heaving rigid wing with a sufficiently high frequency near the ground produced a positive thrust. The studies on the rigid wings oscillating near the ground would help understand the underlying hydrodynamic mechanisms in the ground effect, but could not account for the bio-inspired ground effect since many animals are flexible and deform their bodies.

Blevins and Lauder (2013) used a flexible fin inspired by a freshwater stingray with a fixed kinematics to study the ground effect, where swimming near the ground did not provide the hydrodynamic benefits in the swimming speed, power input, and locomotion cost. Quinn et al. (2014b) used a heaving flexible panel near the ground and observed that the thrust and the propulsive efficiency increased. In the numerical study performed by Ryu et al. (2016), a tethered flexible fin with a transverse heaving motion produced an enhanced thrust near the ground. Several studies adopted a self-propelled system to study the ground effect, where the swimming speed and the body kinematics are dynamically coupled (Dai et al. 2016; Tang et al. 2016; Park et al. 2017). Dai et al. (2016) and Park et al. (2017) modelled a two-dimensional (2D) flexible fin swimming near the ground, and the swimming speed increased with the cost of increasing input power. Tang et al. (2016) defined the expensive, benefited, and uninfluenced regimes for a self-propelled flexible plate near the ground. The swimming speed increased, and a larger amount of input work was required for the locomotion in the expensive regime, while the efficiency increased with the reduced input work due to the decreased bending deformation of the plate in the benefited regime.
For a self-propelled flexible fin near the ground, the swimming speed increased by about 10% for the same heaving motion of the leading edge when comparing to that swimming far from the ground (Park et al. 2017). The gap distance denoted by \( d \) in Fig. 1(a) was measured at the leading edge and the fin was subject to a dynamic ground effect. The increased swimming velocity near the ground attributed to the induced horizontal flow in the swimming direction in between the propulsor and the ground. Figure 2 shows the horizontal velocity contours of the ‘near the ground’ (upper row) and ‘far from the ground’ (lower row) cases during the down-stroke. A reverse von Karman vortex street was formed in the wake of the fin, and a positive/negative horizontal flow was induced in the inside/outside region of the reverse Karman gait respectively in Figs. 2(d), 2(e), and 2(f). For the fin near the ground, the downward flow induced by the fin down-stroke was transformed into the horizontal flow by the solid boundary and accelerated along the swimming direction as shown over ‘A’ region in Fig. 2(b). Fish in a school benefitted from an enhanced flow, which was induced by laterally positioned neighbors, referred to as the channeling effect (Weihs 1973; Daghooghi and Borazjani 2015). The channeling effect, here, was achieved due to the presence of the fixed solid boundary. The upstream flow between the pitching rigid foil and the solid boundary was observed during the up-stroke in the experimental study of Quinn et al. (2014a). The vortex structures were formed at the trailing edge during the up-stroke of the foil, inducing the upstream flow.

Figures 3 shows the vorticity contours at six different moments. Far from the ground, a vortex street symmetric to the heaving axis was generated in the wake of the self-propelled fin. The symmetric vortex street was broken near the ground and deflected upward in Fig. 3. During the up-stroke of the trailing edge, the negative vortex (2) was shed into the wake near the ground in Fig. 3(b). As the down-stroke proceeded, the positive main vortex (1) shed into the wake and moved close to the ground. A horizontal flow was induced in the upstream direction by the vortices (2) and (2*), while the flow was induced downstream by the vortices (1) and (1*). The positive vortex (1) caught up with the negative vortex (2) in the wake in Figs. 3(e) and 3(f). The negative vortex (2) formed during the up-stroke interacted with the positive vortex (1), leading to an upward-induced flow. The vortex deflection could be regarded as an inviscid phenomenon since the induced vorticies (1*) and (2*) were suppressed in the wake of the fins flapping continuously near the ground, and the deflection behaviors were mainly due to the interaction between the main vortices (1) and (2) (Quinn et al. 2014a; Park et al. 2017). The flapping motion of a wing or a propulsor near the ground provided the hydrodynamic benefits of the increased thrust (Quinn et al. 2014a; Ryu et al. 2016; Dai et al. 2016; Park et al. 2017), or the enhanced propulsive efficiency (Quinn et al. 2014b; Park et al. 2017). Some of the previous studies observed the increased power input when operating near the ground (Quinn et al. 2014a; Dai et al. 2016; Tang et al. 2016; Park et al. 2017). The body kinematics was one of the key parameters in determining the thrust and the power input (Park et al. 2017). The near ground benefits or
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penalties were not only the direct results of the hydrodynamic changes, but induced indirectly by the altered body kinematics by swimming near the ground. Both the thrust and the power input increased by the hydrodynamic changes in between the fin and the ground, and decreased by the reduced flapping amplitude of the trailing edge. Park et al. (2017) used the scaling approximation based on the reactive model of Lighthill (1960) to isolate the direct ground effects on the thrust, power input, and propulsive efficiency, where the flexible fin could generate more thrust near the ground with a smaller penalty in the power input, leading to the enhancement of the propulsive efficiency. The absence of the hydrodynamic advantages in the propulsive efficiency by the ground effect would be due to a fixed body kinematics or using a rigid wing (Blevins and Lauder 2013; Quinn et al. 2014a). Fish swimming near the ground would modulate their flapping motions passively or actively for obtaining the hydrodynamic benefits in the propulsive efficiency (Webb 1993; Blevins and Lauder 2013; Park et al. 2017).

3.2. Fish swimming in the wake of a cylinder

Swimming fish can exploit turbulence to reduce locomotion cost by adjusting their flapping kinematics appropriately. Liao et al. (2003a, 2003b) used a D-cylinder to produce a perturbed flow, and examined the hydrodynamic mechanisms where rainbow trout exploit energy from the perturbed flow by modulating their swimming behaviors. The combination of neuroscience and hydrodynamics revealed that rainbow trout activated their muscle along the whole body when swimming in a steady flow, while only activated their anterior muscle in the wake of the D-cylinder (Liao et al. 2003a, 2003b). Trout changed the flapping amplitude and frequency according to the wake wavelength and vortex shedding frequency, controlled by varying the free-stream velocity and the cylinder diameter. The heaving amplitude of the trout increased in the wake of the D-cylinder. Beal et al. (2006) observed that a dead fish initially placed 4 diameters downstream of a cylinder was propelled toward the cylinder. The fish could overcome a net drag by resonating its body in synchrony with the oncoming vortices and by extracting sufficient energy to produce thrust.

Eldredge and Pisani (2008) performed the simulation on the linked rigid body flapping passively in the wake of a circular cylinder. The rigid bodies were initially positioned 4 diameters downstream from the cylinder, and propelled toward the cylinder with a passive flapping motion derived from the oncoming vortices. The suction zone was greatly extended in the streamwise direction due to the presence of fish, leading to a passive upstream propulsion (Eldredge and Pisani 2008; Park et al. 2016). Park et al. (2016) performed the numerical study on the self-propelled flexible fin in the wake of a circular cylinder, and Fig. 4 shows the time histories of the gap distance $G_x$ between the fin leading edge and the cylinder trailing edge (in Fig. 1(b)) for different heaving frequencies and amplitudes of the fin. The shedding frequency of the oncoming vortices formed by the upstream cylinder was about 0.198 at Re = 200, and ‘suction zone’ was created immediately behind the cylinder (typically 2 diameters downstream from the cylinder), where the wake develops a net upstream velocity component. The fin initiated the flapping behavior 8 diameters downstream from the cylinder, which was far enough to avoid interference with the vortex formation process. Figure 4(a) shows that the fin flapping with $A_f = 0.1$ was propelled toward the upstream cylinder for $f_s = 0.1$, 0.2, and 0.3. For $A_f = 0.6$, the flexible fin was propelled upstream only at $f_s = 0.1$ and 0.3. The flexible fin suddenly accelerated toward the cylinder near the suction zone in Figs. 4(a) and 4(b). The flapping motion with $f_s = 0.2$, which was close to the vortex shedding frequency of the circular cylinder ($f_s = 0.198$) enabled the flexible fin to hold a station at a certain distance from the cylinder without using power input (Park et al. 2016).

![Fig. 4 Time histories of the leading edge positions for different flapping frequencies and amplitudes. (a) $A_f = 0.1$, (b) $A_f = 0.6$.](Reproduced from Park, Kim and Sung (2016), with the permission of AIP publishing.)
Fig. 5 (a) Time histories of the leading edge and trailing edge of a flapping fin in the wake of a cylinder. (b) A superimposed flexible fin swimming in the wake of the circular cylinder. (c-d) Vorticity contours at the instants marked in (a). Reproduced from Park, Kim and Sung (2016), with the permission of AIP publishing.

Fig. 6 Time evolution of the vorticity along the vertical line at the leading edge of a flexible fin; (a) Schematic diagram. The flapping amplitude was $A_f = 0.6$ and the flapping frequencies were (b) $f_f = 0.1$, (c) $f_f = 0.2$, and (d) $f_f = 0.3$. The trajectory of the leading edge is marked with a black line. For (d) $f_f = 0.3$, the contour was displayed before the fin made a physical contact with the cylinder as in Fig. 6(b) ($0 < t < 25$). Reproduced from Park, Kim and Sung (2016), with the permission of AIP publishing.

Fig. 7. Schematic diagrams of (a) Karman and (b) reverse Karman vortex streets. Positive and negative vortex structures are denoted by red and blue circular arrows, respectively. Grey indicates the direction of the fluid motions induced by the vortex structures. The green dashed line indicates the leading edge trajectory of the fin (a) slaloming between vortex cores, or (b) swimming through the vortex cores.

The fin–vortex interaction was important for understanding the hydrodynamic mechanism at which the fin benefits from swimming in the Karman gait. Figure 5(a) shows the time histories of the leading and trailing edges of the fin for $A_f = 0.6$ and $f_f = 0.2$. The leading edge of the fin was controlled, and other posterior parts fluttered passively through the fin-vortex interaction. Figure 5(b) shows the superimposed configurations of the fin swimming in the Karman gait, indicating that the fin was trapped at a certain position, as shown in Fig. 4(b). The vortex contours are shown in Figs. 5(c) – 5(f) at the instants marked in Fig. 5(a). Gopalkrishnan et al. (1994) performed experiments to reveal the interactions between the flapping foil and the vortices in the wake of the cylinder, and the distance between them was not dynamically determined, but time-invariant. They found three basic vortex interaction modes depending on the flapping motion of the foil. The vortices formed with (i) reduced circulation and with (ii) increased circulation compared to the oncoming vortices, and (iii) counter-rotating vortices formed. The constructive and destructive vortex interaction modes were accompanied by repositioning of the oncoming vortices after encountering the flapping foil (Gopalkrishnan et al. 1994).
The self-propelled flexible fin modelled by Park et al. (2016) interacted with the oncoming vortices in a constructive mode when the fin adjusted the heaving frequency to the vortex shedding frequency and held a station. The oncoming vortices were not found to be repositioned, which might be due to the differences in the propulsor flexibility and the fact that the flexible fin, here, moved freely along the streamwise direction.

The time evolution of the vortex along the vertical line at the fin leading edge is displayed in Fig. 6 to elucidate in more detail how the fin interacts with the oncoming vortices. Figure 6(a) presents a schematic diagram where the dashed line denotes a vertical line at the fin leading edge. Time evolved from right to left along the x-axis, and the leading edge trajectory is denoted by the black line in Fig. 6. The fins flapping with \( f = 0.1 \) and 0.3 mostly swim through the vortex cores but occasionally slalom between the vortex cores, as shown in Figs. 6(b) and 6(d). The fin flapping with the frequency similar to the vortex shedding frequency slalomed between the vortex cores after a few initial flapping periods, as shown in Fig. 6(c). Figures 7(a) and 7(b) show schematic diagrams of a Karman and reverse Karman vortex streets, respectively. The green dashed line denotes the leading edge trajectory, the grey arrows represent the direction of the induced flows, and the red and blue circular arrows display positive and negative vortex structures, respectively. The fin slaloming between the vortex cores in the Karman gait could enjoy hydrodynamic advantages in both the streamwise and the spanwise directions (Park et al. 2016).

The flows induced in the streamwise direction generated a reduced flow region, decreasing the drag on the fin compared to that in an open flow. The fin flapping motion and the induced flows were in-phase in the spanwise direction, enabling the fin to reduce the power input when slaloming in the Karman gait. The fin swimming through the vortex cores in the Karman gait, on the other hand, does not benefit from the oncoming vortices in terms of the power input (Uddin et al. 2015; Park et al. 2016). This is consistent with the previous findings of Liao et al. (2003a, 2003b), where rainbow trout slalomed between the oncoming vortices and saved power input by activating only anterior muscle. Trout swimming behind the D-cylinder should increase the heaving amplitude to exploit energy from the oncoming vortices, otherwise they moved toward the upstream cylinder with using an additional power input (Park et al. 2016). The suction zone was created immediately behind the cylinder immersed in a flow, and extended in the streamwise direction when fish was positioned within 4 or 5 diameters downstream of the cylinder, which helped fish maintain its relative position to the cylinder with using little energy. This would provide one of the motivations for fish swimming behind structures immersed in a flow.

### 3.3 Fish swimming in school

Weihs (1973) suggested two possible hydrodynamic mechanisms where fish can benefit from being a member of school; 1) the flows induced by the organized oncoming vortices help the downstream fish reduce a drag force, referred to as the vortex hypothesis and 2) the enhanced flows in between laterally positioned fish help them reduce a drag force, referred to as the channeling effect (Breder 1965; Daghooghi and Borazjani 2015; Park and Sung 2016). A diamond schooling configuration was suggested as an optimal according to inviscid theoretical model of Weihs (1973), but there was no valid experimental evidence for such hydrodynamic advantages (Partridge and Pitcher 1979; Pitcher 1986). Many recent experimental studies, however, have shown that fish benefit from swimming in school, and the individual positioning is the important factor in determining such benefits (Killen et al. 2012; Marras et al. 2015).

Many numerical studies have been performed to study fish schooling. The downstream foil benefited from being in the wake of the upstream foil in a tandem configuration and saved energy at any position by appropriately modulating its body motion (Deng et al. 2007; Maertens et al. 2017). Kim et al. (2010) and Uddin et al. (2015) used tethered flexible flags to study fish schooling, and the downstream flag flapping in the wake of the upstream flag decreased drag force by slaloming between oncoming vortices. The optimal diamond configuration was suggested by using the tethered flexible flags, which were passively fluttered by interacting with the oncoming vortices (Uddin et al. 2013). The foil positioned laterally midway between two upstream foils achieved energy savings in an inverted triangular configuration (Deng & Shao 2006). Infinite fish schools of in-line, side-by-side, diamond, and rectangular configurations were modelled by using periodic boundary conditions, and global energy savings were obtained for such schools (Hemelrijk et al. 2015; Daghooghi and Borazjani 2015). The Froude propulsive efficiency was enhanced by about 23% for fish swimming in an optimal diamond configuration when comparing to an isolated swimming fish (Hemelrijk et al. 2015). Daghooghi and Borazjani (2015) found that the fish in the rectangular school with the lateral distance of 0.3 body lengths swim 20% faster than a solitary swimmer by the channeling effect. The dynamic nature of fish schools was not considered in these systems since the relative positions among the schooling members did not change. Zhu et al. (2014) modelled two self-
propelled flexible fins in a tandem configuration, where their relative positions were dynamically determined.

Figure 8 shows the time history of the streamwise gap distance $G_x$ (defined in Fig. 1(c)) between two self-propelled flexible fins in a tandem configuration, displaying that only several discrete gap distances were attainable depending on the initial gap distance. The red and blue lines in Fig. 8 denote for the initial gap distances of $G_{x,i} = 2$ and 3, respectively. The gap distance was maintained as the initial value during the first few flapping periods, and then increased (red) or decreased (blue) depending on how the downstream fin interacted with the oncoming vortices shed from the leading fin (Zhu et al. 2014). After a few flapping periods, they formed a stable configuration spontaneously, and the gap distance was maintained. Figure 9 shows the vorticity contours when the two tandem fins formed the stable configuration. The positive and negative vortices were generated during the down- and up-strokes of the fin, respectively, forming a reverse Karman vortex street. Figure 9(b) shows that the positive vortex shed from the upstream fin was broken by the downstream fin. The vorticity along the vertical line at the leading edge of the downstream fin is displayed with time to reveal how the following fin interacted with the oncoming vortices in Fig. 9(c).

The trajectory of the leading edge denoted by the black line was locked onto the oncoming vortex centers in the tandem stable configuration, which was referred to as the vortex interception mode (Zhu et al. 2014; Uddin et al. 2015; Park et al. 2016). Figure 7(b) shows the schematic of vortex interception mode for fish swimming in a reverse Karman gait, where the leading edge trajectory and the induced flow direction are in-phase in the spanwise direction. Swimming fish use most of their energy in transverse flapping motions, which can be reduced by modulating their flapping motions appropriately to the surrounding fluid. Form the energetics perspective, the optimal trajectory for fish swimming in a Karman vortex street was slaloming between the oncoming vortices, while the vortex interception mode was an optimal for those swimming in a reverse Karman vortex street. In the tandem configuration, the power input was reduced by about 20% (Zhu et al. 2014) or the efficiency was enhanced up to 60% (Maertens et al. 2017) for the following fish. The spanwise offset enabled the downstream fish to reach the efficiency enhancement of about 80% as compared to that of the upstream fish (Maertens et al. 2017). Schooling behaviors could provide members with ecological advantages beyond the hydrodynamics such as reducing predation risk or increasing foraging rate. The hydrodynamic benefits from swimming in schooling are achieved through the flow-mediated interactions between the members, and the potential trade-offs between the ecological and hydrodynamic advantages should be considered simultaneously in determining the schooling configuration or individual positioning within a schooling structure.

![Fig. 8 Time history of the gap distance between the leading and following fins. Only discrete streamwise gap distances are attainable depending on the initial gap distance.](image)

![Fig. 9 Vorticity contour of two tandem flexible fins at (a) $t = 25.2$ and (b) $t = 25.8$. (c) Time evolution of the vorticity along the vertical line at the leading edge of the following fin. Time evolves from right to left.](image)
4. Conclusions

In this paper, we reviewed some of experimental and numerical studies on fish swimming in three different flow environments, and discussed the hydrodynamics of swimming fish by modelling a self-propelled flexible fin.

1) The self-propelled fin can swim faster than that moving far from the ground by the channeling effect, where the enhanced flow generated in between the fin and the ground decreases the drag force. The hydrodynamic pressure variations beneath the fin increase the power input required for the fin flapping motion. The flexible fin can generate more thrust near the ground with a smaller penalty in the power input, leading to the enhancement of the Froude propulsive efficiency. The altered body kinematics by flapping near the ground is one of the important factors in determining the hydrodynamic benefits or penalties by the ground effect. Fish swimming near the ground would modulate their flapping motions both passively and actively to facilitate the ground effect.

2) For the self-propelled flexible fin behind a circular cylinder, the fin maintains the relative position to the upstream cylinder without using any power input when the heaving amplitude is not too small and the heaving frequency is adjusted as the vortex shedding frequency. From the energetics perspective, this would explain the behavior of fish swimming in the wake of a cylinder, where they modulate the heaving motion appropriately to the oncoming vortices by only using their anterior muscle. Only discrete equilibrium gap distances are attainable depending on the initial positions. The fin can swim toward the upstream cylinder using an additional power input when the heaving frequency is not constrained to the vortex shedding frequency.

3) Two tandem self-propelled fins with an identical harmonic heaving motion spontaneously form a stable configuration, where the leading edge trajectory of the following fin is locked onto the oncoming vortex centers, i.e., the vortex interception mode. The cylinder immersed in a flow produces a Karman vortex street in the wake from which swimming fish can exploit energy by slaloming between the oncoming vortices. The self-propelled fin creates a reverse Karman vortex street in the wake where the following fin reduces the power input for keeping pace with the leading fin by passing through the oncoming vortex centers. The flow direction induced by the oncoming vortices and the fin flapping motion are in-phase in the spanwise direction, by which the fin can save energy required in undulating its bodies.

The hydrodynamic mechanism where swimming fish exploit energy and benefit from the ambient perturbed flows would not only help the understanding of characteristics intrinsic to fish swimming behaviors, but also inspire the development of an artificial vehicle that takes advantage of the surroundings, such as a wing-in-ground craft.

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References

Abrahams, H. V. and Colgan, P. W., Risk of predation, hydrodynamic efficiency and their influence on school structure. Environ. Biol. Fishes, Vol. 13, (1985), 195-202.
Abrahams, H. V. and Colgan, P. W., Fish schools and their hydrodynamic function: a reanalysis, Environ. Biol. Fishes Vol. 20, (1987), 79-80.
Alben, S., Wake-mediated synchronization and drafting in coupled flags, J. Fluid Mech., Vol. 641, (2009), 489-496.
Armed, M. and Sharma, S., An investigation on the aerodynamics of a symmetrical airfoil in ground effect, Experimental Thermal and Fluid Science, Vol. 29, No. 6 (2005), 633-647.
Beal, D. N., Hover, F. S., Triantafyllou, M. S, Liao, J. C. and Lauder, G. V., Passive propulsion in vortex wakes, J. Fluid Mech., Vol. 549, (2006), 385-402.
Blake, R. W., The energetics of hovering in the mandarin fish (Synchropus picturatus), J. Exp. Biol., Vol. 82, (1979), 25-33.
Bleishwitz, R., Kat, R. D. and Ganapathisubramani, B. Aeromechanics of membrane and rigid wings in and out of ground-effect at moderated Reynolds numbers, J. Fluids Structures, Vol. 62, (2016), 318-331.
Blevins, E. and Lauder, G. V., Swimming near the substrate: a simple robotic model of stingray locomotion, Bioinspir. Biomim., Vol. 8, (2013), 016005.
Breder, C. M., Vortices and fish schools, Zoologica, Vol. 50, (1965), 97-114.
Daghooghi, M. and Borazjani, I., The hydrodynamic advantages of synchronized swimming in a rectangular pattern.
Bioinspir. Biomim., Vol. 10, (2015), 056018.
Dai, L., He, G. and Zhang, X., Self-propelled swimming of a flexible plunging foil near a solid wall, Bioinspir. Biomim., 11, 046005 (2016).
Deng, J. and Shao X. -M., Hydrodynamics in a diamond-shaped fish school, J. Hydrodyn. B., Vol. 18, No. 3 (2006), 438-442.
Deng, J., Shao, X. -M. and Yu, Z. -X., Hydrodynamic studies on two travelling wavy foils in tandem arrangement. Phys. Fluids, Vol. 19, (2007), 113104.
Dong, G. -J. and Lu, X. -Y., Characteristics of flow over traveling wavy foils in a side-by-side arrangement. Phys. Fluids, Vol. 19, (2007), 057107
Eldredge, J. D. and Pisani, D., Passive locomotion of a simple articulated fish-like system in the wake of an obstacle, J. Fluid Mech., Vol. 607, (2008), 279-288.
Fernandez-prats, R., Raspa, V., Thiria, B., Huera-Huarte, F. and Godoy-Diana, R., Large-amplitude undulatory swimming near a wall, Bioinspir. Biomim., Vol. 10, (2015), 016003.
Gazzola, M., Chatelain, P., Ress, W. M. V. and Kousmoustakos, P., Simulations of single and multiple swimmers with non-divergence free deforming geometries, J. Comp. Phys., Vol. 230, No. 19 (2011), 7093-7114.
Gerstner, C. L., Use of substratum ripples for flow refuging by Atlantic cod. Gadus morhua, Environ, Biol. Fishes, Vol. 55, (1998), 455-460.
Gerstber, C. L. and Webb, P. W., The station-holding performance of plaice, Pleuronectes platessa, on artificial substratum ripples, Can. J. Zool., Vol. 76, (1998), 260-268.
Gopalkrishnan, R., Triantafyllou, M. S., Triantafyllou, G. S. and Barrett, D., Active vorticity control in a shear flow using a flapping foil, J. Fluid Mech., Vol. 274, (1994), 1-21.
Han, C. and Cho, J., Unsteady trailing vortex evolution behind a wing in ground effect, Journal of Aircraft, Vol. 42, No.2 (2005), 429-434.
Hemelrijk, C. K., Reid, D. A. P., Hildenbrandt, H. and Paddling J. T., The increased efficiency of fish swimming in a school, Fish Fisheries, Vol. 16, (2015), 511-521.
Huang, W. X., Shin, S. J. and Sung, H. J., Simulation of flexible flags in a uniform flow by the immersed boundary method, J. Comput. Phys., Vol. 226, (2007), 2206-2228.
Huang, W. X. and Sung, H. J., Three-dimensional simulation of a flapping flag in a uniform flow, J. Fluid Mech., Vol. 653, (2010), 301-336.
Killen, S. S., Marras, S., Steffensen, J. F. and Mckenzie D. J., Aerobic capacity influences the spatial position of individuals within fish schools, Proc. R. Soc. B 279, (2012), 357-364.
Kim, K., Baek, S. J. and Sung, H. J., An implicit velocity decoupling procedure for incompressible Navier-Stokes equations, Int. J. Numer. Meth. Fluids, Vol. 38, (2002), 125-138.
Kim, S., Huang, W. X. and Sung, H. J., Constructive and destructive interaction modes between two tandem flexible flags in viscous flow, J. Fluid Mech., Vol. 661, (2010), 511-521.
Liao, J. C., Beal, D. N., Lauder, G. V. and Triantafyllou, M. S., The Karman gait: novel body kinematics of rainbow trout swimming in a vortex street, J. Exp. Biol., Vol. 206, (2003a), 1059-1073.
Liao, J. C., Beal, D. N., Lauder, G. V. and Triantafyllou, M. S., Fish exploiting vortices decrease muscle activity, Science, Vol. 302, (2003b), 1566-1569.
Lighthill, M. J., Note on the swimming of slender fish, J. Fluid Mech., Vol. 9, (1960), 305-317.
Lin, X., He, G., He, X., Wang, Q. & Chen, L., Numerical study of the hydrodynamic performance of two wiggling hydrofoils in diagonal arrangement, J. App. Mathematics Phys., Vol. 5, (2017), 31-38.
Maertens, A. P., Gao, A. and Triantafyllou, M. S., Optimal undulatory swimming for a single fish-like body and for a pair of interacting swimmers, J. Fluid Mech., Vol. 813, (2017), 301-345.
Marras, S., Killen, S. S., Lindstrom, J., Mckenzie, D. J., Steffensen, J. F. and Domenici, P., Fish swimming in schools save energy regardless of their spatial position, Behav. Ecol., Vol. 69, (2015), 219-226.
Moryossef, Y. and Levy, Y., Effect of oscillations on aerofoils in close proximity to the ground, AIAA, Vol. 42, (2004), 1755-1764.
Park, S. G., Chang, C. B., Huang, W. -X. and Sung, H. J., Simulation of swimming oblate jellyfish with a paddling-based locomotion. J. Fluid Mech. Vol. 748, (2014), 731-755.
Park, S. G., Kim, B. and Sung, H. J., Self-propelled flexible fin in the wake of a circular cylinder, Phys. Fluids, Vol. 28,
Park, S. G. and Sung, H. J., Vortex interaction between two tandem flexible propulsors with a paddling-based locomotion, J. Fluid Mech., Vol. 793, (2016), 612-632.

Park, S. G., Kim, B. and Sung, H. J., Hydrodynamics of a self-propelled flexible fin near the ground. Phys. Fluids, Vol. 29, (2017), 051902.

Park, T. S. and Sung, H. J., A nonlinear low-Reynolds-number k-ε model for turbulent separated and reattaching flows - (I) flow field computations. Int. J. Heat Mass Transfer, Vol. 38, (1995), 2657-2666.

Park, T. S. and Sung, H. J., Development of a near-wall turbulence model and application to jet impingement heat transfer. Int. J. Heat Fluid Flow, Vol. 22, (2001), 10-18.

Partridge, B. L. and Pitcher, T. J., Evidence against a hydrodynamic function for fish schools, Nature, Vol. 279, (1979), 418.

Peskin, C. S., The immersed boundary method, Acta Numer., Vol. 11, (2002), 479–517.

Pitcher, T. J., Functions of shoaling behaviour in teleosts. The behaviour of teleost fishes (1986), p.294-337, Springer.

Quinn, D. B., Mooed, K. W., Dewey, P. A. and Smits, A. J., Unsteady propulsion near a solid boundary, J. Fluid Mech., Vol. 742, (2014a), 152-170.

Quinn, D. B., Lauder, G. V. and Smits, A. J., Flexible propulsors in ground effect, Bioinspir. Biomim., Vol. 9, (2014b), 036008.

Rayner, J. M. V., On the aerodynamics of animal flight in ground effect, Philos. Trans. R. Soc. Lond. B. Biol. Sci., Vol. 334, (1991), 119-128.

Ryu, J., Park, S. G., Kim, B. and Sung, H. J., Flapping dynamics of a flexible propulsor near ground, Acta Mech. Sin., Vol. 32, No. 6 (2016), 991-1000.

Shin, S. J., Huang, W. X. and Sung, H. J., Assessment of regularized delta functions and feedback forcing schemes for an immersed boundary method, Int. J. Numer. Meth. Fluids, Vol. 58, (2008), 263-286.

Su, J. -Y., Tang, J. -H., Wang and Yang, J. -T., A numerical investigation on the ground effect of a flapping-flying bird, Phys. Fluids, Vol. 25, (2013), 093101.

Tang, C., Huang, H., Gao, P. and Lu, X. -Y., Self-propulsion of a flapping flexible plate near the ground, Phys. Rev. E, Vol. 94, (2016), 033113.

Tanida, Y., Ground effect in flight, JSME, Vol. 44, (2001), 481-486.

Tian, F. B., Wang, W., Wu, J. and Sui, Y., Swimming performance and vorticity structures of a mother-calf pair of fish, Computers Fluids, Vol. 124, (2016), 1-11.

Uddin, E., Huang, W. X. and Sung, H. J., Interaction modes of multiple flexible flags in a uniform flow, J. Fluid Mech., Vol. 729, (2013), 563-583.

Uddin, E., Huang, W. X. and Sung, H. J., Actively flapping tandem flexible flags in a viscous flow, J. Fluid Mech., Vol. 780, (2015), 120-142.

Ulrike, K. M., Fish 'n flag, Science, Vol. 302, (2003), 1511-1512.

Webb, P. W., The effect of solid and porous channel walls on steady swimming of steelhead trout Oncorhynchus mykiss, J. Exp. Biol., Vol.178, (1993), 97-108.

Webb, P. W., Entrainment by river chub Nocomis micropogon and smallmouth bass Microterus dolomiei on cylinder, J. Exp. Biol., Vol. 201, (1998), 2403-2412.

Webb, P. W., Kinematics of plaice, Pleuronectes platessa, and cod, Gadus morhua, swimming near the bottom, J. Exp. Biol., Vol.205, (2002), 2125-2134.

Weihs, D., Hydromechanics of fish schooling. Nature, Vol. 241, (1973), 290–291.

Zhu, L., Interaction of two tandem deformable bodies in a viscous incompressible flow, J. Fluid Mech., Vol. 635, (2009), 455-475.

Zhu, X., He, G. and Zhang, X., Flow-mediated interactions between two self-propelled flapping flags in tandem configuration, Phys. Rev. Lett., Vol. 113, (2014), 238105.

Zhu, L. and Peskin, C. S., Interaction of two flapping filaments in a flowing soap film, Phys. Fluids, Vol. 15, (2003), 1954-1960.